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CHALLENGES AND STRATEGIES ON FIBROUS FEEDSTUFFS DENSIFICATION AND ITS INTERACTION WITH LIQUID INGREDIENTS

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Challenges and Strategies on Fibrous Feedstuffs Densification and Its Interaction with Liquid Ingredients

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Herbaceous Biomass in Feed

There has been continuing interest and support in using herbaceous biomass, mostly agricultural crop residues, in the U.S. as feedstocks for producing bioenergy, liquid transportation fuels, and industrial chemicals/materials. With the potential of greater collection of agricultural crop residues for the foregoing industrial applications there will be a commensurate greater availability of crop residues for utilization in agricultural production. Agricultural crop residues are typically used in agricultural production as roughage or bedding for cattle. Use of herbaceous biomass, corn stover of greatest interest at the present time, and processing coproducts thereof, as a feed ingredient presents an opportunity to reduce ration costs and improve livestock enterprise profitability by replacing an amount of corn and other feed grains in livestock diets with proper formulation. The obvious advantage of utilizing corn stover is its wide availability and low cost.

Utilizing corn stover in animal feed is a tempting but challenging proposition. Applications could be as basic as its use as a non-traditional source of fiber or possibly as a principal ingredient in products that could replace corn grain in diets. Other replacement products could be made using the stover as the base ingredient to which dry and liquid byproducts from crop or food processing will be blended. For this proposition, the immediate challenge for feed manufacturers is how to convey corn stover, as the biomass case in point, into feed production facilities that are designed to handle flowable particulate, bulk commodity material.

Stein (2015) listed the common high fiber ingredients and he noted that those ingredients are included in diets primarily for their energy or protein. The most common high fiber ingredients available include wheat middlings, corn germ, corn germ meal, corn gluten feed, soy hulls, and alfalfa meal. However, all of these ingredients are primarily used as energy sources in diets and will, therefore, mostly replace corn in the diets. On the other hand, oilseed meals high in fiber such as canola meal, cotton seed meal, and sunflower meal are primarily used as sources of amino acids and will, therefore, primarily substitute soybean meal in diets. Distillers dried grains with solubles (DDGS) and corn germ are containing high levels of fiber as well as high levels of fat do not directly substitute for any primary feed ingredient. Essentially, these so called fibrous ingredients contribute fiber to diets as an incidental and secondary function. These feedstuffs are actually grain and seed processing by-products high in concentration of fiber. Unlike the foregoing feed ingredients, crop residues are basically all fiber. Dietary fiber consists of remnants of edible plant cell polysaccharides, lignin, and associated substances resistant to hydrolytic digestion by the alimentary tract enzymes of humans and by extension – nonruminant animals. The main components of dietary fiber are cellulose, hemicellulose, starch, pectin substances, and lignin.

Fibrous feedstuffs traditionally have not been used for nonruminants due to their documented depression of diet digestibility in pigs and poultry (Johnston et al., 2003). However, some types of fiber and fiber sources do not exert such negative effects on nutrient digestibility in older growing pigs and sows. Dietary fiber can have positive effects on gut health, welfare, and reproductive performance of pigs. Hence, nutritionists are attempting to gain a more thorough understanding of dietary fiber in swine diets. In contrast, the potential for use of fibrous feedstuffs in poultry diets is more limited with two exceptions. First, high fiber diets have important value in welfare-friendly molting programs for laying hens. Secondly, the need for controlled growth of pullets and turkey breeder candidates makes fibrous feedstuffs useful in these phases of poultry production.

DENSIFICATION OPTIONS

The difficulty with any herbaceous biomass is its low density, typically ranging from (60 – 80) kg/m^3 [(3.74 – 4.99) lb/ft^3] for agricultural straws and grasses (Sokhansanj and Fenton, 2006). These low densities often make biomass material difficult to store, transport, and utilize. Commercially, densification of biomass is performed using pellet mills and other extrusion processes, or briquetting presses, to increase the density about tenfold and help overcome feeding, storing, handling, and transporting problems. The densification process is critical for producing a feedstock material suitable as a commodity product. Densification provides several advantages, including (1) improved handling and conveyance efficiencies, (2) controlled particle size distribution for improved feedstock uniformity and density, (3) fractionated structural components for improved compositional quality. Densification systems for biomass have been adapted from such industries as feed, food, and pharmaceuticals manufacturing. These systems include (a) pellet mill, (b) cuber, (c) briquette press, (d) screw extruder, (e) tablet press, and (f) agglomerator. Among these, the pellet mill, briquette press, and screw extruder are the ones mostly considered for bioenergy feedstock processing.

Pellet Mill

Pelletization is a widely used operation in feed manufacturing, and it can be argued that it is the mainstay of commercial feed processing. In simple terms, pelleting converts finely ground ingredients into dense, free-flowing, durable pellets. A pellet has uniform product characteristics in terms of size [length: (13 – 19) mm ((0.51 – 0.74) in.) and diameter: 6.4 mm (0.25 in.)], shape (cylindrical), and unit densities [(1125 – 1190) kg/m^3, (70.23 – 74.29) lb/ft^3]. A pelletizer consists of a perforated hard steel die with one or two rollers. By rotating either the die or rollers, the feedstock is forced through the perforations to form densified pellets.

Pellet mills are either a ring die and flat die configuration. 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 die. From the conditioner, the feed is discharged over a permanent magnet for stray metal removal and into a feed spout leading to the die. Flights (vanes) in the swing door/die cover or a mechanized center feeder feed the mash evenly to the center of the die. One or two friction-driven rollers that are part of the die assembly force the feed through holes in the die as the die rotates. The feed is forced radially outward through a ring die while it is forced downward through the flat die. Cut-off knives cut the pellets to a desired length as they are extruded from the die, and the pellets then fall through the discharge opening in the swing door. The temperature of pellets coming out of the pellet mill ranges from 70 °C to 90 °C. Pellets are cooled to within 5 °C of ambient temperature in a cooler. Typical commercial units have two rollers to meet the high production rates in the range of (2.5 – 5) t/h [(2.76 – 5.52) ton/h].

Briquette Press

Briquetting is usually performed using hydraulic or mechanical piston presses, or roller presses. Unlike pellet mills, briquetting machines can handle larger-sized particles and material at a higher moisture contents without the addition of binders. Grover and Mishra (1996) found that agricultural material briquettes can be formed at 22 % moisture content using briquette machines. 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.**Error! Bookmark not defined.** These products, when subjected to heat and pressure in the die, act as adhesives and bind the particles together.**Error! Bookmark not defined.** Further addition of heat helps in relaxing the biomass fibers and softens the structure. [Briquettes produced using a hydraulic press have uniform shape and size, typically 40 mm × 40 mm (1.47 in. x 1.47 in.) cylinders, and unit densities in the range of (800 – 1000) kg/m^3 ((49.94 – 62.43) lb/ft^3).] Categorized under briquette presses are (a) hydraulic piston press, (b) mechanical piston press, (c) tablet press, (d) cuber, and (e) roller press. Cubers and roller presses have gained wider interest because of their capacity for higher throughput. Cubers are a familiar in the forage business.

Cuber

The cuber die and press wheel are similar to the die ring of a pellet mill. Cubers have a larger diameter auger, die ring, and a single press wheel. The auger moves the chopped biomass uniformly towards 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. Pressures in the cuber range from (24 – 34) MPa [(3480.9 – 4931).3 $lb/in.^2$]. The natural binders in chopped biomass, the high pressure of the press wheel, and heat generated by forcing biomass through dies combine to bond the cubes. An adjustable deflector around the outside of the die ring breaks the cubes in lengths of (50 – 75) mm [(1.97 – 2.95) in.]. Cubing operators often find it necessary to add a binder to increase cube durability. Typical binders used are bentonite, hydrated lime, starch, and lignosulfonates. Cubes exit the cuber at a temperature of more than 60 °C. A conveyor carries the cubes to the cube cooler where the cubes are cooled and dried to a moisture content of roughly (10 – 12) %. The cooled cubes are stored under roof in a flat storage.

Cubes are larger sized pellets, usually in the form of a square cross section of chopped biomass. Cube sizes range from (12.7 – 38.1) mm [(0.5 – 1.5) in.] in cross section. The length of a cube is usually equal to or longer than the dimensions of the cross section, typically from (25 – 100) mm [0.98 – 3.94) in.]. Cubes are less dense than pellets with bulk density ranging from (450 – 550) kg/m^3 [(28.1 – 34.4) lb/ft^3] depending upon the cube size.

Roller press

Roller presses consist of two rollers of the same diameter mounted horizontally on parallel axes rotating in opposite directions. Ground biomass pulled through the gap between the two rollers, is pressed into small pockets, and is thereby formed into a densified product of a shaped determined by the roller depressions - commonly a puck shape. Since the rollers turn in opposite directions, the biomass above the rollers is drawn in at the downturn of the rollers and the densified product is discharged as the rollers make their upturn. The gap setting between the rollers is set depending on the type of biomass, the particle size, the moisture content, and the addition of binders.**Error! Bookmark not defined.** 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 – 550) kg/m^3.

Screw Extruder

Processing of biomass using screw extruder occurs in four stages: (1) solids conveyance, (2) initial compression, (3) final compression, and (4) discharge. 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. Smaller particle sizes ((2 – 4) mm [(0.08 – 0.16) in.] depending on die diameter) are normally preferred during extrusion as they lead to better binding of the materials. During final compression, material biomass enters the tapered die further moisture evaporation occurs at temperatures in the order of 280 °C, and greater compression is achieved. Finally, during discharge, the pressure throughout the material normalizes, water vapor is flashed off, and a uniform extrudate produced.

Agglomerator

Not very well known in applications around agriculture, 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. 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. Agglomerators can be drum, pan, conical, and plate shaped. A granulation agglomerator involves the following steps: (1) fine raw material is continually added to the pan and wetted by a liquid binder; (2) the disc rotates causing the wetted fines to form small, seed-type particles (nucleation); and (3) the seed particles “snowball” by coalescence into larger particles until they are discharge from the pan.

Factors in Densification

Controlling variables in densification is key for producing densified biomass of a desired quality and performance. Just like any other unit operation in agricultural processing, densification is affected by the physicochemical properties of the feedstock and the process variables. Specifically, the quality of the densified product can be managed by controlling conditions such the manufacturing process, changes in formulation, and the use of additives (MacMahon, 1984). Process variables such as die geometry, roller setting, steam conditioning, and feed rate all affect the quality of densified biomass like density and durability. Feedstock physical properties include moisture content and particle size, shape, and size distribution. Thomas et al. (1998) identified starch, protein, sugar, non-starch polysaccharides (NSP, e.g., protein, fat, cellulose, hemicelluloses, and lignin), fat, fiber, inorganic matter, and water as chemical constituents affecting pellet quality. By extension, these chemical constituents affect any densification operation of any biomass.

Preprocessing of Biomass

Prior to densification, biomass has to be ground to a particle size optimal for the method of densification. This grinding partially breaks down the lignin, increases the specific area of the material, and improves binding. In this regard, the feed value of the biomass is also improved or could be improved with the blending with other ingredients. Fine grinds have more contact points, exposed surface area, and surface energy per unit weight. Apparent water holding capacity of corn stover grinds was measured to be approximately 8.5 mL/g thus they can potentially absorb an amount of water-based by-product liquids for improvement of nutritive value. From their study of wheat and barley straws and corn stover, Mani et al. (2006) concluded that the particle size has significant effect on the mechanical properties of pellets, which is a finding that should translate to other densification options as well.

For the quantities required for bioenergy applications, grinding rates greater than 1 ton/min. are needed. Kaliyan et al. (2012) studied commercial scale grinding of corn stover and perennial grasses with semi-mounted (semi-trailer truck) tub grinders of greater than 475 HP involving moisture and screen size as treatment factors. For moisture content ranging from approximately 10 % to 25 %, they found no moisture-induced effect on particle size was observed for the crops that were tested. Moisture did, however, affect efficiency and production rate. Both efficiency and production rates were reduced by increasing the moisture content of the biomass being processed. By decreasing the size of the screens used, the mean particle size also decreased, but decreasing the screen size also resulted in decreased efficiency. Although it is simple enough to reduce the screen size in the grinder to produce the smallest particle size required, the power input that will be required to achieve that size also needs to be considered to determine what the best and most economical particle size will be.

Any of the industrial grinders contracted to function as a component of the man-machine system developed by ADM Alliance Nutrition, Inc. for applying the calcium hydroxide ($Ca(OH)_2$) treatment process on farm [*grinding corn stover to a (76.2 –127) mm [(3 to 5) in.] chop length then treating with* $Ca(OH)_2$ *at an inclusion level of 6.6% of the stover dry matter, increasing the moisture content of the treated mass to 50% wet basis, and then tightly packing the material*] was capable of grinding corn stover at throughputs in the 1 ton/min. range. The grinders contracted were all semi-mounted industrial tub grinders fitted with screens that are equivalent to a 6 in. round-hole screen. The grinder-screen pairs monitored during commercial treatments produced ground stover with geometric mean particle length of 9.4 mm (0.37 in.) and a geometric standard deviation 8.4 mm (0.33 in.) measured according to ASABE Standard S424.1 (ASABE Standards, 2009). The largest particles in the grinds before alkali treatment had an arithmetic mean length of 109.2 mm (4.3 in.). What appeared consistent in this study and in other research is that moisture content of stover bales stored in the open tended to be higher for older bales. Moreover, particle size and grind rate vary in direct proportion to the screen size used in grinding. Treated stover could be ground further after drying to about (12 – 15) % moisture and could be used as a fiber in a swine diet as was tested by Perez et al. (2015).

POTENTIAL

From firsthand experience, it is evident that corn stover as case in point can only be effectively transported into and conveyed within existing animal feed manufacturing plants and therein utilized as a feed ingredient only when it is converted into a consolidated form that can be handled by bulk solids handling system trains that include conventional gravity conveyance equipment. One solution to this challenge is densification of the corn stover into pellets, briquettes, or cubes. Strategically positioned feed manufacturing facilities or that of commercial partners can serve as centers for the preprocessing of corn stover or, essentially, logistical depots. In this role, this facility will serve as the entry point for herbaceous biomass into the broader production system. Main products from the processing of corn stover at this depot are two stover ingredients: (a) regular stover and (b) enhanced stover] and blended commodity type product(s) such as a corn replacement feed. The enhanced stover results from the chemical treatment of stover to enhance its nutritional value using a chemical treatment process developed by ADM Corporate Research. Another option for the conveyance of corn stover into ANI facilities is to modify designated manufacturing facilities so that ground stover can be delivered directly into the industrial mixer in plants for product formulation. This option would apply to plants directly utilizing corn stover in their production of animal feeds and would involve a subset of the process operations within the depot and installation of a system for handling ground stover with grind size of about ¼ in. (6.4 mm).

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