COLLECTION AND DELIVERY OF BIOMASS FOR FUEL AND POWER PRODUCTION[1]

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ABSTRACT

Biorefineries refer to conversion operations where biomass feedstock is converted to multiple products such as chemicals, fuels, and bioproducts. The concept focuses on maximizing valued extractables while minimizing waste streams. A low cost collection and converting the biomass to feedstock is critical to the success of these emerging industries. A conservative estimate shows that demand for feedstock for biorefineries may reach 172 million dry tons over the next decade (2010) and more than 508 million dry tons in 2020 if biomass technology implementation achieves the stated goals. An orderly supply of this large amount of biomass to biorefineries requires new and robust equipment and well-established infrastructure. At the present, low and inconsistent demand for biomass for energy is the main reason for lack of interest on the part of manufacturers to invest in equipment development. It is important however, that research and development in production and supply technologies proceed in parallel with developments in conversion technologies. This paper reviews the operations involved in biomass supply and identifies three areas of research: moisture control, densification, and systems modeling as key areas of research. Other areas of work such as single step harvesting and on farm fractionation of biomass for added value purposes has also been identified as important areas of work. Manufacturers and processors need reliable engineering data on harvesting and handling of biomass in order to embark on improving and designing new equipment for biomass to feedstock operations.

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[1] This paper is a review of literature and analysis. It does not represent the official policy for research priorities or research methodologies at Oak Ridge National Laboratories or of the Department of Energy.

[2] Sokhansanj is currently on leave from Oak Ridge National Laboratory.

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INTRODUCTION

The increasing commercialization of bioconversion technologies demands a secure supply of high quality biomass feedstock at a competitive price[1]. Some potential biomass feedstocks are industrial by-products, already concentrated at existing processing facilities. Most cellulosic feedstock are widely distributed in loose form and need to be collected, packaged, stored and shipped to conversion facilities. It is projected that the demand for biomass for feedstock may reach more than a half-billion tons annually over the next decade as the conversion technologies evolve and the concepts of biorefining are put in practice[2].

One or several of the following characteristics cast uncertainty on the orderly flow of biomass from field to conversion plant[3]: (a) low bulk density, (b) spoilage due to high moisture, (c) variability in physical and chemical characteristics, (d) geographical and seasonal variations in biomass, (e) conflicting demands on labor and machines, (f) combustibility, (g) competition from soil fertility, (h) local regulations on storage and transport, and (i) sensitivity to price structure for companion products and farm commodities.

Biorefineries refer to conversion operations where biomass feedstock is converted to marketable chemicals including fuels and bioproducts. The concept focuses on maximizing valued extractables while minimizing waste streams. A conservative estimate shows that demand for feedstock for biorefineries may reach 172 million tons over the next decade (2010) and more than 508 million tons in 2020 if biomass technology implementation achieves stated goals[1,2]. An orderly supply of this large amount of biomass to biorefineries requires new and robust equipment and well-established infrastructure. It is estimated that the value of field equipment and power units to collect and bale the biomass demand estimated exceeds \$8.5 billion in 2010 and \$32 billion dollars in 2020. New demands for biomass storage will exceed 4.5 and 14.9 billion cubic ft, generating more than \$3.1 and \$10.6 billion new storage structures in 2010 and 2010, respectively[42].

The cost of feedstock is a direct and often major contributor to the success of conversion technologies[4]. Factors such as environmental implications and energy security are also important social and political issues influencing a bio-based economy. While considerable research efforts go into the development of efficient conversion technologies only a meager research is conducted on problems associated with biomass processing and handling. Preliminary field experiences indicate that the existing grain harvest and forage equipment require major improvements to meet biomass handling and processing specifications.

This paper focuses on technical issues associated with the supply chain – biomass in the field to processed feedstock ready for a bioconversion. It identifies short and long-term research needs toward finding solutions to variability and low bulk density inherent in biomass. Computer tools are proposed to analyze the supply systems and to optimize the delivery networks for cost competitive feedstocks. Biomass species reviewed in this study are limited to crop and forest residue and dedicated energy crops, herbaceous and woody types.

OPERATIONS

Table 1 lists the entire handling system for biomass collection and processing it into feedstock for biorefining. The system is divided into three activity centers (locations): field, countryside, and refinery. Each of these activity centers play parts in converting biomass from its raw form to a finished feedstock for delivery to biorefinery. Activities in the field include those for harvesting and packaging, hauling and temporary storage in the field or moving to an intermediate storage.

Using the existing equipment, field operations involved are similar to forage harvest and collection, mainly cutting, swathing, chopping or baling and hauling. Countryside activities are those processes that reduce variability in biomass. These operations may include size reduction, drying, cubing or pelleting, and storing larger quantities of feedstock. Biorefinery activities include operations such as receiving, sorting, storing, washing and grinding. Normally these operations are included as part of biorefinery analysis. We include these operations here because they are influenced by earlier harvest and handling processes (collection, drying, densification).

Table 1. Entire biomass to feedstock handling system hay or residue

Location or activity center	Major operation	Process	Equipment
FIELD Collecting, packaging and transporting off-the field	Cut & gather	Mowing conditioning	SP Mower – conditioner, disc, sickle, flail
		Raking, tedding, inverting	Rake, tedder, inverter
		Flail shredding and gathering	Flail cutter and windrower
		Combine straw management system	Combine mounted residue chopper and distributor
	Package	Round baling	Round baler with or without crop processor
		Square baling	Large square baler
		Forage harvesting - loose	SP chopper and wagon
		Field cubing	SP or pull type field cuber
	Haul & store in the field	Round bales to field edge - tarping	Automatic bale pickup and mover
		Square bales to field edge - tarping	Automatic stacker, telehandler

COUNTRY SIDE Intermediate storage, processing and handling	Transport	Hauling round bales	Truck trailer – flat bed
		Hauling square bales	Truck trailer – flat bed, container
		Hauling cubes	Truck trailer - container
		Hauling chops	Truck trailer – chop box
	Storage	Stacking and storing round bales	Shed without wall, telehandler
		Stacking and storing square bales	Shed without wall, telehandler
		Unloading and storing cubes	Fat storage with wall, front-end loader
		Unloading chops	Flat storage with wall, front end loader
	Shredding and drying	Grinding round bale	Tub grinder
		Grinding square bales	Square bale shredder
		Drying	Pneumatic drying – rotary drum or fluidized dryer
		Cubing or briquetting	Cuber, bricquetter, hydrothermal conditioning
		Cube conditioning and cooling	Cube cooler
		High density bales	Hydraulic double compaction
REFINERY Receiving and preparing feedstock at the conversion plant	Transport	Receiving and stacking round bales	Truck, telehandler, flat storage without walls
		Receiving and stacking square bales	Truck, telehandler, flat storage without walls
		Receiving and storing cubes	Truck, pit, elevator, distribution, cylindrical bin
	Reclaiming	Reclaiming and preparing round bales	Telehandler, tub grinder, conveyor belt
		Reclaiming and preparing square bales	Telehandler, square bale shredder, conveyor belt
		Reclaiming and preparing cubes	Gravity self unloader conveyor

The price of cellulosic biomass is made up of two distinct components:

- Farm gate price that includes production costs and collection costs plus net return to the crop producer, and
- Delivered price that includes farm gate costs plus handling, storage and transportation costs and some net return to the feedstock supplier.

Opportunities to reduce the collection cost when using the existing equipment comes from two sources[6]: (1) eliminating some of the field operations and (2) improving field performance of the existing equipment. Any success in option (1) would result in direct cost reductions. For example, integrating cutting and raking into a single operation without sacrificing speed reduces the cost by $1.60/ton. Eliminating baling and instead using field chopped biomass may also result in substantial cost reductions depending upon transportation distance. Reductions in costs by improving machine performance are also possible. Sensitivity analyses[7] show that the cost of collection may be reduced from roughly $30 per ton by as much as $5-7 per ton by increasing speed and cutting a wider swath, making a slightly denser bale, and utilizing high speed tractors (for road travel). The same analysis[7] shows that cost of round bale can be reduced as much $11.80 by eliminating raking operation.

Collection costs can be lowered by reducing the number of operations involved in collecting the material from the field. Reducing production and collection costs and increasing the portions of the crop that has market value can enhance profit to the producer. This requires the development of whole-crop harvesting and fractionation. Handling, storage, and transportation costs can be lowered by granulating or comminuting biomass so it can be safely and easily handled by the existing bulk handling equipment. Formulating feedstock composition to increase the value of the feedstock to biorefineries without adding significant cost can enhance profit to the feedstock supplier.

Feedstock engineering evaluations have identified biomass densification and granulation as a key enabling technology needed to support the transformation of biomass from a highly variable resource to a reliable commodity resource for bio-based industries of the future. This evaluation, however, does not rule out other methods of handling and transporting technologies, i.e. ensiling moist biomass and transportation by pipeline. It is believed that these innovative technologies will be developed during the longer-term plans and only for particular logistics and conversion processes.

GAP ANALYSIS – UNCERTAINTIES

Bioprocess community has traditionally regarded the costs and logistics associated with feedstock supply as a non-issue. Designers assume that the existing infrastructure for harvesting of food and feed would respond to increased demands on biomass handling. The bioenergy industry in Europe has long discovered that this is not the case[8]. Europeans identified unique characteristics of biomass that require specialized equipment for handling. They continued leadership in conducting research and development in biomass handling and have developed equipment for energy crops and modifying grain combines for residue collection and management[9].

Published research on biomass collection and pretreatment is sparse and those available in open literature[10,11] are outdated; they do not reflect recent advances in farm and forest equipment industry. In contrast literature on conversion technologies is abundant. Lack of markets and demand for biomass is the main reason behind the meager research on feedstock engineering. Additional research in biomass, especially pilot and full-scale experiments, is expensive and requires substantial resources in highly qualified people and equipment. Research in feedstock engineering is associated with a number of inherent risks that need to be discussed before developing research methodologies.

Equipment and logistics

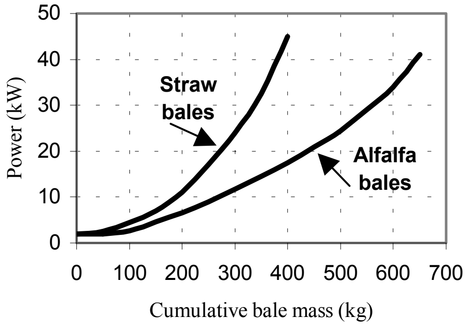

Figure 1: Power requirement of a round baler for wheat straw bales and alfalfa bales

Modern combines are designed to cut and convey in maximum grain but minimum biomass. The innovation has resulted in an increased in the speed of combine from 2-3 mph to almost 5 mph. Any on-the-combine modifications that may result in slow down of the grain harvest process is considered counter productive. The question remains whether it would be economical and logistically feasible to modify the existing grain combines to perform several operations in one pass. Adapting a new harvester for whole crop harvesting of wheat in Canada has not been overly successful[12]. Crop residue plays an important role in protecting and improving soil quality. The interactions between residue removal, soil quality, and crop productivity will be critical in determining how much residue can be removed from any site[40].

Equipment for farming operations is designed for low service life because of the seasonal nature of agricultural operations and small number of working hours in a year. For example service life for balers used in forage harvesting is specified at 1500 hours of operation[13] or about 20,000 to 30,000 bales. Field data (Figure 1) indicates that equipment used for biomass harvest and handling need to be more robust and powerful[14] than equipment used for normal forage operations. Comparable equipment used in forestry or construction have a higher reliability but also more expensive. Plans are under way to develop adequate field data to provide a basis to upgrade the existing equipment or new designs[15].

Field conditions and moisture content

Efficient on-farm and commercial dryers are used to dry grain to less than 15% for safe handling and storage. Biomass dryers are not common since drying is an energy intensive process and may cost as much as $2 per percentage point of moisture to be removed from a ton of wet material[17]. Crop variability and high moisture biomass are among major obstacles facing biomass utilization efforts.

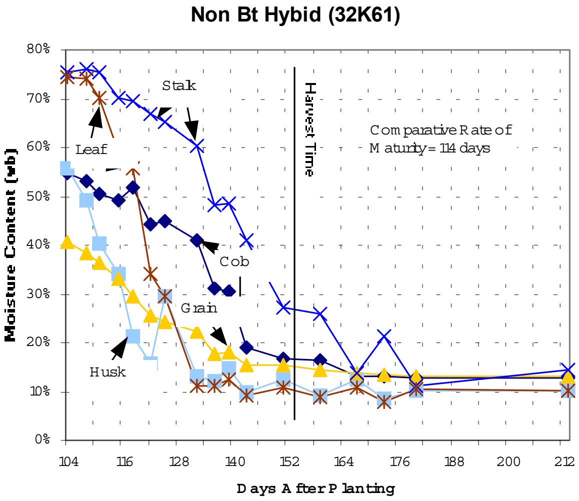

Figure 2. Moisture content of the standing non Bt hybrid over 109-day period.

Collection system

The same factors that influence food crop harvest also influence the performance of biomass harvest. Figure 3 is a diagram of harvest and collection system with its range of input factors and output performances. The central activity in this model is collection, transport, and storage of biomass prior to processing the biomass into feedstock. The system is influenced partly by the following factors:

- Soil must be in a condition on which machinery can operate to minimize damage to the soil. Soil condition depends upon soil type, weather (precipitation and evaporation), and type of crop.
- The growth model represents the state of maturity of the plant material especially for cases where a dedicated crop is grown and harvested.
- The drying model determines the moisture content of the material in the field as a function of weather conditions and crop characteristics. As it was discussed earlier, the crop must be low in moisture content for safe storage and further processing.
- Location model calculates the coordinate of each field, distances from storage and processing centers, yield, and overall design and management of storage and transportation network.
- Fuel use depends upon weather data and type of operations.
- The handling model consists of a series of equations representing the operation of machinery in the field for collection as well as trucks and wagons used for transporting materials.
- Biological and geographical conditions place constraints on the performance of the system.

The system outlined in Figure 3 is applicable to collection of herbaceous and woody crops as well as a mix of several of these crops. The model requires, robust data on regional weather, soil, crop, and operational aspects of machinery. A higher resolution for this data produces more reliable performance data. Although the model is robust in its construct, it requires extensive calibration when applied to a specific biomass collection system.

The entire supply chain

A mature bio based economy, using differing types of biomass from diverse sources to meet multitude of specifications, would be complex. At the present, we do not have established practices or experience dealing with such systems. Relatively small quantities of crop residue (less than %6 of corn stover[19]) are baled for bedding and animal feed by local farmers and for domestic use. Other industrial uses of crop residue, for pulping and pressboard applications are at their initial stage of their commercialization. The forest industry, on the other hand, is vertically integrated in such a way that the conversion plant has an established control over the feedstock supply chain.

Except in a few cases, the production of biomass and processing it into feedstock is expected to be similar to these activities for other agricultural commodities. The biomass is produced on farms, collected and packaged either by farmer or by custom operators and sold to feedstock traders. Depending upon the logistics and type of operations, the biomass may be processed further into a granulated/densified form for longer-term storage and distribution. This or any perceived system of production and distribution for biomass feedstock has yet to be developed and optimized.

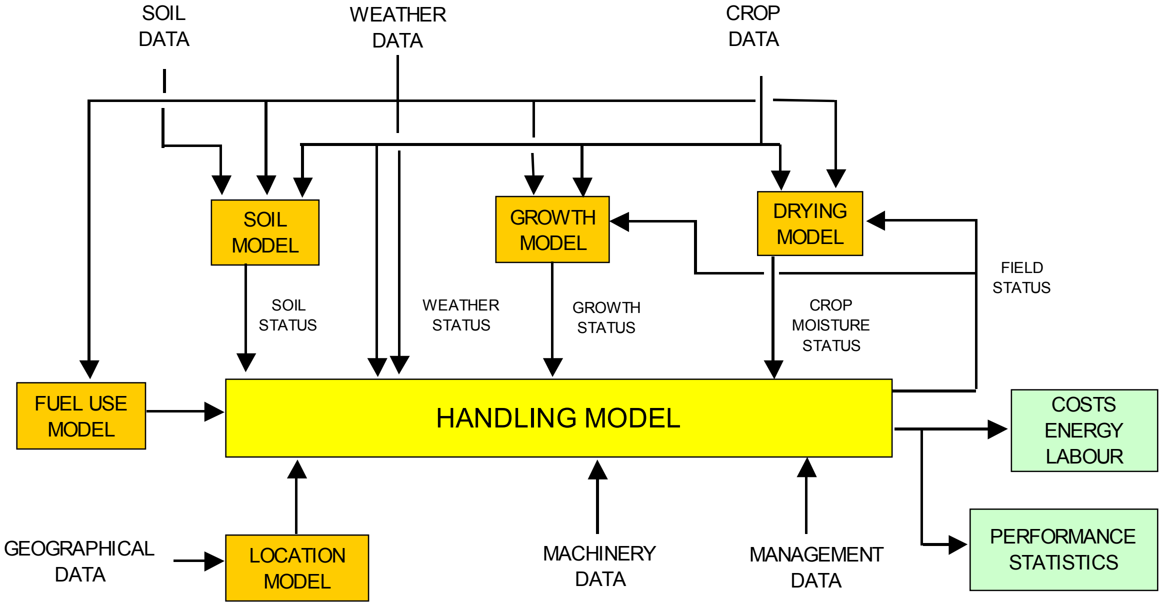

Figure 3. A system model for the analysis of collection and handling of biomass on the farm (adapted from Nilsson, 2001, ref. 18)

Regulations

Large quantities of biomass will be transported on public roadways and stored in a distributed network of strategic locations. There are issues on local, state, and national regulations on maximum size and weight of the load in storage or in transit. Biomass, especially in its natural form (not dried and densified), is susceptible to spontaneous heating and incidental fires. To the knowledge of this author, implication of local, state, and federal ordinances and regulations with regard to transportation and storage have not been investigated. Biomass material is prone to fires and may require a higher insurance premium.

RESEARCH METHODS

The objectives set for this program are based on the gap analysis discussed in the previous section. Major research topics and approach are discussed in the following sub sections.

Operational data

Engineering management data such as timeliness, field efficiency and rate of work for biomass collection are expected to be different from those available for the existing grain and forage harvesting equipment[34]. For example, in a corn stover collection scenario in northern plains, the feedstock may have to be collected just before winter weather prevails and thus the time frame for collection is shorter than that available time for grain harvest[35]. We also expect the biomass equipment will need a higher power and operate at a higher speed than the smaller forage processing equipment. Newly developed time and motion data are essential for system selection and optimization. The research will be designed to determine (1) rate of work, (2) timeliness, (3) soil and climate conditions, (4) field efficiency and reliability, (5) power requirement, and (6) service life for machinery and buildings. Timeliness refers to the most optimum conditions for collection and handling of the material that would result in minimum losses[36].

The scope of the proposed research will cover topics including some of the elements outlined in ASAE EP496.2 Agricultural Machinery Management and ASAE D497.4 Agricultural Machinery Management Data (ASAE, 2001)[13]. The scope of the work, however, goes beyond the existing standard for field machinery to include transportation, storage, and possible grinding and densification processes. The primary crop of interest is corn stover. Including data on other crop residues such as wheat, rice straw, and energy crops such as switchgrass would enhance this research.

Precision agriculture and forestry tools will be applied to bioenergy resource management. These new tools provide “on-line” data gathering capabilities for spotting and estimating the quantities of biomass, optimizing collection schedule, inventory control and other logistics in feedstock supply system[32] including an estimate of crop residue. The proposed systems will also include data acquisition from remote sensing devices (Satellite, LIDAR) and development of information technology tools based on GIS-GPS that would reduce inputs to biomass handling[33]. The integrated data are used to predict biomass concentration prior to harvest and at each stages of the collection afterwards. The resulting improved field and operational efficiencies will reduce costs and increase operator safety. Research method will be aimed at (1) surveying research and commercial tools available for precision agriculture and precision forestry, (2) evaluating the use of these tools in biomass collection and distribution, and (3) developing new tools (instrumentation, computer technology) for spotting, estimating, and managing biomass collection and delivery.

Moisture control

The critical moisture content for safe storage of most agricultural products is less than 15%. Under cooler conditions, biomass can be stored at higher moisture content of up to 20% for a short time (less than a month). The optimum moisture content for cubing is less than 12% and for pelleting is less than 8%[17]. Fresh herbaceous crops have a moisture content of 60 to 80% at the time of harvest. Typical moisture content of the corn stover ranges from 35 to 50% when grain is at its optimum harvest moisture content of 25%. Untimely rain or snow after grain harvest may boost the crop moisture even to higher levels. It is, therefore, imperative to quantify weather factors affecting the drying rate of biomass under field conditions as well as the response of biomass to artificial drying. Limited research in this area has been initiated at The University of Tennessee.

Biomass must be agitated during drying to facilitate the close proximity of solid material and drying air[24]. Rotary drum dryers and simple fluidized bed dryers are versatile and could be used for drying biomass. For finely ground particles flash drying is an effective method but requires careful design. Extensive literature and experience is available on the use of rotary drum dryers in handling fibrous materials while experience on the use of fluidized and flash dryers systems is limited. The most unknown among design parameters in using either of the dryer type is material handling, i.e. introducing material into the dryer and separating the solids from gasses at the dryer exit. Particle size and shape and its aerodynamic properties have large effect on the design of the dryers. Experiments are designed to test fluidized bed dryers on a pilot scale, but tests on rotary drum dryers and flash dryers need to be conducted on full scale systems or systems emulating full scale dryers. Large quantity of material (50 tons dry) may be required to run an experiment on rotary drum dryers.

Most of the dryers in the U.S. run on natural gas. A variety of biomass heaters are commercially available to be integrated with biomass dryers. Depending upon combustion efficiency, opportunities exist to use hot combustion gasses directly in the dryer; indirect heating through a heat exchanger is less efficient. Energy savings of up to 15% are also possible through re-circulation of the exhausted air from a dryer. Further savings in energy and power are realized through reducing airflows through pneumatic dryers.

Drying rate equations and equilibrium moisture relations are fundamental to development of drying heat and mass transfer equations. The drying simulation model is used for design and analysis of a particular drying configuration and energy consumption. Experimental data on bulk and specific density, thermal properties, and particle shape and size characteristics are also important properties for dryer design, selection, and analysis.

Small samples of biomass in loose and densified forms are stored under pre specified humidity and temperature combinations. The samples are monitored continuously for signs of visible mold. Densified samples will be tested for loss of durability and disintegration41. Data will be used to develop mathematical functions describing the storage stability of biomass. These models will be validating against data on full size biomass storage conditions. The validated models are essential to develop control tools for the safe storage of biomass[41].

Densification

Low bulk density, 4-6 lb/ft^3 is fundamental characteristics of loose biomass in its raw form (Table 2). Bulk density is roughly doubled to 8-12 lb/ft^3 when biomass is baled. Further increase in bulk density to 20-30 lb/ft^3 is achievable by chopping and compacting biomass to form cubes or pellets. Dense biomass requires less area and volume for storage and transport than loose biomass. In addition to savings in transportation and storage, granulated biomass lends itself to easy and cost effective handling. Dense cubes pellets have the flow ability characteristics similar to those of cereal grains[25]. Bulk handling equipment for granular material is well developed and available commercially.

Table 2. Transported mass for a load size 8 ft wide, 40 ft long, and 10 ft high

Form of biomass	Density (lb/ft^3)	Mass (ton)
Loose (chopped)	5	8
Baled	10	16
Cubed	25	40

Published literature and in-plant measurements show that power requirement for pelleting and cubing of chopped forage may range from 10 to 50 hp/ton. A multitude of variable process factors such as material characteristics, temperature, moisture content, feed rate, particle size, and pressure used to form pellets and cubes is responsible for variability in power requirement. The binding characteristics of a particular biomass affect its pellet ability and power requirement. For example corn stover was categorized as dry thick hard stalks with high shear and bending resistance[26]. There are indications that pre heating the stalks may reduce power requirements for cubing. The process could also be optimized with respect to applied pressures, particle size, and moisture contents. Experiments showed treatment of ground alfalfa with high temperature (>90^{o}C) resulted in durable pellets[27].

The overall objective of research in densification is, therefore, to develop innovative equipment and processes for low cost densification of biomass with the following sub objectives: (1) Experimentally determine the energy requirements for densifying biomaterials using pressure compaction and friction compaction. Realization of this sub objective leads to the elimination of friction component of pelleting and thence power requirements[28]. (2) Quantify material characteristics, i.e. particle size, moisture content, chemical composition, and their effect on quality of compacted material and energy requirement for compacting. (3) Identify process parameters, i.e. temperatures, steam quality, pressures, and hold time and their effect on quality of compacted material and energy requirement for compacting. Sub objectives 2 and 3 will lead to the development and validation of an engineering mathematical model to be used for analysis and optimization of compacting machines and processes[29].

For field experiments, the smallest capacity conventional pelleters as well as new designs[30,31] that would be capable of processing coarse grinds will be used. The small capacity will allow the testing of a larger number of variables in the shortest time possible. The machine will be tested in two settings: (1) mobile in the field and (2) stationary at a farmyard. For mobile tests, the pelleter mill will be equipped with a pick up, a chopper and blower, a mixing chamber for application of binders, all on a trailer. The unit will be powered using an on-board combustion engine. A tractor will pull the entire assembly over the field. An on-line moisture sensor will be used to test selection and processing of biomass that meets a maximum moisture level. High moisture material not suitable for densification will be rejected. For stationary unit, the power will be supplied using electric power source. A rotary or fluidized bed dryer will also be installed to dry the moist biomass to 12% moisture content prior to cubing. Factors measured will be field efficiency, power consumption, density and durability of pellets and cubes. These data will be used for the development of a robust densification model for design and control of the entire system that will include drying and densification and the associated material handling equipment.

Crop fractionation

The whole-crop harvesting and fractionation concept has been researched for many years[20]. A whole-crop wheat harvester was developed in Sweden in early 1980's[21] at a cost of more than $5 million. The self-propelled machine was able to harvest the entire crop, thresh and clean the grain and bale the straw, all in one step. The chassis could be used for other farm operations (pulling, hauling) when the machine was not in use as a harvester. The concept did not go beyond a few proto-types due to its high capital cost. Recent efforts at the Iowa State University to develop a whole-crop harvesting system for corn are expected to produce positive results[38].

Recently a new combine (McLeod Harvester, St. George, 2000)[12] was developed in Canada. The combine partially fractionates the harvested wheat but the majority of grain cleaning is done at the farmyard. The new machine is credited with higher capacity and efficiency than current grain combines. New markets created by advances in bioconversion may bring this combine into regular production line.

PAMI (1998)[22] conducted an economic analysis to show that whole crop baling resulted in the highest net return among six different systems including McLeod system. For the whole crop baling, the crop (wheat) was cut and placed in a windrow for field drying. The entire crop was then baled and transported to the processing yard. The bales were unwrapped and fed through a stationary processor that performed all the functions of a normal combine. The straw was re baled for transport to a site way from the yard. Drying costs were not included in this analysis.

A new on field one step pelleting machine has been developed by Haimler company[23] Germany 'Biotruck 2000'. The material is firstly mowed and chopped, pre-dried by using the thermal energy of the engine. The material is then compacted, pressed and pelleted without additional binding agents. The end product of the process is a corrugated pellet with a length of 30 to 100 mm. The individual pellet density ranges from 850 to 1000 kg m^{-3} while the bulk density ranges from 300 to 500 kg m^{-3}. The "Biotruck" has a capacity of 3-8 t/h.

As the review of literature shows, research on crop fractionation requires extensive testing on model and full-scale equipment. This area also requires an intimate knowledge of the operational characteristics of combines and baling equipment. Manufacturers of this equipment have access to both human expertise and machinery to make significant contributions to the development of whole crop harvest and fractionation system. The Feedstock Infrastructure program at ORNL will be monitoring progress in the development of this technology and factoring it into the feedstock supply models we will be developing

Systems analysis and optimization

Development of feasible and sustainable systems for harvesting the biomass and transporting it to conversion facilities requires a thorough analysis of several combinations of options[30]. Drying and densification options and modes of transportation can be modeled mathematically and validated using data in collected in the field. The model provides a valuable tool for formulating cost minimization for network analysis. The optimization problem will be subject to constraints stemming from fire prevention, regulations on maximum transport load, and other unforeseen limitations. These activities will include the following research topics: (1) regulations on safety in transport and storage, (2) data on existing biomass collection infrastructure, (3) analyze and optimize collection and transport networks, (4) integrate and apply of information technology, (5) energy, labor, and costs projections.

It is also important to develop tools that would help us to estimate the amount of crop residue. The proposed systems will also include data acquisition from remote sensing devices (Satellite, LIDAR) and development of information technology tools based on GIS-GPS that would reduce inputs to biomass handling. The integrated data will be used to predict biomass concentration prior to harvest and at each stages of the collection afterwards. The resulting improved field and operational efficiencies will reduce costs and increase operator safety.

Improving efficiencies of the existing handling systems can be accomplished relatively quickly. Developing fractionation and densification would require more time and larger research capital. These efforts alone, however, are not expected to produce the least-cost systems for the entire bioenergy production cycle that includes feedstock supply costs and conversion costs. The real contributor to the cost of feedstock is the cost of each operation (gathering, densifying, loading, hauling, stacking, warehousing). Long-term efforts should be directed towards eliminating as many as supply chain operations as possible.

One idea is to move treatment or pretreatment processes from large conversion centers to farms where biomass is produced. The pre treated substrate could be used on site to produce sugars through fermentation, gasification, or direct combustion or the pre-treated substrate can be pumped to a larger central facility for final refinement. The followings are some of the perceived advantage of the proposed system: (1) eliminate the need for reloading bales onto the truck for transport to the plant site; (2) eliminate the cubing or pelleting that may be needed for bulk handling; (3) make it possible to handle higher moisture content material for shorter time periods; (4) reduce the risk of fire and contamination because the central conversion plant does not have to deal with storage and handling of large quantities of loose biomass; (5) reduce handling steps and road traffic by creating substrates which may be pumpable through a piping system; (6) the central facility may have a better control on the specification of the incoming substrates or preprocessed materials. The proposed system could lead to substantial reductions in the overall conversion costs. Systems analysis tools, once developed and validated would provide a cost-effective means of evaluation these options.

IMPLEMENTATION

Practical approach to dealing with research and development opportunities outlined in this paper requires organizing cross cutting research over several disciplines. The multidisciplinary team includes producers, manufacturers, processors, and researchers. Producers (or producer groups) identify cooperating farms where experiments can take place. The manufacturing industry will provide equipment and modifications to equipment. Processors and manufacturers focus on shorter-term solutions specific to a particular piece or set of equipment. Researchers focus on fundamental research that would generate practical data to support the entire industry. The analogy for this organization is the abundant technical data and standards on grain storage and handling. The data include drying rate, allowable temperature and moisture for safe storage, thermal, and mechanical properties of food and feed.

Two models to follow

Two established models provide a clear pathway to developing workable systems for biomass handling infrastructure from farm to conversion process.

Model 1. The grain industry in the U.S. has developed to ensure timely collection and distribution of almost one-half billion tons of various types of grains annually. The farmer harvests, dries, and sometimes cleans the grain, and stores it in farm bins. The grain is moved from temporary farm storage sites to larger grain processing centers in rural centers where several grain types with varying quality from surrounding areas are collected. At the rural centers drying and blending adjust grain moisture. Grain may also be cleaned and graded at these locations. The clean graded grain is transferred from these rural centers to centralized locations (inland or port terminals) from where grain is shipped and distributed to the end users (processors). In this system grain is generally handled in bulk and transported by truck, rail, and ship or barge. Throughout this entire system, the grain quality is checked and managed at transfer points to ensure it meets the user's specifications. The grain handling system is characterized by efficiency, security of supply, and meeting strict regulations that govern orderly supply of grain and grain products.

Model II. The U.S. and Canada process roughly 5 million tons of forage products annually. The pellets, cubes, and dense bales command a high price ($100-$300 per ton) in domestic and overseas markets. In a typical system, forage is received in the form of chops during harvest season and in the form of round or square bales in other times. The chopped that is normally high in moisture content (70-80%) is dried to 8-10% moisture content using gas fired rotary drum dryers[39]. The baled hay, if sufficiently dry is shredded. For cubes the chops or shredded material is pressed after conditioning with water and adding a binder. For pellets biomass is finely ground, conditioned with live steam and pressed. Pellets and cubes are cooled and stored in flat storage building or steel bins.

In recent years, a highly efficient infrastructure has been developed to support production, harvesting, drying, densifying, and shipping of high quality forage. The industry is relatively small and localized and thus it is not well known nationally. The author of this paper believes, however, that a forage processing enterprise provides an excellent model for successful biomass to feedstock enterprise.

PARTNERSHIP

Equipment manufacturers will lead or co-lead one-step harvesting and densification research and development. This area is equipment and technology intensive. Processors and in some cases producers will be the major participants in the efforts. Most of research on densification will be on pilot scale or full-scale equipment. Processors, especially feed processors, have considerable experience in pelletization and therefore could be an important partner in this research.

Producers will provide land, crops, and workspace to the program. It is expected that their full participation in the entire program will help in adoption of the new technologies as well as in assisting technology transfers. Producers could be individual farmers or farmer groups and associations. In some cases farmers could form cooperatives to finance an entire supply chain that may include biomass collection, pre processing biomass to feedstock, conversion to chemicals and fuels, and marketing the final product.

Table 3. Matrix of collaboration for the proposed biomass research and development program

Participant	Function	Responsibility			
		Densification	Moisture control	Operational	Systems analysis
Program manager	Planning and execution of feedstock engineering program	Coordinator[1]	Coordinator[2] and Co-leader	Coordinator	Coordinator and Leader[3]
Manufacturer	Farm equipment, dryer, pellet mill	Co-leader	Collaborator	Co-leader	Collaborator
Producer	Farming, custom operating	Collaborator	Co-leader	Collaborator	Collaborator
Processor	Feed, food, industrial products manufacturing	Co-leader	Collaborator	Collaborator	Collaborator
Researchers[4]	Research, extension technical support	Collaborator	Collaborator	Leader	Collaborator

1. Coordinator: Prepares proposals, outlines technical and research challenges, and facilitates alliances and collaborations.
2. Collaborator: Provides material, equipment, technical personnel, analysis
3. Leader: Assumes ownership and leadership of the project
4. University researchers and Federal laboratory researchers

Universities will be involved in fundamental research to support the entire industry. In recent years universities have focused on precision agriculture with support from USDA. Several strong national programs are capable of assuming leadership on the application of precision agriculture to biomass and participate actively in technology transfer. Progress in research not only generates useful data, but also trains highly qualified personnel in support of future biomass industry. The proposed research is in parallel with bioconversion research at other institutions.

CONCLUSIONS

The objective of Feedstock Engineering task is to develop cost-effective, safe, and sustainable biomass feedstock supply technologies. The task addresses the following inherent characteristics of biomass: (a) low bulk density, (b) variable and often high moisture content, (c) combustibility, (d) affinity to spoilage and infestation (e) geographically dispersed and varied material, (f) seasonal variations in yield and maturity, (g) a short window of opportunity for harvest and demands on labor and machines that often conflict with main crop (grain), and finally (i) local regulations that put limits on store size and transportation loads.

These unique and often troublesome characteristics cast uncertainties on the orderly flow of biomass from field to conversion plant. Engineering research experiments deal with characteristics (a), (b), (c) and (d) in order to adapt, improve, and develop innovative technologies to deal with high moisture and low bulk density. We group these activities under moisture control and densification. Characteristics (e), (f), (g), and (i) require logistics planning and systems optimization. We group these activities under engineering systems analysis and optimization.

From implementation point of view, research and development in feedstock engineering also require continued support and guidance of a number of stakeholders. The prime industries of concern here include the users of feedstock (processors), equipment manufacturers, and farmers. Several national laboratories and universities are actively involved in specific biomass research and conversion technologies. A full integration of all these activities minimizes duplication resulting in an accelerated approach to full utilization of bioenergy resources.

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