A COST ANALYSIS FOR THE DENSIFICATION AND TRANSPORTATION OF CELLULOSIC BIOMASS FOR ETHANOL PRODUCTION

by

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Abstract

The current forage handling equipment in the cellulosic ethanol industry is severely limited by the low bulk densities of baled and ground biomass. Low bulk densities contribute to flowability problems and lack of maximizing trailer capacities. By pelleting we can increase the bulk density and flowability characteristics of forages. The objectives of this research were to evaluate (1) the energy requirements of grinding sorghum stalks, corn stover, wheat straw and big bluestem through two different screen sizes, (2) the energy requirements of pelleting forages from the two grind sizes, and (3) the physical properties of our various end products. The two screen types were found to have significantly different energy consumptions from each other ($P<.0001$). The majority of the four forage types were also found to have significantly different energy consumptions for grinding from each other ($P<.0001$). The exception was big bluestem vs. corn ($P=.2329$). All of the 1/8" vs. 1/8" and 1/8" vs. 3/8" grinds were significantly different from each other (Most $P<.0001$ and all at least $P<.05$). 3/8" sorghum was significant against all other 3/8" forage types. No other comparisons were significant for 3/8" vs. 3/8" (All 3/8" sorghum $P<.0001$). Production rate through the 3/8" screen was almost 3 times that of the 1/8" screen (Average of 400 lb/hr vs. 150 lb/hr). The two screen types were found to have significantly different energy consumptions for pelleting from each other ($P<.0001$). The four forage types were also found to have significantly different energy consumptions from each other ($P<.0001$) while the big blue vs. wheat did not. ($P=.1192$). Particle length for the 1/8" grind ranged from .06 inches to .07 inches, while the 3/8" grind ranged from .08 inches to .12 inches. Pelleting increased bulk density from 6.24 lb/ft^3 to 9.99 lb/ft^3 for biomass grinds to 31.17 lb/ft^3 to 43.77 lb/ft^3 for pelleted biomass. Pellet quality ranged from 93% to 98%. A cost analysis indicated that it would take roughly $20 extra per ton for the transportation, pre-processing and storage of pelleted cellulosic biomass than whole corn. This cost is still almost half that of the cost for baled biomass.

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Dedication

To my wife and my daughter, without whom, I would be nothing.

Introduction

As the U.S. strives to reduce it's dependency on foreign energy, the interest in utilizing renewable agricultural resources, for energy, continues to gain momentum. The concept of utilizing renewable resources to replace petroleum based products is not new; however, the government subsidies associated with the 2002 Energy Independence Policy, resulted in the enormous growth of the renewable fuels industry. This lead to the great boom of corn based ethanol, which affected nearly all the related industries, due to volatile corn prices. If the U.S. is to gain energy independence, without compromising its food supply, it will have to come from multiple sources.

Cellulosic based ethanol is an alternative that could help to lessen the dependency on foreign energy. Cellulosic ethanol is produced from lignocellulose. Lignocellulose if composed of cellulose, hemicellulose and lignin. Examples of such being wheat straw, switchgrass, woodchips, citrus peels and numerous other plant based organic biomass. Cellulosic ethanol is very attractive because of its high net energy yields. The drawback is the additional processing required to make the sugars available for microorganisms to ferment into ethanol.

In 2007 the Energy Independence and Security Act was passed. The act requires the use of 36 billion gallons of renewable ethanol fuels by 2022, 21 billion gallons of which must be derived from non-cornstarch sources, such as cellulosic ethanol. The purpose of the legislation is to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.

Transportation logistics are hindering large scale cellulosic ethanol production. Whereas whole corn is roughly 45 lb/ft^3, most ground cellulosic sources are below 10 lb/ft^3. In order for cellulosic ethanol to become a real solution, improvements on the overall process efficiency will be required. Specifically optimizing the receiving and handling options that ethanol plants can use.

Literature Review

U.S. Energy Policy

High gasoline prices, concerns over global warming, and the desire to economically stimulate domestic rural communities have greatly increased interest in biofuels as an alternative fuel in the U.S. Biofuel use has grown significantly in the past few years as a component of the U.S. fuel supply. Ethanol, the most commonly used biofuel, is blended in nearly half of all U.S. gasoline (Yacobucci and Schnepf, 2007). However, current biofuel supply only represents a small portion of total gasoline demand.

While recent government initiatives have set the goal of significantly expanding biofuel supply in the coming decades, questions remain about the ability of the U.S. biofuel industry to meet rapidly increasing demand. Current U.S. biofuel supply relies almost exclusively on ethanol produced from corn. To meet the proposed ethanol production goals would require more corn than the United States currently produces, if all of the proposed ethanol was manufactured from corn. Thus, the Renewable Fuels Act was proposed, which dictates a volumetric breakdown of total ethanol production between multiple biomass sources.

Due to the concerns with significant expansion in corn-based ethanol supply, interest has grown in expanding the market for biodiesel produced from soybean oil and other cost effective fat sources. However, a significant increase in U.S. biofuels would likely require a movement away from food and grain crops as feedstocks for ethanol production. Other biofuel feedstock sources, including cellulosic biomass, are promising, but technological barriers and infrastructure shortcomings make their future uncertain.

The Renewable Fuel Standard program regulations were developed in collaboration with refiners, renewable fuel producers, and many other stakeholders. The RFS program was created under the Energy Policy Act of 2005, and established the first renewable fuel volume mandate in the United States. The original Renewable Fuel Standard program required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012 (U.S. Congress, 2005).

Under the Energy Independence and Security Act (EISA) of 2007, the RFS program was expanded in several key ways. EISA expanded the RFS program to include diesel, in addition to gasoline, increased the volume of renewable fuel required to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 and required EPA to apply lifecycle greenhouse gas performance threshold standards to ensure that each category of renewable fuel emits fewer greenhouse gases than the petroleum fuel it replaces (U.S. Congress, 2007).

U.S. ethanol production in 2006 consumed roughly 20% of the U.S. corn crop. If only corn is used, expanding ethanol production to 36 billion gallons would require more corn than the United States currently produces (Yacobucci and Schnepf, 2007). Therefore, the EISA requires large amounts of biofuels produced from feedstocks other than corn starch, such as sugarcane, oil crops and cellulosic biomass.

The objectives of the EISA are to significantly reduce greenhouse gas emissions from the use of renewable fuels, reduce the volume of imported petroleum and encourage the development and expansion of our nation's renewable fuels sector. Other facets of the law include mandated fuel economy standards for all new vehicles, new conservation requirements for federal vehicle fleets, new energy consumption standards for light bulbs, expanded federal research on carbon sequestering technologies and a redesigned energy transportation infrastructure (U.S. Congress, 2007).

Ethanol Production Using Corn-Starch

Industry and Growth

In the late 1800's, Henry Ford, Nicholas Otto and others built engines capable of operating on ethanol. The 1908 Model T was equipped with adjustable carburetors that allowed it to function using a combination of gasoline and ethanol. Various alcohol/gasoline blends were marketed during the 1930's under trademarked names such as Alcolene and Agrol. However, after World War II, interest in ethanol decreased because leaded gasoline proved more cost effective and easier to produce while new oil discoveries reduced the necessity of finding alternatives to petroleum (Kovarik, 1998).

Leaded gasoline was phased-out of production in the 1980's by the policies of the Environmental Protection Agency (EPA), interest increased in using ethanol as an octane booster. However, methyl tertiary butyl ether (MTBE) dominated most oxygenated gasoline markets over ethyl tertiary butyl ether (ETBE) throughout the 1990s. In 1980, Congress approved several more tax breaks, as well as loan and price guarantees, to support ethanol producers and blenders. The growth of this industry was again slowed by low gasoline prices following the oil price collapse of the mid 1980s (Solomon et al, 2007).

Over the past decade, specifically since 2002, ethanol production in the United States has seen rapid growth. Ethanol is a high-octane biodegradable engine fuel produced from renewable biomass. It is used as a blend component in more than 90% of the nation's gasoline supply today to improve engine performance, reduce engine knock, reduce harmful emissions, and lessen our reliance on imported oil for our fuel needs (Renewable Fuels Association, 2011b).

Most ethanol is consumed as an additive to gasoline, comprising up to 10 percent of the fuel blend (E10). Increasingly, however, ethanol is being used as a gasoline replacement in the form of "mid-level blends," such as E30, E40 and up to E85. Today, the starch in grains such as corn and sorghum is the feedstock for approximately 99% of all U.S. ethanol production (Renewable Fuels Association, 2011b).

The Renewable Fuels Association estimates that as of January 2011, there are 194 operating ethanol biorefineries in 29 states within the U.S. Collectively, these plants produce 13.5 billion gallons of ethanol each year. There are currently 10 biorefineries under construction or expanding, which will produce an additional 522 million gallons annually (Renewable Fuels Association, 2011a).

Government subsidies have been partially responsible for the rapid growth of the ethanol industry. To meet increasing demand, producers planted greater acres to corn in place of other crops. Concerns have been widely voiced about the sustainability of the ethanol industry, and competition for corn acreage has pushed all commodity prices to an all time high. Debate has also waged regarding the fuel versus food debate and how ethanol production will impact food grade corn availability and price.

Process

The two commonly used methods for extracting starch from corn kernels for ethanol fermentation are dry milling and wet milling. In the dry milling process the entire corn kernel is ground into a flour or meal. The meal is then mixed into slurry by adding water and enzymes, which convert the starch to dextrose. Control of pH is achieved with various additives to optimize conditions for microbes during the fermentation process. The mixture is processed at high-temperatures to reduce the bacteria levels and transferred to fermenters where it is allowed to cool. Microbial cultures are added and conversion from sugar to ethanol and carbon dioxide begins. The microbes utilize the available sugars and generate ethanol as a by-product.

All products are then transferred to distillation columns where the ethanol is removed from the stillage. The bound water molecules are then removed by benzene or molecular sieves to increase the alcohol concentration to approximately to 100%. The remaining stillage then undergoes a drying and separation process resulting in DDGS. Most operations also capture the CO_2 that is released and sold to the carbonated beverage industry (Renewable Fuels Association, 2011c).

The wet milling process involves steeping grain it in a dilute combination of sulfuric acid and water in order to separate the grain into the bran, the germ and the starch components. The corn kernel is then fractionated into its separate components by a degermination machine. Corn oil is a by-product of this process that is extracted from the germ and sold as a high value product. The remaining components of fiber, gluten and starch are segregated with centrifugation.

The gluten protein is dried and filtered to make a corn gluten meal, a high protein feed ingredient. The steeping liquor is concentrated and dried with the fiber and sold as corn gluten feed, as a liquid feed additive or filtered so the water can be recycled back into the fermentation system. The fractionated corn starch is then fermented into ethanol, through a process similar to dry milling.

The wet milling process allows for a much more efficient system and also produces a variety of valuable co-products that can be used in human food and animal feed. The actual fermentation process can be completed through a batch or continuous process. Both of which will yield similar products. Efficiency and up-front manufacturing costs are the driving force behind which fermentation process to install (Renewable Fuels Association, 2011c).

Each bushel of corn yields 2.8 gallons of ethanol and 17 pounds of distiller's grains with solubles and CO_2 gas. Since 2001, energy requirements (thermal BTUs) for ethanol production have fallen 28% and electricity usage is down 32%. Each gallon of ethanol production capacity requires approximately 2.7 gallons of water. That is roughly equal to the amount of water needed to produce a gallon of gasoline. Continuous fermentation processes allow for a portion of this water to be recycled back into the process. Ethanol yields between 1.9 and 2.3 units of energy for every one unit of energy used in production (Renewable Fuels Association, 2011b).

Volatility of Corn Prices

Corn accounts for about 98% of the feedstocks used in ethanol production in the United States. The USDA estimates that 3.2 billion bushels of corn (or 24% of the 2007 corn crop) were used to produce ethanol during the September 2007 to August 2008 corn marketing year (USDA, 2007).

The ethanol-driven surge in corn demand has been associated with a sharp rise in corn prices. For example, the futures contract for July 2011 corn on the Chicago Board of Trade fell from $6.58 per bushel in August 2008 to a contract low of less than $3.80 per bushel in June 2010 (a decrease of 58%). The contract then rose to a high of over $7.80 in April 2011 and is currently trading at $7.45 in May 2011. Corn prices have not only experienced great volatility since ethanol production has grown, but they have also seen a drastic overall price increase (CME, 2011). The average U.S. cash price of corn was $2.15 during the 10-year period stretching from 1997 to 2006 (CBO, 2009).

This sharp rise in corn prices owes its origins largely to increasing corn demand spurred by the rapid expansion of corn-based ethanol production capacity in the United States since mid-2006. The rapid growth in ethanol capacity has been fueled by both strong fuel prices and a variety of government incentives and regulations. Major federal incentives include a tax credit of $0.51 for every gallon of ethanol blended with gasoline, a $1.01 per gallon tax credit for cellulosic ethanol, farm bill programs from the USDA, and loan/grant money from the DOE for renewable energy research and the production of new plants or modification of outdated plants. (Yacobucci, 2008).

Food or Fuel

U.S. ethanol production is not the direct factor behind food prices, but has caused volatility in food prices due to market speculation and corporate marketing strategies. Ethanol production only uses 3% of the world's supply of grain on a net basis (Renewable Fuels Association, Pocket Guide to Ethanol, 2011), but many critics of federal biofuels subsidies and the RFS argue that a sustained rise in grain prices, driven by ethanol feedstock demand, will lead to higher U.S. and world food prices, with potentially harmful effects on consumer budgets and nutrition (CBO, 2009). It is important to distinguish between prices of farm-level crops and retail-level food products because most food prices are largely determined by costs and profits after the commodities leave the farm (USDA, 2011). Basic economics suggests that the price of a particular retail food item will vary based on the price of its underlying ingredients in direct relation to the relative value of that ingredient.

Increases in energy prices have a greater impact on food prices than the price of corn. A 33% increase in crude oil prices, translates into a $1.00 per gallon increase in the price of conventional gasoline results in a 0.6% to 0.9% increase in the CPI for food while an equivalent increase in corn prices ($1.00 per bushel) would cause the CPI for food to increase only 0.3%. It is unlikely that the ethanol-driven corn price surge is a direct factor in current food price inflation estimates (Urbanchuk, 2007). Furthermore, economists generally agree that most retail food price increases are not due to ethanol-driven demand increases, but rather are the result of two major factors: a sharp increase in energy prices, which ripples through all phases of marketing and processing channels, and the strong increase in demand for agricultural products in the international marketplace (Collins, 2007).

In addition to fuel, ethanol producers also supply a growing volume of livestock feed, in the form of dried distiller's grains with solubles (DDGS). One-third of each bushel of corn used in ethanol production is returned to the feed market. Because starch is the only component of grain utilized during the fermentation, the other nutritional attributes, such as protein and fat, are concentrated approximately three times. The production of distiller's grains is of great benefit to the meat production industry. It provides them with a cost competitive ingredient that has 3 times the nutritional value of corn.

However, ethanol production does have an impact on the types of crops planted. In 2010, farmers produced more than 12.45 billion bushels of corn based on 152.8 bushels per acre, the third-largest crop and fourth-highest average yield on record. The 2010 crop was the fourth in a row and the fourth in history larger than 12 billion bushels produced on virtually the same amount of acres used in the mid-1970s (2010 USDA Crop Report).

In the U.S., we have a specific amount of farmland available that is capable of producing a quality crop with acceptable yields per acre. Advances in farming technology and crop genetics have helped to increase yield per acre dramatically (Kaughman and Snell, 1997). USDA trend projections suggest U.S. corn yields per acre will reach 168 bushels in just a few years. Each 5 bushel increase in yield above the current trend level would be the equivalent of adding around 2.5 million acres of corn, enough to produce an additional one billion gallons of ethanol each year (Collins, 2007).

Changes in plant genetic and production practices require time and the quickest way to increase corn production is to replace acres devoted to other crops with corn. With market prices shifting in favor of planting corn at the expense of wheat, soybeans and other crops, a sharp increase in acreage planted is expected to continue for corn. The prospective increase in corn acreage is already having ripple effects on agricultural commodity markets.

We have seen the price of other commodities, such as wheat and soybeans, rise drastically over the past decade alongside corn. This is due in part to a decrease in the amount of acres planted for these commodities. Other issues the market could potentially face include drought, disease, natural disasters or demand overtaking our available supply. The goal of energy independence could be hindered by poor growing seasons resulting in a large increase in ethanol price or a lack of product to produce ethanol (Collins, 2007).

To meet the demand for biofuels, some corn acreage could return to production from land in the long-term Conservation Reserve Program (CRP), as contracts expire, but that land may be environmentally sensitive and would need to be properly farmed. In addition, former CRP land may have lower yields due to terrain, geographical considerations and soil type. This would result in additional time and resources before such land can be made suitable for crop production (Collins, 2007). It would be beneficial to the U.S. to diversify our fermentation substrates through a variety of different products grown in separate geographical locations throughout the U.S in order to lessen the risk of price spikes due to lack of production volume.

Brazilian Alternatives

Behind the U.S., Brazil is the second largest producer of ethanol in the world. Brazil is a leading competitor in the ethanol industry due to its sugar cane production (Solomon et al, 2007). Sugar cane is fermented through a similar process as corn, only an enzymatic breakdown of starch is not necessary. Over half of the cars in Brazil ran on 95% ethanol (E95) in the late 1980's, but sugar shortages and price increases have reduced that figure to 20% today. It is mandated that gasoline sold in Brazil today must have at least a 25% anhydrous alcohol blend (E25). Ethanol currently comprises about 40 percent of the total vehicle fuel used within the country (Knight, 2006).

In addition to expanding domestic production of biofuels, there is some interest in expanding imports of sugar-based ethanol from Brazil and other countries. However, ethanol from Brazil is currently subject to a $0.54 per gallon tariff, by the U.S. govermnet, that in most years is a significant barrier to direct Brazilian imports. In 2006, ethanol prices rose sharply and direct imports from Brazil increased, despite the tariff. Some Brazilian ethanol can be brought into the United States duty free if it is dehydrated in Caribbean Basin Initiative (CBI) countries. Up to 7% of the U.S. ethanol market could be supplied duty-free in this fashion, although historically ethanol dehydrated in CBI countries has only represented about 2% of the total U.S. market (Yacobucci and Schnepf, 2007). Sugar cane production in the U.S. is restricted by our geographical location and growing season. The U.S. is thereby limited to imports instead of manufacturing its own sugarcane in quantities great enough to supply energy needs.

Ethanol Production Using Cellulosic Biomass

General Information and History

The first successful attempt at a cellulosic based fermentation was conducted in Germany during 1898 (Katzen 2005, 2008). They used a diluted acid to hydrolyze the cellulose to glucose, which was then fermented into ethanol by added microbes. This process was very inefficient and only yielded about 18 gallons of ethanol per ton of cellulose. Today our industry focuses on a combination of acidic and enzymatic hydrolysis to break the complex cellulose into glucose. This has lead to a large increase in efficiency.

The potential supply of lignocellulosic biomass sources for ethanol is far greater than that of food crops, but development has been impeded because of the costly and inefficient preprocessing methods of biomass materials necessary for the hydrolysis of cellulose into sugars. Recent developments by enzyme production companies, such as Genencor International and Novozymes Biotech, have resulted in up to a 30-fold drop in the cost of enzymes for hydrolysis (Solomon et al, 2007). More efficient preprocessing will allow cellulosic ethanol to become a competitor with corn based ethanol on a full size production scale. New methods are being actively researched and developed to produce ethanol from cellulosic biomass. These include dilute sulfuric acid and enzymatic hydrolysis, gasification, fast pyrolysis, and concentrated acid processes (So and Brown, 1999). However, chemical pretreatment of the feedstock is still required to pre-hydrolyze hemicellulose, so that it can be more effectively converted into simple sugars.

There are two ways of producing ethanol from cellulose, cellulosic hydrolysis and gasification. Cellulosic hydrolysis consists of a pretreatment phase to make the lignocellulosic material available for hydrolysis, the actual hydrolysis of complex molecules into simple sugars, separation of the sugar solution from lignin, microbial fermentation, distillation and dehydration to bring the alcohol content over 99.5% (Zhu et al, 2009). The gasification process converts the carbon structures of biomass into varying amounts of synthetic gases, using what amounts to partial combustion. The carbon monoxide, carbon dioxide and hydrogen gases are then fermented by a Clostridium variant. This microorganism will consume carbon monoxide, carbon dioxide and hydrogen and produce ethanol and water. The resultant ethanol and water is then distilled and dehydrated (Asadullah et al, 2001).

In its pre-processed form, biomass is difficult to utilize as a fuel because it is bulky, wet and dispersed (Balatinecz, 1983). Disadvantages of biomass as an energy source include inefficient transportation and large volumes required for storage. Solving these problems is essential for the effective utilization of biomass as a fermentation medium.

Production of biomass

Wheat straw, native grasses, corn stover and sorghum stalks represent some of the largest quantities of farmland forages that the U.S. currently produces. The U.S. needs to be capable of producing enough volume to supply the ethanol industry if it hopes to meet the criteria of the Renewable Fuels Act of 2007 in the coming years.

The quantities of wheat straw, corn stover and sorghum stalks are a direct result of acreage planted, tillage practices and residues left in the field. Crop residues play a vital role in maintaining soil characteristics (organic matter and moisture content), controlling erosion, controlling chemical runoff and ensuring long term production of the soil (Walsh, 2008). Consideration will need to be given for farming operations using no-till, which will yield more biomass for ethanol production. Through no-till farming, water and organic matter are retained in the soil and the chances of erosion are decreased. No-till cultivation is practiced on more than 62 million acres, and another 50 million acres are part of another conservation tillage system (CTIC, 2004)

Nelson et al (2004), using average acres and yields from 1997 to 2001, estimated 390 million dry tons of wheat straw could be available in the Midwest if every cropland acre was in the specified rotation (continuous or rotated with other grains), and tillage (no-till, conventional, reduced till) combination assuming sufficient straw quantities remained to control for wind and water erosion at the tolerable soil loss level.

Agriculture is continuing to change and adapt as new technologies become available and circumstances arise. Biotechnology is transforming agriculture by creating an additional market for genetically altered varieties of corn, sorghum and wheat, specifically engineered for ethanol production. Biotech hybrids of corn now account for 40 percent of the total planted acreage (National Corn Growers Association, 2004).

As part of The Billion Ton Study, Perlack et al (2005) evaluated the potential supply that multiple sources of biomass could provide to the cellulosic ethanol industry. They developed multiple scenarios that looked at potential crop yields, residue to grain ratios, tillage practices, land use and secondary processing. They examined the current amount of available biomass, biomass available through technology changes on conventional crops (such as corn or wheat) and biomass available through technology changes in both conventional crops and new perennial crops.

In scenario one, they found that the amount of biomass currently available for ethanol production was about 194 million dry tons annually. This is about 16 percent of the 1.2 billion dry tons of plant material produced yearly on agricultural land before 2005. It included 113 million dry tons of crop residues, 15 million dry tons of grain used for ethanol production, 6 million dry tons of corn fiber, and 60 million dry tons of animal manures and byproducts. The single largest source of this current potential is corn residues or corn stover totaling close to 75 million dry tons. Wheat straw made up 11 million dry tons per year, sorghum accounted for less than 2 million dry tons and native grasses accounted for roughly 21 million dry tons.

They found that corn stover is a major untapped source of agriculture-derived biomass and that only one fifth of the total biomass currently available is being utilized for production purposes.

Scenario two examined the potential increases in biomass production we could expect to see due to technological advances in the agricultural sector. The rates of increase in yield for all crops were the same as those used by USDA-OCE in their baseline projections. Available acreage remained the same as the first scenario.

Under these parameters, total available biomass from cultivated farmland ranged from 423 to 597 million dry tons per year. Crop yield increases were calculated for each biomass types and they ranged from 25% increases to 50% increases. The amount of corn and soybeans available for ethanol and biodiesel was calculated by first subtracting amounts needed to meet food, feed and export requirements. All remaining grain was assumed to be available for biofuels. This worked out to a more than three-fold increase in production volume under the moderate yield increase and more than a five-fold increase under the high yield increase. In this scenario, 75% of total cellulosic biomass is from crop residues. They authors do note that attaining these levels of crop yield increase and collection will require a continuation of research, development of new technologies and incentives, such as government subsidies. Past trends indicate that such increases are certainly attainable given that opportunity and inputs are available.

Scenario three assumes the addition of perennial crop, land use changes and changes in soybean varieties, as well as the technology changes assumed under the previous scenario. Perennial crops grown primarily for ethanol expand to either 35 million acres at 5 dry tons per acre per year, for the moderate yield, or to 55 million acres with average yields of 8 dry tons per acre per year, for the high yield. The land use changes are assuming the conversion of 40 to 60 million acres of unutilized land, cropland and pasture to grow perennial forages. 93% of the perennial crops are assumed available for ethanol and the remainder for other products. A 10% loss is accounted for during harvesting.

Under this scenario, the authors expect to see total availability of biomass increase to levels between 581 and 998 million dry tons per year. The drastic differences are a result of errors accounted for in each biomass types as well as moderate yield versus high yield. The high yield scenario is unlikely to be attainable because of the sacrifices required in pasture and traditional cropland acreage. This scenario has merit if seed crop genetics can be altered so that plants are capable of producing more cellulosic biomass without sacrificing grain yield.

Advantages/Disadvantages of Cellulosic Ethanol

The potential supply of lignocellulosic biomass crops for ethanol far exceeds our supply of food crops. As such, cellulosic ethanol has the capability to compete on an industrial scale with gasoline, if the process can be optimized. Cellulosic ethanol is an attractive alternative to gasoline, due to concerns over climate change, peak oil supply, rising oil prices, and Middle Eastern political instability.

Ethanol produced from cellulosic feedstocks has the potential to improve the energy and environmental effects of U.S. biofuels while offering significant cost savings on the production side. Benefits of forages include a high production yield, they can be grown under a variety of growing conditions/ land types and they are capable of being harvested multiple times throughout the year. Moving away from feed and food crops to dedicated energy crops could avoid some of the agricultural supply and price concerns associated with corn based ethanol.

A key potential benefit of many of cellulosic feedstocks is that many can be grown without the need for chemicals. Reducing or eliminating the need for chemical fertilizers would address one of the largest energy inputs for corn-based ethanol production. Using biomass to power a biofuel production plant could further reduce fossil fuel inputs. Improving the net energy balance of ethanol would also reduce net fuel-cycle greenhouse gas emissions (Yacobucci, 2007).

We are, however, uncertain regarding both the costs of processing forages for ethanol production as well as the costs of producing biofuel from them, in large scale applications. Models for cost and logistics analysis have been developed by Hess (et al, 2007), Krishnakumar (2010) and Mukunda (2007). Since large scale data from operating cellulosic ethanol plants is not available, certain assumption must be made for calculations. Before we can accurately predict the cost savings of preprocessing forages before ethanol production, production scale electrical data must be obtained for calculations and comparisons. High cellulose crops tend to have low bulk densities and this represents a significant problem in terms of harvesting, transportation and storing. Forage production is seasonal and efficient means for product storage must be addressed. It is unlikely that facilities will keep more than two weeks supply of biomass on-hand and product degradation may also become an issue in some situations.

Increases in per-acre yields would be required to make most cellulosic energy crops for fuel production economically competitive. Forages such as photoperiod sensitive sorghum would be ideal for cellulosic ethanol production based on their high cellulosic yields. Questions remain whether high yields can be achieved without the use of fertilizers, pesticides and irrigation though.

The USDA estimates that, by 2030, 1.3 billion tons of biomass could be available for bioenergy production (including electricity from biomass, and fuels from corn and cellulose). From that, enough biofuels could be produced to replace roughly 70 billion gallons of gasoline per year (Perlack et al, 2005). This prediction assumes large increases in per-acre yields and it represents the largest quantity the U.S. is capable of producing.

Other potential environmental drawbacks associated with cellulosic fuels must be addressed, such as the potential for soil erosion, runoff, and the spread of invasive species (many potential biofuel crops are invasive species when introduced

Logistics Problem

Current facilities

The effectiveness and feasibility of cellulosic biomass as an energy source for ethanol production is limited by the current harvesting/processing equipment, transportation system and storage systems that we currently have available for on the farm use. The low bulk densities that bales and ground biomass have make it difficult to handle and transport in the large quantities required for commercial ethanol production.

By increasing the bulk densities of cellulosic biomass, we will positively influence the flow characteristics and allow for easier handling. This will also allow us to maximize the payload that can be hauled by tractor/trailers or railcars. Using an existing corn ethanol plant in Indiana, Mukunda (2007) showed that transportation is the largest component of the logistics cost of delivering biomass from the farm production centers to the plant processing centers.

The physical properties of the ground biomass prevent it from flowing properly during the unloading, storage and transfer operations at a biorefinery. These flow characteristics would require biorefineries to install specialized equipment and would make retrofitting existing corn based ethanol plants into cellulosic ethanol plants almost impossible. Conveying equipment is capable of moving specific volumes of material. If a low bulk density product was introduced into the flow, the performance of all downstream equipment would be affected and plant throughput would be drastically lowered. Other costs associated with handling a low bulk density feedstock include the additional conveyor capacity and storage facilities in order to handle light material. The added cost of the new equipment could be reduced or eliminated if the bulk density of the feedstock could be increased prior to delivery (Mani et al, 2006).

Storage and Degradation Concerns

Biomass utilized for ethanol would most likely require a storage facility before delivery to the ethanol plant in order to prevent degradation of the cellulose content due to weather. This would require a large amount of shed space or full poly wrapped bales, neither of which is cost effective.

In regards to feedstock storage, Cushman et al. (2003) state storage systems (such as baling, compacting or pelleting) need to increase feedstock density by 2.5 times in order to be considered relevant. If biomass from multiple forage sources could be pelleted and stored in grain storage facilities, then a pelleting system could be utilized at different times of the year, such as cool season grasses in early spring, wheat, barley and oat straw during the summer, corn and grain sorghum stalks in the fall, and perennial grasses such as switchgrass in the early winter.

It is unclear what effects degradation would have on cellulosic ethanol conversion, but they would most likely be negative. Decomposition of the cellulosic material decreases the amount of substrates available to the microbes for fermentation. It could also introduce wild fermentations into the production system and result in the formation of volatile fatty acids, which could inhibit the desired fermentation. Therefore, it would be beneficial to develop a model capable of storing forages in existing grain storage facilities.

Transportation

Another limitation is the inability to maximize payload due to the bulk density. Tractor/trailers are regulated based on volume and weight. Ideally, we would reach the weight rating before maximizing volume in order to haul the most material possible. If a semi were capable of hauling 1,100 $lb/ft/^3$ of product, it would hold 49,500 pounds of corn, at 45 $lb/ft/^3$, or 8,800 pounds of ground forages, at 8 $lb/ft/^3$.

Hess et al (2007) stated that feedstock production and logistics constitutes 35 to 50% of the total production costs of cellulosic ethanol. The actual percentage depends upon geographical factors such as biomass species, yield, location, climate, local economy and the types of systems used for harvesting, collection, processing and transportation. Producers can only influence the variety of crops grown and the types of equipment used for harvest and processing. Increasing the bulk density through additional processing can have a significant impact on our bottom line and also increase the distances we can afford to transport product.

A pilot study (Hess et al., 2006) of a straw based ethanol plant reported that at feedstock bulk densities of 128 kg m^{-3} (8 lbs ft^{-3}), 80 percent of the feedstocks available within a 100 mile radius of the plant must be delivered to the plant. To reduce transportation costs, 76 percent must come from with 80 km of the plant, 17 percent from 80 to 120 km of the plant, and 12 percent from 120 to 160 km of the plant to supply 105 percent of demand. If transportation costs can be reduced by increasing feedstock density, it possible that these percentages can be reduced and the radius that feedstocks are drawn from can be increased to ease the pressure on fields near the biorefinery to supply feedstocks.

Cushman (et al., 2003) observed several goals, limitations and research needs in order for biomass based feedstocks to be feasible. Most limitations were associated with harvesting, preprocessing, transporting, and handling of the feedstocks since the current forage technology is not capable of producing and transporting the 800,000 to 1 million tons of feedstocks annually to a biorefinery efficiently. Strategic goals of increasing efficiency by utilizing existing transportation infrastructure, demonstrating cost effective storage systems for mega-ton quantities, and increasing biomass value at every stage of the feedstock chain can be addressed with pelleting biomass. If biomass is pelleted, it can be handled and transported with grain handling equipment in the field, on the road and at the biorefinery.

Forage Grinding

Purpose

Biomass particle size reduction reduces the shape, increases bulk density, improves flow properties, increases porosity and generates additional surface area (Drzymala, 1993). Particle size reduction also aids in the utilization efficiencies of animal and microbial digestion by exposing for surface area for degradation by acids and enzymes.

Size reduction accounts for a huge portion of the power requirements needed for the conversion of cellulose into ethanol. Energy requirements for grinding depend on its initial particle size, moisture content, material properties, machine throughput and other machine variables (Mani et al, 2004).

Types of Grinders

Scholten (et al, 1985) reported that hammer mills have achieved merit because of their ability to finely grind materials better than any other machine. Hammermills use high-velocity rotating shafts connected to a central hub that houses either free swinging or fixed blades that are known as the hammers. Typically these hammers will be rectangular in shape and blunt, but they can be sharp. The leading edge of the hammers impact the biomass until it is small enough to pass though the screen openings. The hammers can be inverted and rotated such that each hammer can be used in two or four different positions. This allows for maximum wear before the hammer needs to be replaced. Special care must be taken to ensure that the hammers stay balanced. Hammermills spin at such high RPMs, the resulting vibrations from an unbalanced central hub can be catastrophic.

The hammermill is especially efficient for grinding medium and fine sized particles. The capacity of a particular grinder depends upon the physical properties incoming material, grind size, power available, throughput, and moisture content of the product.

Roller mills use large corrugated cylinders to grind a variety of materials through shear force, rather than crushing them as hammermills operate. Roller mills are commonly used for wheat milling applications and for grinding feed ingredients to very specific particle sizes. The advantage of rollers mills is the ability to fine tune the average particle size and standard deviation. This can be accomplished by adjusting the gap settings, modifying roll corrugations, changing roll speed differentials or changing product throughput. This allows for a more uniform grind whereas there are few adjustment settings for hammermills (Wondra, 1995).

Tub grinders are typically used in feedlot operations and industrial wood chipping. These machines use carbide tipped flail hammers to pulverize wood and forages rather than cutting or shear forces. Tub grinders are often affixed to semi-trailers and can easily be moved. Since they are mobile, they are often run from diesel power supplies. Tub grinders operate in a very similar manner to hammer mills. They hammers spin in a centrifugal manner by means of a central shaft and material is impact ground until particle are small enough to pass through the screen on the outside edge. The main difference is hammer mills are generally horizontal and electrically operated and tub grinders are mobile and horizontally operated.

Particle size reduction and densification are important for harvesting, transporting and drying an otherwise unwieldy crop (Lopo, 2002). Lopo compared three kinds of grinders (hammermill, roll mill, and horizontal hammermill) that could produce a particle size in the range of 600 to 800 μm. He found that hammer tip speed was a critical factor for good grinding. Typical tip speeds ranged from 81 to 117 m/s. He also concluded that the grind size depended on the roll gap. By bringing the two rolls closer together, we reduce the open area for the product to pass through. He also notes that a roll speed differential is useful in improving size reduction. This simply means that one of the rolls should rotate faster than the other, with the typical speed differentials ranging from 1.2:1 to 2.0:1. Typical roll speeds range from 6.6 m/s for a 23-cm roll and 16 m/s for a 30-cm roll. He determined that a roller mill was more efficient than a hammermill or horizontal mill. Comparing the vertical hammermill and horizontal hammermill, the vertical hammermill had lower energy consumption, less moisture loss, reduced grinding shrink, narrower particle size, and fewer fines.

The main drawbacks of the roller mill are the operating variables and training required to fine tune grinds. They are also subject to greater amounts of wear and maintenance. It should also be noted that the study conducted by Lopo (2002) look at grinding granular shaped feed ingredients and the grinding characteristics will change based on the physical properties of the ingredients utilized. He also states that roller mills are more efficient at grinding brittle materials such as grain seeds.

Input Variables

Equipment Specifications

To optimize grinding performance factors that affect hammermill performance, including tip speed, grinding rate, screen size, and clearance, must be identified and standardized. The size of the resulting particles depends on the size of the screen holes installed in the machine and on the feed rate of biomass into the grinder. The capacity of a machine to grind particles depends on the rated throughput of the machine, the volume of material the machine can handle and also the final size and moisture content of the resulting particles.

Vigneault (et al. 1992) looked at hammer thickness and its impact on hammermill grinding rate and energy consumption for grains and forage pellets. They examined 3.18 and 6.35 mm thick hammers for grinding wheat, corn and alfalfa pellets. They determined that thin hammers saved 13.6% in energy consumption and increased the grinding rate by 11.1%. They obtained a similar particle size and standard grind for each hammer thickness. The results also showed specific energies ranged from 5.5 to 9.5 kWh/ton for hammer thicknesses of 1.59 mm and 8.00 mm, respectively. Specific energies also ranged from 4.6 to 12.9 kWh/ton for hammer tip speeds ranging from 54 to 86 m/s, respectively, for a 6.35 mm thick hammer. Hammer tip speed showed a significant impact on the end power consumption and efficiency.

Forage Type

Mani (et al, 2004) measured grinding efficiencies of wheat and barley straw, corn stover, and switchgrass with a hammermill. He investigated three different screen sizes (3.175 mm, 1.588 mm, and 0.794 mm) (2002). The densities of the biomass ranged from 40 to 250 kg/m3. Switchgrass used the most kWh/ton and corn stover required the least energy. Physical characteristics of the particles were measured including the distribution of particle sizes, moisture content, geometric mean diameter, and resulting densities. The experiment found that the large hammermill screen size resulted in reduced energy requirements for all types of tested biomass. This was simply due to the increased throughput in the energy requirement calculations.

Bitra (et al, 2009) measured the specific energy required for grinding switchgrass, wheat straw and corn stover when operational variables, such as hammer design and tip speed were modified. He found that grinding efficiency was positively influenced by an increase in tip speed and efficiency was relatively unaffected by blunt or sharpened hammers. They also noted that the ground switchgrass and corn stover had a fairly uniform particle size distribution while wheat straw particle size varied considerably. This could be due to the hollow structure of wheat straw resulting in uneven flow causing the hammermill to surge.

Particle Size and Shape

The bulk density and flowability of the biomass particles are highly influenced by the particle size and shape (Mani et al., 2004). Mani reported the bulk and specific densities increase with increasing geometric particle diameter at the same moisture content and developed the second or third order polynomial models relating the bulk and specific densities of agricultural biomass grinds to their respective geometric particle diameter of the biomass grinds within the range of 0.18-1.43 mm. The biomass grinds used in the experiment were a mixture of different particle sizes remaining on each mesh. The packing and flow properties of biomass were also said to change with particle diameter.

Consideration must also be given to the effect that grinding will have on particle shape and the resultant flow properties. Size reduction of biomass is a critical factor prior to densification, which will boost transportation efficiency and volumetric storage capacities, as well as preparing small particle size for fuel conversion (Naimi et al., 2006). The reduced particle size will provide a larger surface area and additional contact points of the biomass to bind together in the compaction process (Drzymala, 1993). In wood pellet manufacturing facilities, the wood chips require grinding into small particle size by the hammermill and are then compacted to form pellets or briquette.

Shear Stress

Tensile and shear properties of the biomass can influence the energy requirements for biomass size reduction. Some authors have studied cutting and shearing forces for biomass materials. Usrey (et al. 1992) studied internal shear (tensile test) and shear strengths, and the pressure-density relationships of rice straw during compression. The result showed that the cross-sectional shearing strength of rice straw stems ranged from 28 to 87 N.

The physical properties of tensile and shear strength of cutting stems (wheat straw) at different maturity levels were studied by O'Dogherty et al. (1995). Tensile strength was in the range 21.2 to 31.2 MPa and shear strength in the range 4.91 to 7.26 MPa for the four stages of plant maturity. They found that increasing plant maturity had some significant effects on shear strength. The additional lignin content of mature forages caused an increase in the required shear strength.

Bulk Density

Lam (et al, 2008) reported the bulk density of switchgrass and wheat straw stem particles increased with decreasing particle lengths. They also observed that the bulk density of the switchgrass and wheat straw stems increased by 10% to 50%, due to tapping. This shows that compaction will have a large impact on the bulk density and flow of the product. Because of our transportation infrastructure, vibrations (from railcars and semis) will always be a concern. If ground biomass were loaded into a truck, the bulk density would increase because of the compaction due to vibration. As a result, the product will not flow well because of the interlocked pieces and the cohesive nature of cellulosic biomass particles.

Lam concluded that different degree's of grinding showed different packing and flow characteristics. Switchgrass, wheat straw and corn stover were ground by a cutting mill with 2 mm square hole screen. The average diameter of switchgrass, wheat straw and corn stover were 0.3829 mm, 0.4945 mm and 0.4416 mm, respectively. The resultant grinds were split into 4 different particle sizes which were obtained by sieving with mesh numbers 25, 35, 45 and 60.

The bulk density of switchgrass increased from 149 to 194 kg/m^3 with increasing particle sizes while the tapped density of switchgrass decreases from 219 to 190 kg/m^3 with decreasing particle sizes. This can be explained much in the same way we look at ground corn bulk densities when grinding. The whole corn kernel is the most dense for it can every be because of the way the particles within the corn kernel are aligned. The finer we grind, the more spread out and expanded those particles become. The bulk densities of wheat straw with different particle sizes were similar with an average value of 115 kg/m^3. The tapped density of the wheat straw increased from 146 to 159 kg/m^3 with decreasing particle size. The bulk and tapped densities of the corn stover increased from 91 to 124 kg/m^3 and from 98 to 159 kg/m^3, respectively, with decreasing particle size.

The switchgrass exhibited the best flow characteristics, while wheat straw and corn stover particles were cohesive. This was derived from the result of angle of repose (35.56°-43.03°, 43.05°- 47.44° and 43.57°- 45.64°, respectively). Individual particle size analysis by microscopy revealed that wheat straw and switchgrass grinds were rectangular in shape. The particle size and shape analysis is useful to model the heat and mass transfer of fluid into the particles.

Bulk density of the incoming materials will affect the throughput of the machinery. Grinders are generally limited by the weight of material it can process during a given time. With biomass however, the machinery will reach a volumetric limit before the weight limit is reached because of the low density of material. As forages have a very broad density spectrum ranging from dense material, such as wood chips, to light materials, such as straw, it is likely that machine throughput will be affected. This will have a considerable impact on the time it takes to process a given amount of material, as well as the energy consumption of the machinery.

Forage Pelleting

Overview and Purpose

Biomass densification is defined as compression or compaction of biomass to remove inter- and intra-particle voids (Balatinecz, 1983). Since the introduction of pelleting in the 1930s, it has become a standard processing technology utilized in numerous industries. Pelleting can be generally described as "the agglomeration of small particles into larger particles by the means of a mechanical process, and in some applications, thermal processing" (Falk, 1985). Pelleting systems have evolved in size and capacity, and implementation of automated process control systems has enabled pellet mills to be operated with less labor and greater precision.

Pelleting is typically used in the animal feed industry and has the capabilities to increase bulk density and improve flow properties. During the production process, good flow is important when transferring ingredients from bulk bins into trucks in order to keep loading times at a manageable limit. Proper flow out of the bulk truck keeps unloading times as short as possible, can decrease clean-up times as less material will bridge and limit the amount of dust produced, thereby reducing air pollution. Flowability is especially important in automated systems where bridging can cause damage to equipment by backing up the flow and overloading conveyors earlier in the process. Pellet quality needs to be considered when talking about flow. When maximizing bulk density and flow characteristics for transportation situations, the amount of fines mixed within the pellets needs to be considered. The gains in flow and bulk density increase need to be balanced with the cost of producing pelleted products. Costs we need to consider include electrical energy to operate our mill, feeder and conveyor systems, a cooling system (if required by a specific process) and maintenance or replacement parts for the various parts of the system.

Pelleting materials is accomplished using heat and pressure or results in the creation of heat during the extrusion process. These conditions may affect sugar yields and resulting ethanol production.

Recent studies reveal increasing interest in preprocessing of biomass feedstocks for logistics purposes. The research by Sokhansanj and Fenton (2006) outlined a detailed analysis of cost, energy requirements, and carbon emissions for biomass collection and preprocessing enterprises in Canada. They observed multiple forms of preprocessing including chopped biomass, ground biomass, briquettes, cubes and pellets. The pellets had the highest density at 500-800 kg/m^3. Wood shavings at 10% wet basis moisture content were considered as a burner fuel with a fuel cost of 40 \$/ton delivered to the pelleting plant. Cost of wood shavings is considerably high due to the high demand for animal bedding materials and as a fuel for the pulp mills. The capital and operating cost of producing biomass pellets are 5.64 and 25.18 \$/ton of pellet production, respectively. The cost of producing cellulosic pellets (30.83 \$/ton) may be further reduced if the plant capacity is increased. It should be noted that the production plant has a pelleting capacity of 6 ton/hour, which is relatively small by industry standards and that the cost for pellet production is inflated because of this. He goes on to state that by moving the grinding and pelleting operations to the field we might reduce the cost of production by up to \$10/ton and that we could also reduce the cost by changing the mill run schedule and achieving higher densities.

Sokhansanj and Turhollow (2004) calculated a cost for cubing of corn stover at 26.17 \$/ton. Although cubed biomass is easier and safer to handle and store, it was more expensive as a feedstock for a conversion plant than biomass bales. The delivered cost of bales, including a final grinding cost, is \$54.57/dry ton, whereas for cubes the cost is estimated at \$72.77/dry ton, which included drying costs at roughly \$4.10/dry ton) and a profit. Opportunities exist to reduce the cost of cubing to levels equal to baling forages. Again by moving the grinding and pelleting operations to the field we could effectively reduce the cost of pelleting to be competitive with baling.

Mechanical Aspects

The formation of the pellet actually occurs at the point of contact between the rolls and the die, referred to as the nip angle. This is the point when the biomass is compressed through the die hole and forms a pellet. All other processes leading up to this point are support functions that lead to this end goal. In order to influence the process to improve throughput, energy consumption and end pellet quality, the physical process of pellet formation must be understood.

Depending upon the physical characteristics, most importantly bulk density, of the incoming product, a large function of the pellet mill is compression. If the formula contains high amounts of forages, such as wheat straw or corn stover, the pellet mill will primarily utilize its mechanical energy to compress the fibers into the density and shape of a pellet. Since we are limited by the amount of volume that the pellet mill can compress, we will limit throughput.

The pellet mill rolls exert force on the incoming ingredients in order to compress them through the die holes. The nip angle, the roll surface corrugations/hardness and the physical properties of the incoming ingredients determine the magnitude of this potential force.

The die hole exit is the point at which the mash has reached pellet density and begins to flow from the die holes. There are many physical forces that must be dealt with in the pelleting process such as pressure release when the pellet exits, friction, rotating speed and shear stress when the pellet is cut from the surface of the die.

The die is the mold that provides the final form and diameter to the pellet and it does so through the resistive force between the sidewalls and the ingredients. These forces generated from the rolls and die are conflicting but must work in tandem to produce quality pellets at an acceptable production rate. The force generated by the roll that forces ingredients through the die must be greater than the resistive force provided by the die. If it is not, feed will not flow through the die and nothing will be produced.

Factors Influencing Pellet Quality and Energy Consumption

Early models for biomass renewable fuels production placed the preprocessing of feedstocks at the biorefinery. However, recent research has illustrated that a distributed, or in-field, preprocessing model is likely to reduce costs (Wright et al., 2006). This typically will take place without the use of steam conditioning and with the lowest energy costs as possible to create an acceptable pellet for transport and transfer within a biorefinery.

When we remove steam conditioning some interesting concerns are raised. We add steam conditioning before the pellet die in order to gelatinize starch in the incoming ingredients and add a source of lubrication so material can slide through the pellet die holes with less friction, in essence reducing the force and energy requirements to form a pellet. Skoch et al. (1981) researched the importance of steam conditioning and its effects on pellet quality. Rations were pelleted with steam conditioning and without. Steam addition increased production rates by up to 64% and increased pellet durability indexes (PDI) by up to 26%. The feed temperature across the die decreased by 5 C when diets were conditioned with steam compared with an increase of up to 42 C when diets were pelleted dry. The results of this study indicated that steam conditioning improves pellet durability, increases production rate, decreased the amount of fine particles/ broken pellets generated and energy consumption. It was concluded that steam acted as a lubricant to reduce friction during pelleting.

In a review conducted by Kaliyan and More (2009), they proposed factors in biomass pelleting could influence pellet quality. They summarize by stating that factors we need to be interested in include biomass nutritional properties (such as protein, fiber, fat and moisture content), pelleting binding additives, steam conditioning, equipment used, cooling/drying, throughput and pressure. They also state that due to interactions from all the above listed variables, the optimum densification variables may need to be determined by using an optimization procedure. If cellulosic ethanol is to be produced on a large scale we need to develop acceptance levels for the physical characteristics of the incoming ingredients. If a plant is receiving pellets, for example, they will need a standard for moisture level, physical dimensions, approximate density, plant maturity level and a list of approved additives.

During operation, a pellet die absorbs frictional heat as the pellets pass though. Behnke (1998) hypothesized that proteins and carbohydrates can literally melt and then adhere to the surface of a die. In reality, the amount of protein or starch burned onto the die surface is a tiny fraction of the diet content and would not affect the composition of the diet in any way. However, this thin layer of organic material can result in a significant increase in frictional drag as the pellet passes through a die hole. It might be necessary for mineral to be added to cellulosic biomass for the purpose of souring the die surface to prevent buildup.

The ease or difficulty experienced by the pellet mill in forcing feed though a die hole is dependent on the coefficient of friction between the pellet surface and the surface of the die hole. Other factors such as die hole volume and die hole length to diameter ratio (L/d ration) are useful in describing die resistance, the coefficient of friction created as the pellet surface is forced past the die hole surface during operation is a major factor in energy required for pelleting.

Die heat transfer and friction ca be measure by performing a hot pellet test. This is easily accomplished by taking a sample immediately after pelleting and measuring the pellet temperature rise in an insulated container. This temperature is compared with the conditioner mash temperature to express die friction. Temperature will generally rise during pelleting, indicating that the pellet mash was heated by friction as it passed through the die hole during pellet formation and it is generally accepted that friction is the only source of heat energy available at that point in the system. Excessive moisture content in diets can lead to too much lubrication at the die resulting in a temperature decrease (Behnke, 1998). This will lead to the formation of very low quality pellets or the complete failure to form pellets at all.

Numerous factors influence the amount of moisture we add to diets, including the absorption diffusivity of the ingredients, steam quality, steam quantity, degree of mixing during conditioning, and the conditioning chamber dimensions. Steam is used not only to increase the mash moisture but also to increase mash temperature. In a study by Briggs (et al 1999), all rations were conditioned to 77 C by adjusting the steam flow rate. They hypothesized that the increase in mash temperature caused by conditioning softens the protein polymers and may cause some starch gelatinization. In forages starch gelatinization is not a concern, but we are interested in the heat transfer and how it can affect the cellulose structure and integrity of the final products.

Water may be removed by drying ingredients or added to ingredients in order to alter moisture content. In the interest of energy conservation we would like to resist drying ingredients to remove moisture because of the intense energy requirements of drying. Adding moisture at the conditioner or mixer and serves to soften feed particles and lubricate the mash as it moves through the die.

The initial moisture of ingredients dictates how much additional steam or water we can add to the system since the pellet mill can only tolerate a specific amount of moisture. Experiments conducted at the Kansas State University pilot feed mill have compared the effects of mash moisture contents of 12%, 13%, 14%, 14.5% and 15% on pellet quality. The results show that there is a high correlation between cold mash moisture and PDI ad also a correlation between mash moisture content and called pellet moisture content. They also showed that the moisture application point was critical, citing differences in PDI and ending moisture content between runs which had water added at the mixer and runs that had water added at the conditioner. The mixer was much more thorough at water application than the conditioner (Greer and Fairchild, 1999). Adjustment of mash moisture to 14% produced the highest quality pellet with the most efficient pellet mill operating conditions (Muirhead, 1999).

It is also speculated that chemical properties of the forages to pellet can be impacted by the heat transfer resulting from pelleting. Depending on the length of pellet die used, temperatures could be observed over 180°F. This could aid in the breakdown of cellulose and improve the ethanol yield. Pelleting process may result in physical and chemical property changes as well as chemical composition change, depending on processing conditions such as pressure, steam temperature, and type of binders.

Decreasing the particle size of the incoming ingredients, results in a greater surface area to volume ratio. Smaller particles will have a greater number of contact points within a pellet matrix as compared to larger particles. This will have an impact on the amount of compression we see within a pellet and its ability to maintain its structure through handling (a direct correlation of PDI). Wondra (et al 1995) found that reducing particle size increased electrical energy required for milling and decreased milling production rates, especially as particle size was decreased from 600 to 400 microns. They also observed an increase in pellet durability as particle size was reduced from 1000 to 400 microns.

Bulk Density and Pellet Quality

Through pelleting it is suggested that we could increase the bulk density of biomass so that it would be similar to that of whole corn or other whole grains. O'Dogherty (1984) conducted research using individual cylinders to create wafer pellets. Three different diameters were investigated and it was also noted that wafers could not be formed if moisture content was above 35%. The pressure required to form a wafer increased exponentially with both wafer relaxed density and die diameter. Also by increasing the amount of straw in the die, they increased the relaxed wafer density. O'Dogherty (et al 1989) also compacted wheat straw and observed an increase of flowability, through a shear strength test, and a decrease in coefficient of friction. Product bulk densities were between 500 kg/m^3 and 700 kg/m^3 (31.2 lb/ft^3 and 43.7 lb/ft^3).

Pellet density and hardness are some of the most influential factors that will impact logistics and transportation efficiencies. Mani (et al, 2006) examined at mechanical properties of wheat straw, barley straw, corn stover and switchgrass compacted at different compression forces, particle sizes and moisture contents. Ground biomass samples were compressed with five levels of compressive forces, three levels of particle sizes (3.2, 1.6 and 0.8 mm) at two levels of moisture levels (12% and 15%). They then establish compression and relaxation data. Pellet dimensions and mass were measured to calculate pellet density. Corn stover produced the highest pellet density at low pressure during compression. Compression force, particle size and moisture content significantly affected the pellet density of barley straw, corn stover and switchgrass. The different particle sizes of wheat straw did not produce any significant difference on pellet density. The relaxation densities were analyzed to determine the asymptotic modulus of biomass pellets. The asymptotic modulus is an empirical index of solidity, which is the ability of a compressed powder to sustain unrelaxed stresses. Barley straw had the highest asymptotic modulus among all biomass. This indicated that barley pellets were more rigid than all other varieties of biomass pellets. Asymptotic modulus increased linearly with an increase in compressive pressure. A simple linear model was developed by Mani to relate asymptotic modulus and maximum compressive pressure.

Logistics Models

Sokhansanj et al. (2006) discussed the cost analysis of using bales, chops and pellets for a combined heat and power production system for a 151.4 million liter per year dry mill ethanol plant. The scenario was carried out using a Microsoft Excel spreadsheet. The feedstocks evaluated were corn grain, corn stover bales, corn stover pellets, switchgrass bales, and switchgrass pellets. For pellet production, a pellet manufacturing facility at a central location in the feedstock area was assumed. Baled biomass was then transported from outlying locations to the central processing facility. A comparative study of the total number of truckloads required to carry the feedstocks from the farms to the ethanol plant was done. The proposed combined heat and power plant produces 10 Mega Watts power and 48 Mega Watts process heat with an overall thermal efficiency of 76.5%. The excess power is for sale to the grid. The CHP plant runs with 100% biomass delivered to the heating plant in three formats (square bale, dry chop and pellets). Each format of biomass collection, processing and transport cost are different and will affect the annual cost savings from the biomass-based CHP plant. Among the different forms of biomass studied, dry chops have the highest delivered cost followed by pellets.

In a study conducted in 2010, (Krishnakumar and Ileleji, 2010) logistical requirements of different biomass feedstocks and the physical processed forms of the biomass sources were studied. The primary objective of the study was to analyze the technical requirements and economics of transporting, storing and handling cellulosic biomass feedstocks for the production of ethanol in five different plant sizes. The five biomass sources analyzed were whole corn kernels, baled corn stover, baled switchgrass, pelleted corn stover and pelleted switchgrass. The cost per Mg of transporting switchgrass pellets was the least out of all physical types analyzed for larger ethanol manufacturing plants. For the small ethanol plants, the baled corn stover was the most cost effective. This is due to the high cost of pelleting and the fact that as we increase plant throughput we can overcome these costs because of the increase in bulk density. The storage cost per Mg of bales was almost three times that of pellets for plant sizes above 227.1 million liters per year. He did however find that the total cost per liter of corn stover and switchgrass pellets before conversion to ethanol was higher than corn grain for all plant sizes, again this is simply due to the additional processing required to manufacture pellets. Retrofitted corn ethanol plants would be able to take advantage of the benefits that pelleting gives us because they would not need to retool their operation due to handling restrictions of ground biomass. Biomass pellets yielded very good flow characteristics, were five times denser than the baled biomass and can also be transported and were stored using the existing grain handling equipment and supply structure. Despite this advantage, the overall cost per liter of the feedstock before processing to ethanol was significantly higher for pellets than the other feedstocks for all the plant sizes, not accounting for additional handling equipment requirements. Pelletized biomass allows for greater amounts of feedstock to be transported from the farms and shows promise if we are able to optimize the production and gain a more accurate understanding of the costs involved and actual production throughput.

Ileleji wrote an article for feedstuffs magazine outlining some of the challenges associated with biomass pellets (Ileleji, 2010). He noted many of the same challenges that biomass pellets face such as increase cost due to additional processing, equipment costs and yield. He draws attention to the amount of fines produced from the pelleting process. In their study, they had as much as a 50% loss in material due to pellet fines. Pellet fines are produced because of pellet mill wear, roll face wear, moisture imbalance, low operating temperatures, poor pellet quality or a number of other pellet mill variables. Because of the amount of fines, the pelleting process was not feasible compared to simply baling the biomass for transport.

In this study, we will perform preliminary research to obtain the optimum moisture content of the forages for pelleting, before we begin our trial runs. It has been suggested that correcting the moisture content so it is closer to that of steam conditioned feed will help reduce the amount of fines produced.

Cost and Logistics of Biomass Densification for Ethanol Production

The main benefit of our approach is that we are proposing the use of technology and equipment readily available for a new application. In recent years, densification machinery has been expanded to the home heating industry with the pelleting of wood. The difference between these two uses and our proposal is that we intend to determine if cellulosic biomass can be pelleted in the field or at a remote location with lower energy inputs than required by the other two industries that use this technology.

Biomass must be preprocessed (ground and exposed to hot water) and we intend to combine these steps with the pelleting process. Preprocessing farther away from the biorefinery has been reported to reduce overall costs within the biofuel production system (Wright et al., 2006).

Depending on the industrial application, there are numerous benefits of pelleting a material, including increasing the bulk density and improving material handling properties. Increased bulk density and handling properties of pelleted material are particularly advantageous on fibrous ingredients (Blasi et al., 1998). Utilizing pelleting to convert the physical form and properties of a relatively light, hard to handle material such as forages, to a dense, free flowing material could facilitate the use of cellulosic feedstocks for ethanol production. The economic feasibility of utilizing pellets by existing corn grain ethanol plants transitioning to cellulose ethanol production from the storage perspective was also discussed.

Solutions

An accurate measure of the energy required for grinding and pelleting cellulosic biomass needs to be established as well as measurement of the physical characteristics of processed cellulosic biomass. During the course of this study, we will conduct a series of experiments aimed at obtaining electrical data required for processing as well as measuring the physical characteristics of the products. These values will be essential in establishing a model that can help predict the cost advantage of biomass densification for ethanol production.

We hypothesize that we can reduce the particle size of the biomass so that it can be pelleted as well as meet particle size requirements necessary for optimum ethanol fermentation. If compared with current biomass handling systems, the field biomass densification not only leads to decreased transportation cost, dust emission, and storage requirements, but it also leads to elimination of size reduction step in the processing plants. Handling low-density ground biomass is a challenge to the biorefinery industry. The dense pellets have the flowability characteristics similar to those of cereal grains. This will make the pellets easy to handle using the equipment already developed and available commercially and also eliminate the need for ethanol plants to invest in additional equipment designed for transporting and moving baled forages.

It is conceivable that the process of pelleting will assist in the biomass destruction. The microbial cultures are sensitive to the inhibitory substances such as furfural, HMF, ferrulic acid and acetic acid generated during acid pretreatment process. It is possible pellets will require less stringent pretreatments due to exposure to high temperature and mechanical processing. Further, the appropriate particle size of the biomass as desired for pelleting process will result in better enzymatic utilization, which should result in superior sugar quality and higher sugar concentrations. Therefore, we can expect the fermentation of the sugar streams generated from pellet hydrolysis should result in increased ethanol yield, concentrations and productivity.

Chapter 1 - Energy Requirements and Physical Properties of Ground and Pelleted Forages

Introduction

The current forage handling equipment in the cellulosic ethanol industry is severely limited by the low bulk densities of baled or ground biomass. Low bulk densities can contribute to flowability problems and the lack of maximizing trailer capacities. Ethanol plants, in their current form, are not designed to handle material with these physical properties. By grinding and pelleting forages we can increase bulk density, thereby reducing flowability and weight concerns. If a system were developed that would take the burden of handling inefficient, unprocessed biomass off of the ethanol plant, it could greatly increase the feasibility of organic-based fuels by allowing for additional plant throughput and reduce the amount of inputs, most importantly labor, required to produce cellulosic based ethanol.

Biomass particle size reduction reduces the shape, increases bulk density, improves flow properties, increases porosity and generates additional surface area (Drzymala, 1993). Particle size reduction also aids in the utilization efficiencies of animal and microbial digestion by exposing for surface area for degradation by acids and enzymes. Size reduction accounts for a huge portion of the power requirements needed for the conversion of cellulose into ethanol. Energy requirements for grinding depend on its initial particle size, moisture content, material properties, machine throughput and other machine variables (Mani et al, 2004).

The poor flow characteristics and bulk densities of ground biomass prevent it from flowing properly during the unloading, storage and transfer operations at a biorefinery. These flow characteristics would require biorefineries to install specialized equipment and would make retrofitting existing corn based ethanol plants into cellulosic ethanol plants almost impossible. The added cost of the new equipment could be reduced or eliminated if the bulk density of the feedstock can be increased prior to delivery. Other costs associated with handling a low bulk density feedstock are the additional conveyor capacity and storage area required.

Pellet durability is a cause for major concern. Low pellet quality can cause a decrease in flowability, a decrease in bulk density, an increased risk of explosions due to airborne dust and an increase in production costs due to the need to recycle pellet fines back into the system for further processing. Krishnakumar and Ileleji (2010) indicate that pelleting was not a feasible option for increasing the bulk density of biomass due to the losses they observed during the pelleting process.

Preliminary Study

A preliminary study was conducted prior to measuring electrical efficiencies and physical properties of the pelleted biomass. In this study, we examined the impact that moisture content had on the quality of pellets, amount of fines produced and motor load. We were basically trying to determine the optimum pellet mill variables for our mill before running the experiment. Since we are removing the conditioning step, which adds a significant amount of water to the product, it was thought that we would need to add water during the mixing process to increase the overall water content of the biomass. We did this for a lubrication effect in the die, to increase pellet quality and increase throughput. During the course of this study, we looked at pelleting the forages at the initial moisture contents (between 9% and 10% based on forage type) and adjusted moisture contents of 15% and 20%.

Typical feed rations require added moisture to reduce friction when the material is passing through the die and reduce load on the machine. Small, 10 pound runs were mixed at the varying moisture contents and pelleted. During this portion of the study, contents of the batches were added by hand through a force feeder into the pellet mill. This allowed us to meter in small amount of the forages and monitor motor load very closely. This also allowed us to be situated closer to the motor control panel so we could shut the mill down if the process yielded too much friction for the pellet mill to handle.

The unadjusted moisture forages created pellets, but they were very low quality. The pellets were very brittle and yielded less than a 23% PDI. The amount of fines produced with these pellets was also very high, almost 55% of the total run weight. The 15% adjusted moisture pellets yielded the best quality of pellets, above 90% PDI. They also produced very few fines (between 5% and 8% which is an acceptable limit for most feed production scenarios). We have no numerical data on the 20% adjusted moisture pellets because we were unable to create any.

When the pellet mill is exposed to very high levels of moisture, the rolls will in essence "slip". When this occurs, the pad between the rolls and die becomes displaced and the pressure that the rolls exert is not great enough to force the product through the die holes. The pellet die then becomes filled with product and when it can finally hold no more, product is forced through the cone and the operation is halted. When this occurs the entire pelleting operation must be stopped, the cone removed and the die manually cleaned out or removed based on how bad the "plug" was. This is what occurred when we attempted to pellet the 20% adjusted moisture forages. It was concluded that the 15% adjusted moisture forages would be used for the duration of the pelleting study and additional pellet mill variables, such as operation speed were also determined during this preliminary study.

The objectives of this study were to compare the differences in energy consumption (in kWh/ton) for grinding wheat straw, corn stover, big bluestem and sorghum stalks through a 1/8" hammermill screen and a 3/8" hammermill screen. Particle sizes (in inches) and bulk densities (in pounds/cubic foot) from the chopped biomass, the 1/8" grind and the 3/8" grind were analyzed.

Forages were also pelleted through a 3/8" x 1 ¾" pellet die. Differences in energy consumption (kWh/ton) were measured for both forage sizes. Samples were obtained for analysis of pellet durability and particle size

Materials and Methods

General

Big bluestem bales were swathed and baled in Beloit, Kansas, by Doug Thiessen in January 2009. The big bluestem bales were donated by Star Seed in Beloit, Kansas. Wheat straw and corn stover were sourced by the Kansas State University Agronomy Farm from local producers. Photoperiod sensitive forage sorghum stalks (Cultivar 'PS 1990, Sorghum Partners, New Deal, Texas) were harvested by the Kansas State Agronomy Farm in November of 2008 and December of 2009. Wheat straw, big bluestem and corn stover bales were obtained in the form of 6ft x 4ft x 4ft square bales and the sorghum stalks were baled in round bales.

Our current model for the grinding and pelleting of forages utilized a two-stage grinding step. The initial step used a large tub grinder to reduce forage particle size. The forages will then be ground through the hammer mill.

The tub grinder (Haybuster H-1150 series) was powered by a diesel engine which ground a large round bale in under 30 seconds. This made energy collection almost impossible. All forages were chopped to a very similar stem length (approximately 7-9 inches in length). Due to the small amount of material ground, we were unable to accurately measure the fuel consumed during operation. A study by Hess (et al, 2007) yielded ground forages with very similar particle sizes and bulk densities to the product we created. These results were used during the logistics calculations.

All four forage types were transported to the Bioprocessing and Industrial Value Added Program (BIVAP) building located at 1980 Kimball Avenue in Manhattan, KS.

Forages were subjected to further particle size reduction through a Schutte Buffalo hammermill Model 18-7-300. This hammer mill is a top-fed, teardrop style mill. The hammermill was powered by a three phase wye wire electrical motor operating at 10 horsepower, 3600 rotations per minute and 11.6 amperes, at 460 Volts. Product was pre-weighed to 30 pounds and placed in separate barrels for each run. Biomass was then manually loaded onto a belt conveyor which fed into the hammermill. The belt conveyer power line was run through a variable speed drive (VFD) operated at 30 Hz of the rated capacity for the belt conveyer. This allowed us to regulate the speed of the belt. The main challenge at this point of the study was attempting to maintain a similar volumetric feed rate into the hammer mill. It was concluded through a series of preliminary runs that a product bed depth of about 2 inches on the belt conveyor would provide sufficient product flow without overloading the machine. The belt speed was 11 ft/min and the belt width was 11.25 inches.

A Grizzly air suction system and cyclone were attached to the hammermill to remove the ground forages. The storage container could hold between 30 and 35 pounds of ground forages, depending on the bulk density. Biomass was ground using two screen sizes, 1/8" and 3/8". The Grizzly air suction system used a mesh filter to separate fine dust particulates into a separate container. These very fine particles were mixed back into the finished run and the total amount of ground material was weighed.

The hammermill runs were blocked by screen size and replication, randomized and replicated three times.

Electrical data was collected for each run by an Amprobe DM II-Plus across the leads of the main power supply for the hammermill. The Amprobe software was set to collect a set of data points every second. Energy data collected included the power factor, motor load, current across each phase, the average amperage, voltage and the subsequent watts.

Production rate was measured by taking the total amount of recovered ground material over the grind time. These values were then converted into pounds per hour.

Kilo Watts Hours per Ton (kWh/ton) were calculated by taking the observed wattage/2000 (converting it into kilowatts) over the production rate, in pounds per hour/2000 (converting it into tons per hour). Ground samples were obtained for an analysis on particle size and bulk density.

The 1/8" and 3/8" ground product was transported back to the K-State Pilot Feed Mill, located in Shellenberger Hall, to be pelleted. Forages were pelleted using a 30 HP Master Model Series 1000 California Pellet Mill and were ran through a ¼" x 1 3/4" die. Product was fed into the pellet mill through a 1000 pound capacity surge bin located above a conditioner and feeder screw, which metered the product flow. A pneumatic vibratory device was attached to the surge bin to prevent bridging during the runs.

Forage moisture content was increased to 17% for all pellet runs for a total to a weight of 25.00 lbs for each run. The water was used in place of steam to simulate on-farm pelleting where a boiler would not be available. Forages were mixed in a custom built ribbon mixer and water was added with a particulate sprayer. Mix time for all treatments was 3 minutes. In a production setting this step could be conducted using a conditioner with a metered water flow rate. Because our operation required such little material, we mixed all runs before pelleting.

Throughput was calculated by taking the weight of the sifted pellets produced over the length of the run. This allowed us to obtain a production rate of the actual amounts of pellets produced as opposed to the amount of product run through the machine. This also allowed us to look at the amount of fines produced. In a typical operation we would expect the fines to be sifted off and reintegrated back into the flow before pelleting.

Pellet mill RPM and feeder rate were held constant across all runs. Feeder rate was controlled by a variable frequency drive (VFD). Bulk density, however, did change from forage to forage as noted in the previous chapter. The feeder screw is capable of moving a specific volume of product at different RPM's, because of the varying bulk densities, production rates varied, which in turn influenced kWh/ton. As was the case with grinding, our pellet mill was not limited by motor load, but by the amount of volume it could process. Pellet runs were blocked by replication and randomized.

The individual runs were added by hand into the surge bin above the pellet mill. We chose to do this because our spouting and turnhead in the feed mill is designed to handle feed ingredients and is not large enough to accommodate ground forages. This also helped to ensure that the run was completely finished and there was no risk of a previously run forage contaminating another run. The pellet die was cleaned with wheat middlings between each run. This gave us a color change and indicated when we could start taking samples and timing for the next runs beginning. In addition to the need for representative samples, it allowed us to remove the very dense pellets created by the forages and replaced them with a relatively easy pelleting by-product. This aided in the start up procedure for the ensuing run.

Electrical data was collected for each run by an Amprobe DM II-plus across the leads of the main power supply of the pellet mill. Energy data collected included the power factor, motor load, current across each phase, the average amperage, voltage and the subsequent wattage.

Production rate was measured by taking the total amount of sifted, fully formed pellets over the amount of time it took to produce those pellets. These values were then converted into pounds per hour. This allowed us to obtain the production rate of actual pellets being produced.

KWh/ton were calculated by taking the observed wattage/2000 (converting it into kilowatts) over the production rate, in pounds per hour/2000 (converting it into tons per hour).

All pellets were retained for an analysis of pellet durability index (PDI), bulk density and a subsequent fermentation study as part of another trial.

Pellet quality was measured using the tumbling box procedure ASAE S269.4 (ASAE, 2007) and results are reported as the PDI. Pellets were collected directly from the pellet mill and cooled with forced air in trays using a locally constructed batch cooler. They were then sieved on a U.S. Number 6 sieve to remove fines. Two standard and two modified (addition of five ½" hex nuts) PDI tests were conducted for each production run, and an average value for each was determined.

Bulk density of pellets was determined using a Seedburo Model 8860 High Capacity Grain/Test Weight Scale. Three bulk density samples were taken for each of the pelleted forages during each production run, and the values were averaged.

Statistical Analysis

The grinding experiment was run as a split plot randomized design (SPRD), with the screen size as the whole plot and the forage type as the sub plot. The run order of forage types within each screen size was randomized and the runs within each replication were completed within a four hour time frame. Three replications of each treatment were conducted, with each replication being a single production run. Data was analyzed using SAS (v. 9.1) using the Mixed Procedure. Treatments were compared using LS Means. Using a SPRD, we could compare the impact of the screen size and forage type on the significance of the data comparison. Analyses were completed for the bulk densities, production rates and kWh/ton.

The pelleting experiment was run as a split plot randomized design (SPRD), with the screen size as the whole plot and the forage type as the sub plot. The orders of forage types within each screen size were randomized and each of the runs within a replication were completed within a four hour time frame. Three replications of each treatment were conducted, with each replication being a single production run. Data was analyzed using SAS (v. 9.1) using the Mixed Procedure. Treatments were compared using LS Means. Using a SPRD, we could compare the impact of the screen size and forage type on the significance of the data comparison. Analyses were completed for the bulk densities, production rates, pdi and kWh/ton.

Results and Discussion

Electrical Analysis

Table 1-1 illustrates the electrical data obtained during the different forages runs on the two separate screen sizes. Amperage was measured and recorded across each phase by the Amprobe during operation. In a three phase system, the voltage stays constant. From these values the Amprobe calculated the Wattage. The Wattage and production rate from each run were used to calculate the kWh/ton. The values represented in the table are averages of the three replications. The power factor and motor load varied slightly between forage types and grind sizes but were consistent with their corresponding values for kWh/ton.

The two screen types were found to have significantly different energy consumptions from each other ($P<0.0001$). All four of the forage types, with the exception of big bluestem vs. corn stover ($P=0.2329$) were found to have significantly different energy consumptions from each other ($P<0.0001$).

All of the 1/8” vs. 1/8” and 1/8” vs. 3/8” grinds were significantly different from each other (Most $P<0.0001$ and all at least $P<.05$). No comparisons were significant for 3/8” vs. 3/8” ($P>0.05$).

Table 1-2 illustrates the electrical measurements of the pelleted ground forage. The two screen types were found to have significantly different energy consumptions from each other ($P<0.0001$). The four forage types were also found to have significantly different energy consumptions from each other ($P<0.0001$) while the big bluestem vs. wheat straw did not. ($P=0.1192$)

Of the comparisons, 1/8" big bluestem vs. 1/8" corn stover, 1/8" big bluestem vs. 3/8" corn stover, 1/8" corn stover vs. 3/8" corn stover, 1/8" sorghum stalks vs. 3/8" sorghum stalks, 1/8" wheat straw vs. 3/8" sorghum stalks and 3/8" big bluestem vs. 3/8" wheat straw were not significant (P>0.05). All other comparisons were significantly different (P<0.05).

Production rate was relatively similar for both grind sizes. However, the 3/8" big bluestem and 3/8" wheat straw had lower production rates, due to inconsistent flow and bridging. This is the cause for the higher kilowatt hour per ton for these two forages. It appeared that the cohesive nature of the wheat straw and big bluestem was compounded during flow when left at a larger particle size. This is possibly due to the flat plate-like structures present in the larger grinds versus a more granular appearance in the finer grinds. Throughput and consistent flow are both very important attributes to an industrial production process. This could represent a possible shortcoming for the energy savings we gain by leaving particle size larger for the wheat straw and big bluestem. A visual analysis of corn stover and sorghum stalk indicated that flow was relatively similar for both grind sizes.

Physical Properties of Ground Forages

Table 1-3 outlines the bulk density characteristics and the production rates of the forages through different screen sizes.

Production rate through the 3/8" screen was almost 3 times that of the 1/8" screen (Average of 400 lb/hr vs. 150 lb/hr). The increased hole size of the 3/8" screen allows for a greater volume of forages to be passed through, the consequence is an increased particle size. This had a significant impact not only on throughput, but also the kWh/ton. Industrially used hammer mills will operate at over 90% motor load. We were unable to accomplish this because with forages, we will maximize the amount of volume a machine can process before we can maximize the tonnage.

Within the 1/8" grind size, the production rates of the corn stover and big bluestem were significantly different from the production rates of the sorghum stalks and wheat straw (P<0.05). For the 3/8" screen size, all forages differed significantly from the wheat straw, but corn stover vs. big bluestem was the only other comparison that differed significantly (P<0.05).

It was found that bulk density significantly (P<0.05 or less) varied not only between grind sizes, but also varied between most forages within the screen size. The chopped forages all yielded very similar results in bulk densities, but they did differ dramatically from the two grind sizes, which is to be expected since chopping was the initial grinding step. Sorghum stalks differed from all other forages types significantly within the 3/8" grind size ($P<0.05$), but within the 1/8" grind all of the forage comparisons were significant. This leads us to believe that as we are grinding to a smaller particle size, the natural characteristics of the individual forages are being compounded. Meaning that because of the nature of wheat straw (hollow stems) it will naturally be less dense at a finer particle size than a heavy material such as sorghum stalks.

Table 1-3 also focuses on the particle size of the individual forage grinds. Chopped lengths were obtained by physically measure the length of stalks. Due to their large size this was the most accurate analysis we could obtain.

Particle sizes for both the 3/8" grind and the 1/8" grind were obtained using the Penn State Forage Particle Size Analysis method (PSFPSA). The analysis method indicates that is a ration contains more than 8% long particles (on the top screen), then the actual average particle size needs to be measured by hand. This is why we measure the length of the chopped forages. The PSFPSA utilizes three separate screens and a pan. A very intensive sieving method, which designates a specific number of box turns and shakes, was outlined and followed. Sieves were then separated and the amounts on top of the screens were weighed an entered into an Excel spreadsheet to obtain an average particle length and standard deviation in inches. The spreadsheet has additional functions and graphs used for dairy cattle ration analysis which were not utilized.

Though the length did not vary by much between the grind sizes, practical and visual analysis indicated a significant difference between the grind sizes. This is supported by the differences in energy data and production rate.

Physical Properties of Pelleted Forages

Bulk density values are represented in Table 1-4. Statistical analysis showed a significant difference among the two screen sizes ($P<.0001$). The 3/8" grind produced denser pellets than the 1/8" grind. All four of the forage types were also found to have significantly different energy consumptions from each other ($P<.0001$). Sorghum stalk pellets, of both the 1/8" and 3/8" grinds showed the lowest bulk densities (31.18 and 32.2 lb/ft^3, respectively).

Comparisons of the bulk density increases from ground forages to pelleted forages are all significant (P<.0001) and increase between 3 and 9 times, depending on the forage type. This increase in bulk density will not only improve the flow characteristics of the forages, by also our ability to maximize truck payloads. It has been reported that the factors that increase pellet durability would also increase pellet density (Kaliyan and Morey, 2009). Based on our data, incoming biomass grind size has a significant effect on bulk density.

The sorghum stalk pellets were less durable and as a result more fines were produced. During the pelleting process, we observed that the sorghum pellets tended to not compact as well as the others and tended to have large fissures along the length of the pellet. They also showed a tendency to expand and lose shape, relative to the other pellets, during the cooling process. This is not to say that sorghum pellets would be the worst option for a production process. Bulk density and pellet quality must be evaluated with consideration to the cost and grinding and producing pellets, and sorghum yielded some of the best energy efficiencies of all forages.

Table 1-5 reviews both the average standard and average modified PDI for all forages of both grind sizes. Pellet durability was tested using the tumble box method. Statistical analysis showed that there was a significant difference between the sorghum pellets and all other forage types for both grind sizes (P<.05). With the exception of sorghum pellets (92-93%), all pellets were above 96% PDI. Practical analysis states that a difference of less than 5% PDI is not significant in real world applications. All pellets displayed very high pellet durability's relative to expected quality standards.

Hot pellet temperatures and percent fines were also measured for each of the pellet runs. Hot pellet temperatures are obtained by filling a Styrofoam container full of pellets straight from the pellet mill chute and immediately placing a lid on top of the bucket with a temperature probe inserted. The highest value on the temperature probe is recorded as the hot pellet temperature. The temperature change between the forages before the pelleting process and after the pelleting process gives us an indication of the heat transfer between the die and forages.

We did not observe any significant differences between the hot pellet temperatures of grind sizes or forage types. We did see an increase in temperatures from 78°F to between 170°F and 180°F. This represents a very large increase in temperatures that could possible have an effect on the breakdown of cellulosic fibers and the end fermentation process. It would also necessitate the use of a cooling system if pellets were meant to be kept in long term storage.

As we saw in the preliminary study, pellet fines were between 5% and 8%. This was a significant improvement over the previous researches outcomes. Differences between forage types and grind sizes were not significant. We felt like this was an acceptable quantity of fines and this number could be further reduced by manipulating the types of rolls used during the production process (closed ended rolls vs. open ended rolls).

Implications

During the course of this study, we confirmed that grind size had a significant impact on electrical consumption, bulk density, production rate and particle size produced. Similar grinding studies have been conducted, but it was necessary in our case to establish differences between forage types and to establish a baseline to compare electrical values from the pelleting study.

The 3/8" grind used less than half of the amount of electricity required for the 1/8" grind. Ideally if the pelleting electrical consumptions do not differ and ethanol fermentation is not impacted, we would recommend this grind in the interest of conserving production costs. We must keep in mind we need to consider the total electrical costs for the combination of grinding and pelleting when we make our final assumptions.

On a side note, the initial grinding step represented a significant problem for us. Since we are operating this study on a lab scale, we were limited by the equipment we had available. Even though we could not quantify the electrical costs for the tub grinder, they would still need to be considered for an industry scale application. Some of the more modern tub grinder are equipped with different screen sizes and could combine these two grinding steps into one. This would decrease the production time required for the grinding step as well as decrease equipment purchasing and upkeep costs. For the purpose of this study we were more interested in realizing the differences between the forage types themselves, rather than optimizing the methods of industry production.

Water Replacement Study

One obvious fault of the process we utilized for the formation of biomass pellets was the extra addition of water. There is a possibility that forages could be harvested and raked until the optimum moisture is achieved for pelleting. This is probably not a realistic approach for all situations because its dependant upon weather patterns and very specific farming practices. We still wanted to investigate possible alternatives to increasing the moisture content in case forages are harvested at moisture contents below 15%.

Fat is added to animal rations to increase the energy concentration of the diet as well as add moisture and ease the friction from product passing through the die. As a result, it helps to lower motor load and yields an energy savings. Increasing the energy content of the diets also means increasing the costs of the diet. Adding fat to the pellets could also inhibit the fermentation process by disrupting the microbes. Because of this, and the expensive nature at fat sources, we investigated the effects of adding glycerol, in place of water, to the mixture in order to adjust the moisture content.

Biodiesel is produced through a process called transesterification, which chemically alters organic oils, such as soybean oil or animal fat, forming biodiesel fuel and resulting in approximately 10% crude glycerol by weight. Glycerol is a very versatile, nontoxic, viscous liquid used in many commercial and industrial applications. Crude glycerol contains particulates from the oil extraction process. In the case of soybean oil, it will contain pieces of the soybean meat. Refined glycerol can be found in many applications including food processing and cosmetics. Crude glycerol is much cheaper than its refined form and would be feasible for the process of producing pelleted forages as well as providing glycerol producers and additional marketplace for their product. The U.S. market for crude glycerol has become saturated because of the production of biodiesel. This makes glycerol attractive as a feed additive because it is a cheap source of energy. In our case we would be looking to benefit from the viscous nature of glycerol. Recently, feed production studies have been run at the K-State Pilot Feed Mill, which look at the nutritious aspect of glycerol and its effects on animal performance and feed quality (Groesbeck et al, 2008 and Mader, 2010).

We had extra material of the 3/8" ground biomass and replicated a pelleting study exactly like the previous one, only this time utilizing glycerol instead of water to raise the moisture content of the forages to 15%. Data and material collection remained the same and the results were compared with the results obtained from the previous 3/8" grind study.

Results and Discussion

Electrical Analysis

Table 1-6 illustrates comparisons for the electrical measurements of the pelleted ground forages created with water as an additive and the pelleted ground forages created with glycerol as an additive. The two additive types were found to have significantly different energy consumptions from each other ($P<0.05$). The sorghum stalks vs. corn stover, sorghum stalks vs. big bluestem, sorghum stalks vs. wheat straw, corn stover vs. big bluestem and corn stover vs. wheat straw were all significant ($P<0.05$).

The comparisons between the additive types and forages types yielded interesting results. Corn stover and sorghum stalks stayed at relatively similar kWh/ton between the two additives. Big bluestem and wheat both differed between additive types and both follows a similar trend of decreased energy consumption when glycerol was used over water.

This drop in energy consumption was most likely due to the flow of product in the surge bin. As stated before, the 3/8” grinds for wheat straw and big bluestem had difficulty flowing when water was used as an additive. This decrease in production rate was one of the causes for high energy consumption. While the wheat straw and big bluestem with glycerol added did not flow exceptionally well, they never bridged in the surge bin and flow was much more consistent. This was evident by the increase in production rates noted in Table 1-7.

Physical Properties of Pelleted Forages with Glycerol

As it was with the energy data, the production rate values stayed fairly consistent with those of the original 3/8” ground biomass. The difference came from an increase in production rates for wheat straw and big bluestem (159.16 and 129.51 for the water additive and 185.36 and 172.76 for the glycerol additive). It should also be noted that these were also significant differences ($P<0.05$).

Bulk density followed the exact same trend for the glycerol additive biomass as it did for the water additive biomass. There was a slight decrease in pelleted corn and wheat straw bulk densities and a slight increase in pelleted sorghum stalk bulk densities. None of these increases were statistically significant.

Even though the data showed little variation for switching to glycerol instead of water, with the exception of wheat straw and big bluestem, it still has potential. The ethanol conversion process utilized a large amount of water and the areas where these facilities are generally located rely on these water tables for cropland irrigation. By switching to glycerol we would be utilizing a by-product of another fermentation process and conserving water. A study is currently being conducted at Kansas State University to conclude whether the addition of glycerol to the pellets has any negative or positive effects on the end fermentation process.

Implications

Through pelleting we were able to increase the bulk density of the forages by a significant amount, and by doing so also improve the flow properties. Total energy consumption, which was a combination of the energy required for grinding and pelleting, was found to be the lowest for 3/8" ground corn and sorghum, while the highest energy consumption came from the 3/8" big bluestem and wheat. It is our opinion that the 3/8" grind would be more efficient in all forages because the throughput was almost four times greater for the 3/8" screen than the 1/8" screen for grinding.

At this point, we are relying solely on energy usages for the basis of our assumptions. Fermentation studies are in progress by Karnnalin Theerarattonanoon and preliminary glucose yield results suggest that ethanol yield is much greater in the 1/8" ground pelleted material than the yield from the 3/8" ground pelleted material (See Appendix II for details). After the pellets dissolve, more surface area is exposed to the microbes thus increasing the efficiency of fermentations. Additional calculations will be required once this data becomes available to conclude which grind size is more feasible based on the inputs required (energy and processing time) vs. the output (final ethanol yield and profit margins).

The amount of heat produced during the pelleting process is also of great interest to us. If the product were to heat to this extent during the commercial process, cooling would need to be considered if long term storage is required or wild fermentations and mold could become an issue. It is thought that the heat transfer could contain an added benefit for the fermentation process though. Preliminary fermentation studies even suggest that we are breaking portions of the cellulose and hemi-cellulose because of the heat transfer caused by the friction from pelleting.

We also showed that if it could be obtained at a reasonable cost, glycerol would be a good candidate for the replacement of water during the pelleting process. The wheat straw and big bluestem even benefited from the addition of glycerol over water.

On a final note, if cellulosic ethanol is to ever become a realistic option as an energy source, machinery would likely need to be developed specifically for the processing of the biomass. Amandus Kahl has recently donated a flat bed pellet mill to the feed mill at Kansas State University. This pellet mill has a revolutionary design that is tailor made to produce pellets out of fibrous materials. Material enters the pellet press by gravity and is pressed by rollers through a flat die plate to form dense uniform cylinders. Product densification is varied by adjusting the compression distance in the die. Kahl pellet mills have been applied successfully for compacting organic products of different particle sizes, moisture contents, and bulk densities. Possible applications of the KAHL pelleting presses are wood waste, wood shavings, wood chips, sawdust, sanding dust and other organic forage material. Perhaps the most exciting aspect of the pellet mill is its ability to pellet materials containing very high moisture contents. This could help to greatly optimize the harvesting process for the forages and allow for less water addition during the fermentation process, if the material was used in a timely fashion.

Follow Up Study

A series of studies were conducted by Karnnalin Theerarattonanoon using the ground and pelleted forages we obtained through our study. Karnnalin performed proximate analysis and enzymatic cellulosic breakdowns to measure glucose yield of the processed and unprocessed forages. Included in her analysis were pellets produced during a small preliminary run necessary for determining which die to use. These forages were pelleted though a 5/32" x 1 ¼" die using the 1/8" ground material. She also used both the 1/8" and 3/8" ground material pelleted through the 3/8" x 1 ¾" die. Her tables are presented in Appendix B.

Table 1 provides a breakdown of the separate chemical components of the forages on a % dry basis. The lignin, glucan, xylan and ash contents are represented. There appears to be a trend of increasing lignin and glucan content as forages are subjected to the stresses of compaction and heat.

Table 2 outlines the moisture contents of the various forages as well as the water soluble and ethanol soluble portions of the forages. She found that moisture contents of the pellets ranged from 10.9 to 13.5 % wet basis. These values indicate the forages should have a stable shelf life. The water soluble portion of the extracts were generally 2 to 5 times higher than the ethanol soluble portions. A trend indicates that as forages are pelleted a greater amount of the extracts become ethanol soluble.

Forages were then subjected to a dilute-acid pretreatment at 140°C for 30 minutes. Results are indicated in Table 3. A significant portion of the xylan content has been converted to glucan and lignin through an acid-pretreatment step. The effect of pelleting had little statistical significance on glucan yield after the acid pretreatment step. This step could be included during the water addition stage of the pelleting process to streamline production in an industrial scenario.

Table 4 provides a breakdown of the sugar components contained in untreated forages. Xylose, arabinose and glucose levels were measured as a component of a 100 gram sample. The table shows an increase in all sugar yields as forages are pelleted.

Table 5 shows that pelleting has a positive effect on the total amount of cellulosic conversion to glucose by enzymes. Most forages saw a 2 to 5 % increase in %ECC. Big bluestem benefitted the most from a 82% ECC or unprocessed straw to a 91.1% ECC for 3/8" ground pelleted.

Table 1-1

Table 1-1: Electrical Measurements of Grinding Forages

Screen	Forage	Average kWh/ton	Average Power Factor	Average % Motor Load
1/8"[a]	Corn Stover [a]	35.07 [a]	0.78	43.48
	Sorghum Stalks [b]	29.33 [b]	0.77	42.69
	Big Bluestem [a]	33.53 [a]	0.77	41.93
	Wheat Straw [c]	25.57 [c]	0.74	39.63
3/8"[b]	Corn Stover [a]	12.79 [d]	0.78	43.98
	Sorghum Stalks [b]	12.42 [d]	0.76	42.46
	Big Bluestem [a]	12.26 [d]	0.74	39.99
	Wheat Straw [c]	12.73 [d]	0.69	36.10

[(a, b, c, d)] Variables within a column with differing superscripts are significantly different ($p<0.05$)

Table 1-2

Table 1-2: Electrical Measurements of Pelleting Ground Forages

Screen	Forage [(1)]	Average kWh/ton	Average Power Factor	Average % Motor Load
1/8" [a]	Corn Stover [a]	111.69 [a]	0.67	53.53
	Sorghum Stalks [b]	84.36 [b]	0.63	50.94
	Big Bluestem [c]	108.17 [a]	0.70	55.71
	Wheat Straw [c]	95.49 [c]	0.61	49.61
3/8" [b]	Corn Stover [a]	111.44 [a]	0.66	53.21
	Sorghum Stalks [b]	90.38 [b]	0.58	47.50
	Big Bluestem [c]	152.80 [d]	0.66	53.22
	Wheat Straw [c]	157.15 [d]	0.60	49.09

[(a, b, c, d)] Variables within a column with differing superscripts are significantly different ($p<0.05$).

[(1)] All forages were pelleted with a 3/8" x 1 3/4" pellet die.

Table 1-3

Table 1-3: Bulk Densities, Production Rates and Particle Sizes of Ground Forages

Screen	Forage	Average Bulk Density [(1)]	Average Production Rate [(2)]	Average Length
Chopped	Corn Stover	2.56 [a]	N/A	6.5 in.
	Sorghum Stalks	2.98 [a]	N/A	6.5 in.
	Big Bluestem	2.35 [a]	N/A	7.0 in.
	Wheat Straw	2.40 [a]	N/A	7.0 in.
1/8"	Corn Stover	7.61 [b]	150.40 [b]	.06 in.
	Sorghum Stalks	10.07 [c]	189.80 [c,]	.06 in.
	Big Bluestem	7.37 [d]	159.60 [b, c]	.07 in.
	Wheat Straw	6.56 [e]	191.60 [c]	.07 in.
3/8"	Corn Stover	4.66 [f]	448.60 [d]	.10 in.
	Sorghum Stalks	6.27 [g]	437.00 [d, e]	.08 in.
	Big Bluestem	4.73 [f]	404.60 [e]	.12 in.
	Wheat Straw	4.77 [f]	326.40 [f]	.12 in.

[(a, b, c, d, e, f , g)] Variables within a column with differing superscripts are significantly different ($p<0.05$)

[(1)] Bulk Densities are expressed in lb/ft^3

[(2)] Production Rates are expressed in lb/hour

Table 1-4

Table 1-4: Bulk Densities and Production Rates of Pelleted Ground Forages

Screen	Forage [3]	Average Bulk Density [1]	Average Production Rate [2]
1/8"	Corn Stover	39.86 [a]	223.43 [a]
	Sorghum Stalks	31.18 [b]	265.95 [b]
	Big Bluestem	39.32 [a]	248.62 [c]
	Wheat Straw	36.88 [c]	223.54 [a]
3/8"	Corn Stover	43.77 [d]	227.60 [a]
	Sorghum Stalks	32.2 [b]	208.68 [a]
	Big Bluestem	40.68 [a, e]	159.16 [d]
	Wheat Straw	42.45 [d, e]	129.51 [e]

[a, b, c, d, e] Variables within a column with differing superscripts are significantly different ($p<0.05$).

[1] Bulk Densities are expressed in lb/ft^3.

[2] Production Rates are expressed in lb/hour.

[3] All forages were pelleted with a 3/8" x 1 3/4" pellet die.

Table 1-5

Table 1-5: Pellet Durability Indexes of Pelleted Ground Forages

Screen	Forage [1], [3]	Average Standard PDI %	Average Modified PDI % [2]
1/8" [a]	Corn Stover	97.43 [a]	97.30 [a]
	Sorghum Stalks	92.20 [b]	91.60 [b]
	Big Bluestem	97.00 [a]	96.40 [a]
	Wheat Straw	96.80 [a]	96.2 [a]
3/8" [b]	Corn Stover	98.00 [a]	97.30 [a]
	Sorghum Stalks	96.00 [a]	94.20 [c]
	Big Bluestem	97.40 [a]	96.80 [a]
	Wheat Straw	98.00 [a]	97.58 [a]

(a, b, c) Variables within a column with differing superscripts are significantly different ($p<0.05$).

(1) All forages were pelleted with a 3/8" x 1 3/4" pellet die.

(2) Two standard and two modified (addition of five ½” hex nuts).

(3) PDI tests were conducted for each production run.

Table 1-6

Table 1-6: Electrical Measurements of Pelleting 3/8" Ground Forages Utilizing Water and Glycerol

Additive	Forage [(1)]	Average kWh/ton	Average Power Factor	Average % Motor Load
Water [a]	Corn Stover [a]	111.44 [a]	0.66	53.21
	Sorghum Stalks [b]	90.38 [b]	0.58	47.50
	Big Bluestem [c]	152.80 [c]	0.66	53.22
	Wheat Straw [c]	157.15 [c]	0.60	49.09
Glycerol [b]	Corn Stover [a]	106.80 [a]	0.66	52.31
	Sorghum Stalks [b]	87.37 [b]	0.58	45.30
	Big Bluestem [d]	123.83 [d]	0.64	54.58
	Wheat Straw [d]	125.60 [d]	0.63	51.09

[(a, b, c, d)] Variables within a column with differing superscripts are significantly different (p,0.05).

[(1)] All forages were pelleted with a 3/8" x 1 3/4" pellet die.

Table 1-7

Table 1-7: Bulk Densities and Production Rates of Pelleted Ground Forages Utilizing Water and Glycerol

Additive	Forage [3]	Average Bulk Density [1]	Average Production Rate [2]
Water	Corn Stover	43.77 [a]	227.60 [a]
	Sorghum Stalks	32.2 [b]	208.68 [a]
	Big Bluestem	40.68 [c]	159.16 [b]
	Wheat Straw	42.45 [a, c]	129.51 [c]
Glycerol	Corn Stover	42.98 [a, c]	225.38 [a]
	Sorghum Stalks	33.02 [b]	214.5 [a]
	Big Bluestem	40.27 [c]	185.36 [d]
	Wheat Straw	41.85 [c]	172.76 [b, d]

[a, b, c, d,] Variables within a column with differing superscripts are significantly different (p,0.05).

(1) Bulk Densities are expressed in $lb/ft^{3.}$

(2) Production Rates are expressed in lb/hour.

(3) All forages were pelleted with a 3/8" x 1 3/4" pellet die.

Chapter 2 - Logistical Cost Benefits of Pelleting Cellulosic Biomass

Introduction

Models for cost and logistics analysis have been developed by Hess (2007), Krishnakumar (2010), Mukunda (2007) and Sokhansanj (2006). Since large scale data from operating cellulosic ethanol plants is not available, certain assumption must be made for calculations. Before we can accurately predict the cost savings of preprocessing forages before ethanol production, production scale electrical data must be obtained for calculations and comparisons. High cellulose crops tend to have low bulk densities and this represents a significant problem in terms of harvesting, transportation and storing. Forage production is seasonal and efficient means for product storage and transportation must be addressed. It is unlikely that plants will have enough on-hand storage for forages year round and product degradation may also become an issue in some situations.

The effectiveness and feasibility of cellulosic biomass as an energy source for ethanol production is limited by the current harvesting/processing equipment, transportation system and storage systems that we currently have available for on the farm use. The low bulk densities that bales and ground biomass have make it hard to handle and transport in the large quantities that would be required for commercial ethanol production.

By increasing the bulk densities of cellulosic biomass, we will positively influence the flow characteristics and allow for easier handling. This will also allow us to maximize the payload that can be hauled by tractor/trailers or railcars. Using an existing corn ethanol plant in Indiana, Mukunda (2007) showed that transportation is the largest component of the logistics cost of delivering biomass from the farm production centers to the plant processing centers.

The physical properties of the ground biomass prevent it from flowing properly during the unloading, storage and transfer operations at a biorefinery. These flow characteristics would require biorefineries to install specialized equipment and would make retrofitting existing corn based ethanol plants into cellulosic ethanol plants almost impossible. Conveying equipment is capable of moving specific volumes of material. If a low bulk density product was introduced into the flow, the performance of all downstream equipment would be affected and plant throughput would be drastically lowered. The added cost of the new equipment could be reduced or eliminated if the bulk density of the feedstock could be increased prior to delivery (Mani et al, 2006). Other costs associated with handling a low bulk density feedstock include the additional conveyor capacity and storage facilities in order to handle light material.

Biomass utilized for ethanol would most likely require a storage facility before delivery to the ethanol plant in order to prevent degradation of the cellulose content due to weather. This would require a large amount of shed space or full poly wrapped bales, neither of which is cost effective for this processing situation.

In regards to feedstock storage, Cushman et al. (2003) state storage systems (such as baling, compacting or pelleting) need to increase feedstock density by 2.5 times in order to be considered relevant. A similar target was set for preprocessing which included the development of ways to increase biomass availability through affective year round storage methods and making normally unavailable biomass source useable. If biomass from any source can be pelleted and stored in grain storage facilities, then a pelleting system could be utilized at different times of the year to pellet and store numerous sources, such as cool season grasses in early spring, wheat, barley and oat straw during the summer, corn and grain sorghum stalks in the fall, and perennial grasses such as switchgrass in the early winter.

It is unclear what effects degradation would have on cellulosic ethanol conversion, but they would most likely be negative. Decomposition of the cellulosic material decreases the amount of substrates available to the microbes for fermentation. It could also introduce wild fermentations into the production system and result in the formation of volatile fatty acids, which could inhibit the desired fermentation.

Another limitation is the inability to maximize payload due to the bulk density. Tractor/trailers are regulated based on volume and weight. Ideally, we would reach the weight rating before maximizing volume in order to haul the most material possible. If a semi were capable of hauling 1,100 $lb/ft/^3$ of product, it would hold 49,500 pounds of corn, at 45 $lb/ft/^3$, or 8,800 pounds of ground forages, at 8 $lb/ft/^3$. Increasing the bulk density through additional processing, can have a significant impact on our bottom line and also increase the distances we can afford to transport product.

A pilot study (Hess et al., 2006) of a straw based ethanol plant reported that at feedstock bulk densities of 128 kg m^{-3} (8 lbs ft^{-3}), 80 percent of the feedstocks available within a 100 mile radius of the plant must be delivered to the plant. To reduce transportation costs, 76 percent must come from with 80 km of the plant, 17 percent from 80 to 120 km of the plant, and 12 percent from 120 to 160 km of the plant to supply 105 percent of demand. If transportation costs can be reduced by increasing feedstock density, it possible that these percentages can be reduced and the radius that feedstocks are drawn from can be increased to ease the pressure on fields near the biorefinery to supply feedstocks.

Cushman (et al., 2003) observed several goals, limitations and research needs in order for biomass based feedstocks to be feasible. Most limitations were associated with harvesting, preprocessing, transporting, and handling of the feedstocks since the current forage technology is not capable of producing and transporting the 800,000 to 1 million tons of feedstocks annually to a biorefinery efficiently. Strategic goals of increasing efficiency by utilizing existing transportation infrastructure, demonstrating cost effective storage systems for mega-ton quantities, and increasing biomass value at every stage of the feedstock chain can be addressed with pelleting biomass. If biomass is pelleted, it can be handled and transported with grain handling equipment in the field, on the road and at the biorefinery.

Processing Costs

Krishnakumar and Ileleji (2010) summarized the costs of pre-processing corn grain, corn stover pellets and bales and switchgrass pellets and bales for ethanol conversion. The summary is represented in the table below.

Figure 2-1

Feedstock Type/Form	On-farm Feedstock Cost ($ Mg^{-1})	Pre-processing Cost ($ Mg^{-1})	Source
Corn grain	143.4-170.8	N/A	World Agricultural Supply & Demand Estimates, USDA (Dec, 2008)
Corn stover bales	37.3[a]	N/A	Brechbill et al, 2008
Corn Stover pellets	37.3[a]	40.5[b]	Brechbill et al. (2008), Sokhansanj and Fenton (2006), and Sokhansanj et al. (2006)
Switchgrass bales	59.7[a]	N/A	Brechbill et al., 2008
Switchgrass pellets	59.7[a]	40.5[b]	Brechbil et al. (2008), Sokhansanj and Fenton (2006), and Sokhansanj et al. (2006)

[a] Assuming custom equipment was used and bales were stored covered with twine for a period of 1 year. Includes cost for waiting time for loading on farm and unloading at ethanol plant.
[b] Assuming the cost included de-stringing and debaling costs (Sokansanj et al., 2006).

Source: Krishnakumar and Ileleji, 2010

The costs are represented in dollars per Mg. A Mg is equal to 1 metric ton or 1.102 short tons. The authors indicate the three costs for corn grain and baled biomass are feedstock cost on farm, farm to biorefinery transport cost and handling/storage at biorefinery. The costs for pelleted cellulosic biomass are the same as above but also include, farm to preprocessing plant transportation and preprocessing cost. Their model is assuming forages will be transported from the field to a pelleting and cooling substation then transported to the ethanol facilities. By moving the grinding and pelleting operation to the field we could dramatically increase the efficiency of the operations, reduce the total amount of steps and reduce overhead from transportation costs.

Sokhansanj (et al, 2006) detailed the costs, energy inputs and carbon emissions for biomass collection and preprocessing. The costs of grinding, pelleting and cooling biomass for ethanol conversion are listed in the table below.

Figure 2-2

Table 9. Cost of biomass pellet production for the base case (2004 US dollars)

Pellet process operations	Capital cost ($\$ t^{-1}$)	Operating cost ($\$ t^{-1}$)	Total cost ($\$ t^{-1}$)	Energy use ($GJ\ t^{-1}$)
Drying operation	2.46	7.84	10.30	0.350
Hammer mill	0.25	0.70	0.95	0.100
Pellet mill	1.43	1.88	3.31	0.268
Pellet cooler	0.13	0.21	0.34	0.013
Screening	0.11	0.05	0.16	0.006
Packing	0.56	1.37	1.93	0.006
Pellet Storage	0.07	0.01	0.08	0.026
Miscellaneous equipment	0.42	0.33	0.76	0.052
personnel cost	0.00	12.74	12.74	-
land use & building	0.21	0.05	0.26	-
Total cost[1]	5.64	25.18	30.83	0.821
	3.18	17.34	20.53	0.471

[1]First row of total cost includes drying. Second row of total cost does not include drying

Source: Sokhansanj, 2006

Sokhansanj obtained the costs for grinding, pelleting and cooling bases its assumptions from data provided by Mani (et al, 2006). Mani conducted a study which looked at the specific energy of compacting corn stover into briquettes. This process utilized a single cylinder hydraulic press for the creating of pellets. By applying our electrical data we can determine a more accurate measurement of the costs for densification using a ring-style pellet die.

Table 2-2 substitutes the energy related costs for grinding and pelleting of cellulosic biomass obtained during our study with the approximate values from the analysis by Sokhansanj. While the derived values from both studies are very similar the new data illustrates some additional methods of savings. For example, grinding wheat straw and big bluestem through a 1/8" screen used less total energy than grinding through a 3/8" screen (by $3.13/ton and $1.70/ton, respectively). Corn stover and sorghum stalks ground through the 3/8" screen were the most energy efficient forages, at $27.96/ton and $26.59.

Many of the cost saving measures suggested by Sokhansanj are also relevant for us. Increasing the production capacity of our machinery would decrease the kWh/ton and increasing the frequency of machinery usage.

Since we were unable to measure the energy used during tub grinding, similar data was included from a study by Hess (et al, 2006). They measured the fuel usage of a tub grinder using different screen sizes. The kWh/ton from a grind size very similar to the chopped forages we obtained was used for our total energy usage calculation. It should also be noted that the pellet mill used in our study is the smallest production model manufactured by CPM. Pellet mill energy usage accounted for 20-32% of the total costs of grinding and pelleting. By doubling our efficiency by switching to a larger pellet mill, we could reduce the cost/ton by up to $4.80.

Transportation Costs

The transportation costs vary on the bulk density of the products being transported, the method of transportation and the distance from the field to ethanol production center. Sokhansanj (et al, 2006) also outlined costs associated with transporting cellulosic biomass by way of truck, railcars and pipelines. He does note that the transport costs for trucking and rail do not change with the overall size of the contract. In a live scenario, price breaks would likely be given based on the overall tonnage consumed by the ethanol plants.

The rail systems become a more efficient means for transport over trucking at distance of 110 km or more. These estimates are also dependent on the location of the fields and ethanol plants to the rail systems and the location of railroad substations.

Figure 2-3

Table 8. Cost and energy consumption equations for transporting biomass using truck, rail, or pipeline*

Transport mode	Cost ($\$ t^{-1}$)	Energy consumption ($MJ\ t^{-1}$)
Truck	5.70+0.1367 L	1.3 L
Rail	17.10+0.0277 L	0.68 L
Pipeline*	$2.67Q^{-0.87}+0.37LQ^{-0.44}$	$160.2Q^{-0.87}+22.2\ LQ^{-0.44}$

L distance (km)
Q annual supply (million dry t)
* the cost and energy values for pipe line are in $ and in MJ

Source: Sokhansanj, 2006

As bulk density is one of the main limiting factors in transportation and logistics, we wanted to include a cost structure that accounts for the differences in bulk density based on processing. Table 2-1 outlines the impact of bulk density on fuel usage and costs. The USDA Weekly Grain Transportation Report (USDA, 2011) stated that for the week ending 5/23/2011 diesel prices in the Midwest were on average $3.942/gallon. The fuel mileage for loaded grain semis ranges from 5-8 mpg. The table shows that as bulk density decreases, efficiency decreases due to total truck weight and the number of trucks required for supplying biomass to the plants increases. It should be noted that all other cost factors associated with transportation (labor, truck maintenance costs, initial equipment costs, ect.) will also increase because of the additional trucks needed for transportation.

Storage Costs

Krishnakumar and Ileleji (2010) also calculated the costs associated with the storage of biomass. These costs vary depending on feedstock variety and plant size. As plant capacity is increased, additional bins are needed for storage but throughput allows the operation to become more electrically efficient. The costs of storage are represented in the tables below.

Figure 2-4

Table 5. Storage requirements and costs for corn grain.

Capacity (MLPY)	Inventory Required (Mg)	No. of Bins	Volume of Each Bin[a] (cu. m)	Diameter of Bin[a] (m)	Total Cost ($ Mg-1)
151.4	10,390	2	7150	18.3	34.7
227.1	15,585	2	10725	22	34.7
378.5	25,975	2	17875	27.4	27.06
567.8	38,962	3	17875	27.4	27.06
757.1	51,949	3	23833	32	27.06

[a] Source: Commercial Grain Bin Specifications, GSI Grain Systems, 2009.

Table 7. Storage requirements and costs for pellets.

Capacity (MLPY)	Inventory Required (Mg)	No. of Bins	Volume of Each Bin[a] (cu. m)	Diameter of Bin[a] (m)	Total Cost ($ Mg-1)
151.4	14431	2	13,228	23.77	32.77
227.1	21646	2	19,482	32	24.42
378.5	36076	3	22,046	32	24.42
567.8	54113	5	19,842	32	24.42
757.1	72151	6	22,046	32	24.42

[a] Source: Commercial Grain Bin Specifications, GSI Grain Systems, 2009.

Table 6. Storage requirements and costs for bales.

Capacity (MLPY)	Inventory Required (Mg)	Area of Storage (m-2)	No. of Bale Handlers	Storage Cost ($ Mg-1)
151.4	14431	35,000	9	82.1
227.1	21646	53,000	13	79.8
378.5	36076	88,000	21	77.8
567.8	54113	131,000	30	77.2
757.1	72151	175,000	40	76.3

Source: Krishnakumar and Ileleji, 2010

While baled cellulose benefits from the lack of pre-processing costs, it costs over twice the amount of storage for pellets due to the large amounts of space required.

The amount of bin space required for pellets was calculated by Krishnakumar by a bulk density of 600 kg/m^3 or 37.5 lb/ft^3. With the exception of sorghum pellets, all other forage pellets were around 40 lb/ft^3, which would further decrease the size of the bins needed or increase the amount of an-hand inventory plants could hold.

Summary

The total costs of biomass preprocessing, incoming transportation costs and costs of storage and unloading are represented on Table 3-3. The low costs of transporting corn grain, baled biomass and the averages of all pellets are $31.70/ton, $100.77/ton and $52.91, respectively. The high costs of transporting corn grain, baled biomass and the averages of all pellets are $28.62/ton, $102.45/ton and $56.62, respectively. The high cost accounts for 5 MPG in semis and the low cost accounts for 8 MPG in semis. Although the cost of transporting pelleted cellulosic biomass is almost twice the cost of transporting whole corn, it is a much more efficient means of transportation than baling biomass. It would be possible to further reduce the costs of pelleting by increasing the total throughput of the machinery, designing machinery specifically for this application or designing the cellulosic ethanol infrastructure to utilize primarily railroads. The prohibitive logistical costs of forages have prevented cellulosic ethanol form becoming a viable competitor in the energy market. By utilizing a variety of feedstocks and a mobile densification process, these logistical shortcomings can be overcome. The results of this study show that through pelleting we are able to significantly decrease the amount of truck traffic and unloading necessary to operate cellulosic ethanol plants. By optimizing the receive process of ethanol plants, the man hours required for operation can be reduced, conveying equipment can be utilized to its full potential and bin space within the facility can be maximized. Our study shows that through pelleting, the logistical structure of the cellulosic ethanol industry can be optimized and might even benefit from the additional sugars yielded through the heating due to the pelleting process.

Table 2-1

Table 2-1: Impact of Bulk Density on Transportation Costs

			1/8" Ground Pellets				3/8" Ground Pellets			
	Whole Corn	Baled Biomass	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover
Bulk Density lb/ft^3	45.00	9.4 [3]	36.88	31.18	39.32	39.86	42.45	32.20	40.68	43.77
Truckload Weight (tons) [1]	30.00	17.6 [3]	24.59	20.79	26.21	26.57	28.30	21.47	27.12	29.18
Fuel Price ($/mile/ton) at 5 MPG [2]	0.0262	0.0448	0.0321	0.0379	0.0301	0.0297	0.0279	0.0367	0.0291	0.0270
Fuel Price ($/mile/ton) at 8 MPG [2]	0.0164	0.0280	0.0200	0.0237	0.0188	0.0185	0.0174	0.0230	0.0182	0.0169
Equipment and Operating Costs ($/ Mile) [4]	0.4310	0.4310	0.4310	0.4310	0.4310	0.4310	0.4310	0.4310	0.4310	0.4310
Price of 100 miles/truck at 5 MPG	121.71	121.95	121.94	121.94	121.94	121.94	121.94	121.94	121.94	121.94
Price of 100 miles/truck at 8 MPG	92.30	92.38	92.38	92.38	92.38	92.38	92.38	92.38	92.38	92.38
Number of Trucks for 5000 tons	167	285	203	241	191	188	177	233	184	171
Incoming Costs $ at 5 MPG for 5000 tons	20325.57	34755.75	24797.99	29331.30	23259.16	22944.05	21544.17	28402.17	22481.56	20894.45
Incoming Costs $ at 8 MPG for 5000 tons	15414.10	26328.30	18785.59	22219.77	17619.85	17381.15	16320.67	21515.92	17030.79	15828.48

(1) Assuming Truck Volume of 1,333.3 ft^3

(2) Diesel Price of $3.942/gallon

(3) Source: Krishnakumar and Ileleji, 2010

(4) Source: Iowa State University Extension, 2011

Table 2-2

Table 2-2: Energy Costs of Grinding and Pelleting Biomass

	1/8" Grind				3/8" Grind			
	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover
kWh/ton Tub Grinding [(1)]	36.19	36.19	36.19	36.19	36.19	36.19	36.19	36.19
kWh/ton Grinding	25.57	29.33	33.53	35.07	12.73	12.42	12.26	12.79
kWh/ton Pelleting	95.49	84.36	108.17	111.69	157.15	90.38	152.80	111.44
Total kWh/ton	157.25	149.88	177.89	182.95	206.07	138.99	201.25	160.42
Energy Cost $ [(2)]	10.08	9.61	11.20	11.73	13.21	8.91	12.90	10.28
Additional Capital Costs $ [(3)]	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
Additional Operating Costs $ [(3)]	14.71	14.71	14.71	14.71	14.71	14.71	14.71	14.71
Total Cost/Ton $	27.76	27.29	28.88	29.41	30.89	26.59	30.58	27.96

[(1)] Source: Hess et al, 2007
[(2)] Industrial kWh/ton price in Kansas is $.0641 Source : U.S. Energy Information Administration Average

[(3)] Source: Sokhansanj et al, 2006

Table 2-3

Table 2-3: Preprocessing, Transportation and Storage Costs of Cellulosic Biomass to Ethanol Plants

			1/8" Grind				3/8" Grind			
	Whole Corn	Baled Biomass	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover	Wheat Straw	Sorghum Stalks	Big Bluestem	Corn Stover
Preprocessing Costs $/ton	N/A	17.7 [(1)]	27.76	27.29	28.88	29.41	30.89	26.59	30.58	27.96
High Incoming Costs $/mile/ton	0.041	0.070	0.050	0.059	0.047	0.046	0.043	0.057	0.045	0.042
Low Incoming Costs $/mile/ton	0.031	0.053	0.038	0.044	0.035	0.035	0.033	0.043	0.034	0.032
Cost of Storage and Unloading[(2)]	24.56	77.80	19.87	23.50	18.64	18.38	17.26	22.76	18.01	16.74
Total High Cost 100 mile transport [(3)]	31.70	100.77	52.59	56.66	52.17	52.38	52.46	55.03	53.09	48.88
Total Low Cost 100 mile transport [(4)]	28.62	102.45	56.40	61.16	55.74	55.91	55.77	59.39	56.54	52.09

[(1)] Source: Hess et al, 2007

[(2)] Source : Krishnakumar and Ileleji, 2010 (accounts for varying bulk density of pellets and 378.5 MLPY plant capacity)

[(3)] High cost assumes 5 MPG semi fuel economy

[(1)] Low cost assumes 8 MPG semi fuel economy

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Appendix A - Calculations

Pellet Durability Index (PDI %)

Pellet Durability (%) = (Weight of the pellets after tumbling / Weight of the pellets before tumbling) * 100

500 grams of sifted pellets, tumbled for 10 minutes, sifted with a U.S. number 6 sieve

% Moisture Calculations

Moisture Content (dry basis percent) = (Loss in Weight x 100) / Weight of Dry Sample

25 gram sample, dried at 103° C for 24 hours.

Bulk Density

1 gram / U.S. quart = 0.0659668899 lb/ft^3

1 lb/ft^3 = 1.24445608 lb/bushel

1 lb/ft^3 = 16.0184634 kg/m^3

Production Rate

Pounds / minute x 60 = (pounds / hour) / 2000 pounds / ton = tons / hour

Particle Size

Calculation of average particle size (mm)

Pore size in	Retention g	Retention % (M_i)	d_i mm	log d_i	M_i log d_i
0.75	A	(A/sum) * 100	30	1.48	((Retention % A) * log d_I A
0.31	B	(B/sum) * 100	12.33	1.09	((Retention % B) * log d_I B
0.07	C	(C/sum) * 100	3.66	0.56	((Retention % C) * log d_I C
0	D	(D/sum) * 100	0.83	-0.08	((Retention % D) * log d_I C
sum	A+B+C=D	addition of the above values			addition of the above values

d_{gm} = 10^(M_I log D_I A / Sum of the Retention %)

$M_i (\log d_i - \log d_{gm})^2$
Retention % A * ((log d_l A - LOG (sum of retention in grams)) ^2)
Retention % A * ((log d_l A - LOG (sum of retention in grams)) ^2)
Retention % A * ((log d_l A - LOG (sum of retention in grams)) ^2)
Retention % A * ((log d_l A - LOG (sum of retention in grams)) ^2)
addition of the above values
S_{gm} = 10^(((M_l log Dl - log d_{gm}) A / sum of the retention %) ^0.5)

Logistics Calculations

Truck Payload

(1333.33 ft^3 x Bulk Density of Product) / 2000 lb/ton = Payload

Fuel Price $/Mile/Ton

($3.942/Gallon Fuel / Fuel Mileage) / Payload = Fuel Price/Mile/Ton

Total Incoming Costs $/Mile/Ton

(Equipment and Operating Costs $ Per Mile / Payload) + Fuel Price $/Mile/Ton
= Total Incoming Costs $/Mile/Ton

Appendix B - Sugar Yields

Table 1 Chemical composition of <u>untreated</u> biomass as affected by mill screen size, die thickness, and L/D ratio of the die

Biomass feedstock	Pelleting conditions			Chemical component of solid fractions (%, db)[a]			
	Mill screen size (mm)	Die thickness (mm)	L/D ratio	Lignin	Glucan	Xylan	Ash
Wheat straw		Unpelleted		16.3 a	41.2 a	23.8 a	3.11 a
	3.2	31.8	8	18.0 a	43.2 a	24.1 a	3.04 a
	3.2	44.5	7	17.5 a	44.8 a	22.8 a	4.13 a
	6.5	44.5	7	17.6 a	46.1 a	23.7 a	3.31 a
Corn stover		Unpelleted		18.2 a	42.2 a	23.3 a	2.13 a
	3.2	31.8	8	18.4 a	41.5 a	23.3 a	3.31 a
	3.2	44.5	7	18.9 a	42.6 a	22.9 a	3.29 a
	6.5	44.5	7	19.6 a	43.2 a	24.5 a	2.55 a
Big bluestem		Unpelleted		18.7 a	40.1 a	21.6 a	2.37 a
	3.2	31.8	8	18.0 a	40.9 a	23.1 a	2.81 a
	3.2	44.5	7	19.7 a	43.2 a	23.5 a	2.68 a
	6.5	44.5	7	19.8 a	42.7 a	24.1 a	2.50 a
Sorghum stalk		Unpelleted		18.2 a	41.7 a	23.0 a	2.02 a
	3.2	31.8	8	17.5 a	40.6 a	22.2 a	3.34 a
	3.2	44.5	7	18.3 a	42.3 a	22.5 a	3.24 a
	6.5	44.5	7	18.8 a	41.5 a	23.6 a	3.24 a

[a] Means in the same biomass followed by different letters are significantly different at $p<0.05$

Source: Theerarattonanoon, 2011

Table 2 Effects of mill screen size, die thickness, and L/D ratio of the die on extractives of pellets made from wheat straw, big bluestem, corn stover, and sorghum stalks

Biomass feedstock	Pelleting conditions				Extractives (% db)		
	Mill screen size (mm)	Die thickness (mm)	L/D ratio	Moisture content (%, wb)	Water soluble	Ethanol soluble	Total
Wheat straw		Unpelleted		3.73±0.68	12.7±1.19	3.80±0.24	16.5±1.43
	3.2	31.8	8	11.6±0.01	13.3±0.92	4.81±0.07	18.2±0.86
	3.2	44.5	7	12.7±0.45	12.9±0.71	4.42±0.24	17.4±0.84
	6.5	44.5	7	11.1±0.13	11.2±0.72	5.00±0.21	16.2±0.74
Corn stover		Unpelleted		3.69±0.11	17.0±2.15	4.54±0.00	21.6±1.95
	3.2	31.8	8	12.3±0.04	15.2±0.89	6.49±0.36	21.7±0.53
	3.2	44.5	7	10.9±0.44	17.8±0.85	6.07±0.11	23.9±0.81
	6.5	44.5	7	12.9±0.02	17.8±0.55	6.88±0.15	24.7±0.52
Big bluestem		Unpelleted		2.83±0.07	11.1±2.14	2.91±0.86	14.0±1.25
	3.2	31.8	8	12.1±0.02	12.4±0.71	6.07±0.37	18.7±0.95
	3.2	44.5	7	11.7±0.21	12.1±0.81	5.21±0.15	17.4±0.73
	6.5	44.5	7	11.3±0.03	10.7±0.76	5.91±0.18	16.6±0.66
Sorghum stalk		Unpelleted		3.24±0.26	23.6±1.43	5.45±0.21	29.1±1.22
	3.2	31.8	8	12.9±0.08	21.4±1.51	7.33±0.19	28.7±1.82
	3.2	44.5	7	12.5±0.19	19.3±0.94	7.43±0.30	26.8±0.89
	6.5	44.5	7	13.5±0.06	19.7±0.63	8.26±0.11	27.9±0.74

Source: Theerarattonanoon, 2011

Table 3 Chemical composition of biomass as affected by dilute-acid pretreatment (140 ^{o}C, 30 min) and pelleting process

Biomass feedstock	Pelleting conditions			Component in solid fractions (%)[a]					
	Mill screen size (mm)	Die thickness (mm)	L/D ratio	Lignin	Glucan	Xylan	Ash	Mass recovery (%)	Cellulose recovery (%)
Wheat straw	Unpelleted			34.4 a	55.9 a	1.58 a	5.64 a	58.9	79.9
	3.2	31.8	8	34.1 a	52.9 b	1.95 b	5.48 a	63.1	77.3
	3.2	44.5	7	34.2 a	58.2 c	1.59 a	7.62 b	55.7	72.3
	6.5	44.5	7	34.8 a	55.6 a	1.82 b	8.29 c	61.7	74.4
Corn stover	Unpelleted			34.6 a	56.1 a	1.68 a	2.85 a	60.6	80.6
	3.2	31.8	8	34.0 a	52.5 a	2.36 b	4.87 b	64.2	81.3
	3.2	44.5	7	35.8 a	56.6 b	1.68 a	6.22 c	63	83.6
	6.5	44.5	7	35.4 a	54.1 b a	1.93 a	5.59 c b	67.1	84.1
Big bluestem	Unpelleted			34.9 a	54.5 a	1.64 a	2.84 a	57.9	78.6
	3.2	31.8	8	35.1 a	53.3 a	1.89 a	5.49 b	61.8	80.5
	3.2	44.5	7	35.3 a	58.5 b	1.59 a	4.12 c	60.2	81.6
	6.5	44.5	7	34.4 a	58.1 b	2.30 b	4.66 c b	59.4	80.8
Sorghum stalk	Unpelleted			33.3 a	53.4 a	1.53 a	3.25 a	60.6	77.6
	3.2	31.8	8	33.7 a	53.4 a	2.42 a	5.76 b	59.5	78.2
	3.2	44.5	7	37.0 a	58.0 b	1.62 a	5.73 b	56.2	77
	6.5	44.5	7	36.2 a	54.4 a	1.46 a	6.55 b	58.5	76.7

[a] Means in the same biomass followed by different letters are significantly different at $p<0.05$

Source: Theerarattonanoon, 2011

Table 4 Sugar yield in filtrate of biomass after dilute acid pretreatment as affected by mill screen size, die thickness, and L/D ratio of the die

Biomass feedstock	Pelleting conditions			Component in filtrate fractions (g/100 g of dry, untreated biomass)		
	Mill screen size (mm)	Die thickness (mm)	L/D ratio	Xylose	Arabinose	Glucose
Wheat straw		Unpelleted		14.4±1.83	2.55±.28	8.28±.03
	3.2	31.8	8	17.1±.3	2.53±.05	9.8±.03
	3.2	44.5	7	17.2±.41	2.69±.04	12.4±.09
	6.5	44.5	7	16.3±.23	4±.08	11.8±.18
Corn stover		Unpelleted		15.9±.09	2.5±.08	8.57±.07
	3.2	31.8	8	16.3±.27	2.86±.06	7.96±.46
	3.2	44.5	7	18.3±1.43	2.59±.03	7.97±.12
	6.5	44.5	7	16±.66	4.36±.38	8.19±.06
Big bluestem		Unpelleted		16.8±.07	2.98±.06	8.18±.11
	3.2	31.8	8	17.3±3.79	2.69±.12	7.77±1.73
	3.2	44.5	7	19.6±.39	2.69±.01	6.97±.22
	6.5	44.5	7	18.0±.55	4.50±.14	6.89±.49
Sorghum stalk		Unpelleted		16.6±.1	2.49±.06	9.34±.02
	3.2	31.8	8	16.8±1.70	2.34±.18	8.84±.8
	3.2	44.5	7	16.7±.04	1.41±1.99	9.72±.1
	6.5	44.5	7	15.8±.89	4.78±.08	9.69±.39

Source: Theerarattonanoon, 2011

Table 5 Maximum Enzymatic Conversion of Cellulose (%ECC) of biomass samples as affected by mill screen size, die thickness, and L/D ratio of the die

Biomass feedstock	Pelleting conditions			Maximum %ECC
	Mill screen size (mm)	Die thickness (mm)	L/D ratio	
Wheat straw		Unpelleted		91.2±.1 a
	3.2	31.8	8	92.5±.1 b
	3.2	44.5	7	93.1±.5 bc
	6.5	44.5	7	94.1±..1 c
Corn stover		Unpelleted		89.5±..1 a
	3.2	31.8	8	84.6±.1 b
	3.2	44.5	7	92.1±.5 c
	6.5	44.5	7	93.1±.1 c
Big bluestem		Unpelleted		82.0±..1 a
	3.2	31.8	8	83.6±.1 b
	3.2	44.5	7	89.0±..1 c
	6.5	44.5	7	91.1±..1 c
Sorghum stalk		Unpelleted		87.1±.1 a
	3.2	31.8	8	91.4±.1 b
	3.2	44.5	7	92.1±..3 c
	6.5	44.5	7	92.1±.3 c

[a] Means in the same biomass followed by different letters are significantly different at $p<0.05$

Source: Theerarattonanoon, 2011