INL/EXT-20-57621-Rev000

Engineering Assessment of Publicly Proposed Cellulosic Biofuel Plant Design

February 2020

Task 1 Report: Communication of industry knowledge, best practices, and lessons learned in the space of cellulosic biofuels plant design, project development and execution and operations

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Contractor:
Idaho National Laboratory
Idaho Falls, ID
Technical Service Agreement No. 19509

Sponsor:
ExxonMobil Research & Engineering Company
Annandale, NJ
Agreement No. LAW-2019-3267

Changing the World's Energy Future

Idaho National Laboratory

SUMMARY

Most pioneer cellulosic biofuel plants worldwide failed to achieve design-production capacity, and many have shut down. The major causes of failure to achieve the design throughput include: (i) feedstock logistics causing significant variability of the properties of raw biomass delivered to the plants, (ii) inability of the plants to handle the variability in biomass properties, which leads to low feedstock throughput and low product yield, (iii) integration of feedstock preprocessing unit operations with downstream conversion processes at the plants, which leads to unreliable operation as operating difficulties in one area can cause process upset or shutdown of the other.

ExxonMobil Research and Engineering Company, via a technical services agreement, engages Idaho National Laboratory (INL) to provide general industry knowledge, best practices, and lessons learned in cellulosic ethanol plant design, project execution, and operations. INL will also assess publicly proposed cellulosic plant designs. The scope of work will be accomplished in three tasks: Task 1, Communicate industry knowledge; Task 2, Present high-level lessons learned; Task 3, Provide an engineering assessment of publicly proposed ethanol plant designs.

This Task 1 report provides a high-level summary of general industry knowledge, best practice, and lessons learned in biomass feedstock logistics and integration with bioconversion processes. Based on INL's more than 15 years of research and development (R&D) in biomass feedstock preprocessing and the author's more than 40 years of R&D, engineering design and cellulosic ethanol plant operating experience and published research results related to biomass harvest, collection, transportation, and storage, the following observations can be drawn:

i. The bale logistics currently practiced by the agricultural sector are not suitable for biofuel conversion because they do not meet the required feedstock specifications.
ii. The one-pass chopped biomass harvest and collection plus ensiled storage can meet the feedstock specifications for biofuel conversion.
iii. Feedstock preprocessing should be performed at depots—not integrated with biofuel conversion operation—to improve the operational reliability of both facilities. Furthermore, a feedstock preprocessing depot can produce multiple products (one of which is conversion-ready feedstock for biofuel production). This approach should lead to lower feedstock cost and improved operability for biorefineries.
iv. R&D into on-line sensors for measuring critical attributes of incoming biomass, intermediate process and product streams, and their impact on the performance of equipment are required for robust equipment design and process integration and control.
v. The use of an adaptive, machine-learning process-control approach should improve equipment performance.

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ACRONYMS

BETO	Bioenergy Technologies Office
BFNUF	Biomass Feedstock National User Facility
CIP	Clean in place
CMA	Critical Material Attributes
CPP	Critical Process Parameters
CQA	Critical Quality Attributes
DMR	De-acetyl Mechanical Refining
DOE	Department of Energy
EPC	Engineering Procurement and Construction
FCIC	Feedstock Conversion Interface Consortium
IBRs	Integrated Biorefineries
INL	Idaho National Laboratory
MDF	Medium-density fiberboard
R&D	Research and Development

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Engineering Assessment of Publicly Proposed Cellulosic Biofuel Plant Design

1. INTRODUCTION

Pioneer cellulosic ethanol plants encountered many difficulties in material handling which led to lengthy startup periods and not achieving design throughput. The U.S. Department of Energy Bioenergy (DOE) Technologies Office (BETO) held the Biorefinery Optimization Workshop from October 5–6, 2016.[1] The key findings include: 1) challenges related to transportation, storage, logistics, and engineering processes within the integrated biorefineries (IBRs); 2) process intensification was noted as a critical area for increasing efficiency and decreasing both upfront investment, as well as operational expenses of IBRs; 3) it is vital for projects to perform robust data collection and ensure proper pilot- and demonstration-scale testing activities before scaling up to the commercial level; and 4) monetizing the waste, coproducts, and byproducts is often an important aspect of achieving profitability in an IBR.

For the scope of this project, Contractor will provide Sponsor general industry knowledge, best practices, and lessons learned in cellulosic-biofuels plant design, project development and execution, and operations. Much of this knowledge and best practices come from Idaho National Laboratory (INL) research activities in biomass-feedstock logistics and preprocessing over the past 15 years and Quang Nguyen’s more than 40 years of research and development (R&D), process design and scaleup, and operational experience in pulp and paper, forest products, and cellulosic ethanol.

The scope of the project will be accomplished in three tasks:

Task 1: Contractor will communicate industry knowledge, best practices, and lessons learned regarding cellulosic-biofuels plant design, project development and execution and operations.

Task 2: Contractor will present high-level lessons learned and answers to Sponsor’s questions and will participate in in-person discussion.

Task 3: Contractor will perform an engineering assessment of publicly proposed cellulosic-ethanol plant designs.

This Task 1 report provides relevant information and knowledge regarding difficulties encountered in scaling cellulosic ethanol and best practices for achieving robust plant design, project development, execution and operations. The information is presented in the following sections: Section 2, process areas, Section 3, engineering procurement and construction, Section 4, plant commissioning, startup, and operation, and Section 5, conclusion.

2. PROCESS AREAS

2.1 Feedstock Logistics and Storage

2.1.1 Harvest, Collection and Transportation: Impact on Biomass Properties

Pioneer cellulosic ethanol plants generally adopt existing agricultural practice of using multipass harvesting, windrowing, collecting, and baling methods for corn stover. The amount of stover collected typically ranges from about 1.0 to 1.5 ton (dry basis)/acre depending on the corn yield and harvesting and collecting technique. The harvest is generally less than 50% of available stover to prevent soil erosion and minimize impact of nutrient removal, but also reflects the inefficiency of multipass harvesting, collection, and baling methods. Traditional methods use three passes, comprising 1) chopping the corn stalks and spreading the chopped stover on the field to dry upon harvesting, 2) raking the chopped stover to form windrows, and 3) baling. The raking step causes heavy soil contamination of the stover and results in total ash content as high as 12%. At least one pioneer biorefinery was investigating a chopped biomass and ensiling storage method.

POET, LLC, uses a two-pass, high-cut method (which eliminates the raking step) to reduce the nonstructural ash (i.e., soil) content.[2] Single-pass harvest and baling can further reduce the nonstructural ash content of baled corn stover to about 3–5% (wet basis) and reduce baling costs. Hillco Technologies (of Nezperce, ID) and John Deere (of Ottumwa, IA) jointly developed single-pass round balers, shown in Figure 1.[3] AGCO has developed single-pass square balers, exemplified in Figure 2.[4] In single-pass methods, the chopped stover is blown directly into the baler. One major issue with the current single-pass baling technology is that it slows down the speed of the harvester. Thus, without premium price for single-pass bales, farmers would not adopt single-pass balers because of the lower productivity of grain harvesting and new capital investment with uncertain return on investment.

2.1.2 Square Bales Vs. Round Bales: Pros and Cons

Pioneer biorefineries typically use large square bales, 4 ft wide × 8 ft long × 3 ft high and round bales 5 ft wide and 6 ft in diameter. Larger square bales typically have a bulk density of about 10–11 lb/ft^3 and weigh about 1,062 lb dry basis each. Round bales typically have a bulk density of about 8–9 lb/ft^3 and weigh about 1,244 lb dry basis each. Each square bale is held together by six multi-strand polypropylene twines. Each round bale is typically wrapped with four layers of net wrap around the circumference of the bale. Round balers, because of lower purchase price per unit, are more common than square balers. Utilization on each square and round bale will generate 132 ft of twine and 75 ft × 5 ft of net wrap, respectively, that require proper disposal. Most large square balers leave several 1–2-in. twine tailings on the bales, which are difficult to spot and remove (see Figure 3). Current mechanical bale de-stringers for square bales are about 95% successful. Twine and net wrap, if not removed, can cause severe plugging of piping and equipment.[5]

JB510 Hillco SPRB System - http://www.hillcotechnologies.com/jb510.html

Figure 1. Hillco single-pass round baler system.

https://www.energy.gov/eere/articles/five-harvesting-technologies-are-making-biofuels-more-competitive-marketplace

Figure 2. AGCO single-pass square baler.

Figure 3. Twine tailings from square baling.

Table 1 lists the custom rate of baling and hauling bales and silage in Kansas and gives rough cost estimates of corn stover delivered to a biorefinery, satellite-storage, or feedstock-preprocessing depot.

Table 1. Average custom rates in Kansas for forage, 2018, and rough cost estimate of corn stover delivered to satellite storage areas and biorefinery.[6]

Estimated Operating Cost (2018 dollars)	Large square bales	Large round bales
Harvesting, $/acre	27.00	27.00
Raking, $/acre	4.53	4.53
Baling, $/bale	13.29	12.15
Hauling bale to satellite storage, $/bale	3.38	5.50
Hauling of bale from satellite storage to biorefinery, $/bale	3.38	5.50
Average cost of baling (as is), $/bale		
Assumed payment to growers, $/acre	25.00	25.00
Average cost of corn stover delivered to satellite storage or directly to biorefinery as bales (dry basis), $/ton	61.61	60.36
Average cost of corn stover delivered to satellite storage then to biorefinery as bales (dry basis), $/ton	68.37	70.36

Assuming:

2 ton of corn stover collected/acre, 1,000 lb/square bale, 1,100 lb/round bale – all dry basis

Average moisture content of baled material = 15%

Dry matter losses due to microbial degradation and spill are not included in the cost estimate

2.1.3 Ensiled Storage

Three pioneered biorefineries and one commercial pelletized-feed plant processing corn stover in the U.S. had severe difficulties in handling, storing, and preprocessing bales, mainly because of variability in chemical composition and physical and mechanical properties of the raw materials. Ensiling agricultural residue and crops are common practice in the feed industry. Because of the high moisture (50–65%) and high bulk density of chopped biomass, transportation is economical only for short distances. The availability of compacting wagons (which are more commonly used in Europe and Canada), lowers the operating cost of transporting biomass from the field to the ensiling storage areas.[7] The bulk density of the compacted biomass approaches that of bulk density of round bales.

Ensiled corn stover, stored in compacted piles, not only has significantly lower dry matter loss (5% compared to losses of 12% for bales), but also maintains more consistent moisture content.[8] For herbaceous energy crops, a major advantage of the chop harvesting method over the baling method is the much narrower particle-size distribution and lower content of fines in processed feedstock.

2.1.4 Weather Impact on Harvest, Collection, Storage, and Biomass Properties

The typical window of harvesting corn stover is between mid-September and end of November.[9] This short harvest window depends on weather patterns that can delay planting and harvesting. For example, at the beginning of December 2019, only about 90% of the corn crops were harvested in Iowa. When corn is harvested in late November, it is not practical to leave corn stover in the field to dry because the drying rate in cold-weather areas is very slow. In this case, farmers tend not to harvest and bale corn stover; as a result, biomass supply may be reduced due to competing uses for roughage and animal bedding. Precipitation can also increase the soil content of stover spread on the ground or in windrows and the variation in moisture content in a bale.

In a study comparing wet and dry corn stover harvest and storage by Shinners et al., corn stover was shredded, windrowed, and chopped to 0.25 in. and 0.75 in.[10] The chopped material was collected in a side-dumping forage wagon, then stored in plastic silo bags. The tests were conducted in October at the University of Wisconsin, Arlington, Agricultural Research Station, located about 20 miles north of Madison, WI. The authors concluded that:

- Drying was challenged by low temperature and frequent precipitation. In only one out of four trials did stover dry to baling moisture (about 20%) within 4 days of the grain harvest. Note: the precipitation in Madison, WI, typically ranges from 2.1 to 3.3 inch in October.
- The harvesting efficiency, i.e. ratio of stover harvested to mass available in the field averaged 55%, 50% and 37%, respectively, for chopping, wet baling and dry baling.
- The harvesting capacity was 26.2, 16.0 and 9.8 metric ton (dry basis)/hour when harvesting shredded stover with a forage harvester, a large square baler, and a large round baler, respectively.
- The bulk density of chopped corn stover was 4.5 lb/ft^3 (dry basis) in the truck and 8.75 lb/ft^3 in the bag silo.

Table 2 lists the states with greater than 1 million acres of corn harvested, where stover would be available. Wheat acreages are also provided to assess the availability of an additional biomass source that does not have the same harvesting time as corn stover. Table 3 lists the grain harvesting time and precipitation during the most active harvesting period for the areas that major crops (either corn or wheat) are grown.

Although Iowa has the most corn acreage, the risk associated with single source supply and high precipitation makes conventional dry bale feedstock logistics less viable. Essentially all of agricultural residue feedstock supply for a biorefinery must be harvested in a 2-3 months period which can cause several issues: (i) mobilization of significant machinery and labor resources to harvest, collect and bale corn stover, (ii) risk of not collecting enough biomass in wet weather or collecting biomass with highly variable properties (soil and moisture content), (iii) large storage area of bales is needed, (iv) costly long-term storage of bales (land and bale handling costs), and (v) high dry matter loss due to microbial degradation and deterioration of bale integrity (i.e., broken bales).

States which can supply both corn stover and a high percentage of wheat straw (highlighted in gold color in Table 2) may be better suited for locating biorefineries to reduce the risks associated with single-feedstock state mentioned above. States with relatively low precipitation (<3 inch/month, highlighted in light blue) during active corn harvesting period include Minnesota, Kansas, South Dakota, North Dakota, Michigan, Texas, and Colorado. During active wheat harvesting months, only Colorado has relatively low precipitation. Spring wheat is predominant in Minnesota, South Dakota, and North Dakota. Winter wheat is predominant in Nebraska, Kansas, Texas, and Colorado. Since the active harvesting time of wheat is earlier than that of corn, the states growing corn and wheat can supply biomass to feedstock preprocessing depots over a longer periods of time compared to single-feedstock states (e.g., Iowa, Illinois, Indiana, Missouri, Ohio, Michigan, and Kentucky), and therefore these dual-feedstock states can more reliably supply biomass at lower cost to the depots.

The precipitation given in Table 3 is a snapshot of an area indicated for each state. Other grain producing areas may have higher or lower precipitation. For example, the northeastern part of Kansas has significantly higher precipitation than the northwestern (e.g., Colby, KS) of the state. For baling logistics, locating a biorefinery should be given for an area that has low precipitation during harvesting months and have access to multiple biomass sources.

The precipitation records for Iowa, Nebraska, and Kansas for the past several years (see the Appendix) show that precipitation amounts varied. 2019 is a wet year with widespread delay in planting and harvesting corn. Corn stover supply, which is directly related to corn production and harvesting time, is expected to be lower in 2019 and results in variable bale properties (e.g., moisture and ash content, extent of degradation in storage.) The higher levels of precipitation (>4 inch/month) increase the probability of high moisture content (>20% moisture) of baled biomass.

Table 2. States with greater than 1 million acres harvested for grain.[11]

Rank for Corn	State	Corn	All Wheat	Corn + Wheat	% Wheat
		1,000 acres	1,000 acres	1,000 acres	
		Areas Harvested for Grain	Areas Harvested for Grain	Areas Harvested for Grain	
1	Iowa	12,800	6	12,806	0
2	Illinois	10,850	560	11,410	5
3	Nebraska	9,310	1,010	10,320	10
4	Minnesota	7,940	1,575	9,065	17
5	Indiana	5,200	260	5,460	5
6	Kansas	5,000	7,300	12,300	59
7	South Dakota	4,860	1,628	6,488	25
8	Missouri	3,330	520	3,850	14
9	Ohio	3,300	450	3,750	12
10	North Dakota	2,930	7,635	10,565	72
11	Michigan	1,940	470	2,410	20
12	Texas	1,750	1,750	3,500	50
13	Kentucky	1,230	300	1,530	20
14	Colorado	1,200	1,954	3,154	62

States which can supply large quantities of corn stover and wheat straw are highlighted in gold

Table 3. Harvesting periods for corn and wheat and average precipitation for major corn producing states.[9,12] †

State	Active Harvesting Period			Precipitation (in./month)	
	Corn	Spring Wheat	Winter Wheat	Wheat Harvest	Corn Harvest
Iowa	Oct 5–Nov 9				2.4–3.5
Illinois	Sep 23–Nov 5				1.8–3.2
Nebraska	Oct 4–Nov 10		Jul 3–Jul 21	3.5–4.7	1.5–3.3
Minnesota	Oct 8–Nov 8	Aug 5–Sep 9		2.7–3.7	1.5–2.5
Indiana	Oct 1–Nov 10				2.2–4.2
Kansas	Sep 10–Oct 25		Jun 20–Jul 5	2.3–3.4	1.5–2.5
South Dakota	Oct 6–Nov 16	Jul 27–Aug 20		2.6–3.6	1.6–2.2
Missouri	Sep 8–Nov 3				2.0–3.9
Ohio	Oct 11–Nov 20				1.5–3.4
North Dakota	Oct 8–Nov 19	Aug 8–Sep 13		2.7–3.6	1.2–2.5
Michigan	Oct 10–Nov 25				1.4–2.7
Texas	Aug 1–Oct 11		Jun 1–Jul 2	2.2–3.5	1.5–2.5
Kentucky	Sep 9–Oct 24				1.5–3.5
Colorado	Oct 8–Nov 13		Jul 2–Jul 21	1.8–2.7	0.7–2.2

† Precipitation value assigned for each state grain growing area: Iowa: Ames, Illinois: Peoria, Nebraska, York, Minnesota: Marshall, Indiana: Indianapolis, Kansas: Colby, South Dakota: Watertown, Missouri: Joplin, Ohio: Dayton, North Dakota: Grand Forks, Michigan: Kalamazoo, Texas: Amarillo, Kentucky: Paducah, Colorado: Lamar.
High precipitation during active harvesting months are highlighted in blue

2.1.5 Bale Storage Vs. Ensiled Storage: Issues, Effect on Degradation and Variation of Biomass Properties

Ensiled storage has many advantages over bale storage that are relevant to producing consistent quality feedstock for biorefineries. Table 4 compares the major characteristics of bale and ensiled storage of corn stover. Indoor storage of bales is too expensive for large biorefineries. Assuming an average dry weight of 1,000 lb per bale (3 × 4 × 8 ft), a 2,000 ton/day biorefinery will process 4,000 bales per day. A 3-day inventory at the biorefinery requires four 3,000 bale stacks. Each bale stack (7 bales high) has a footprint of about 13,800 ft^2. To minimize the spread of fire between the stacks, a minimum cross distance between the stacks of 200 ft is recommended.[13] As a result, the total area required for a 3-day storage area is about 5.2 acres. Stacking these bales and moving them into the biorefinery will require considerable effort using forklifts and trucks.

By contrast, a 3-day ensiled storage pile, which occupies about 1 acre of land, can be located next to the biorefinery. The biomass material can be reclaimed from the pile and conveyed into the plant.

Long-term storage of bales can cause the integrity of biodegraded bales to weaken. As some of the biomass degrades, the size and shape of a bale can change, and the twine and bale wrap become loose, which may lead to the loss of a whole bale when handled by a forklift. In the winter, when freeze and thaw cycles occur, the net wraps of large round bales can interlock, which leads to bale breakage when one bale is removed by forklift.

Table 4. Comparison of bale storage and ensiled storage of corn stover.

Characteristics	Bale storage	Ensiled storage	Note
Storage area	Many satellite storage areas	One large storage area next to the biorefinery	Total storage areas of bales are many times greater than ensiled storage
Dry matter loss	7–12% due to microbial degradation	About 6%	Actual material losses for bales are higher due to spillage
Fire risk	High	Negligible	
Storage and handling cost	High due to many bale storage areas and far distances between bale stacks	Low	Hauling bales costs \$3.4/ square bale and \$5.5/round bale in Kansas
Properties	Highly variable, and difficult to manage Moisture migration within a bale and between bales	More consistent and can be managed	Highly variable properties of corn stover lead to low operational reliability and low product yield

2.1.6 Fire Risk of Bale Storage: Cost Impacts

Fires in stacks of corn-stover bales have been caused by arson, lightning strike, and self-combustion. All three pioneer biorefineries in the U.S. have experienced bale fires. There is no effective way to extinguish fires in a stack of bales. High winds can cause the fire to spread to adjacent stacks. Therefore, the large bale stacks (2,000 bales or more) are set far apart to prevent the spread of fire. As a result, the costs of leasing agricultural land for storage and transporting bales increase significantly.

2.1.7 Feedstock Supply: Farmers, Farm Co-Op, Custom Harvesters, Biomass Integrators: Which One and How?

The biggest issue with obtaining raw biomass directly from farmers and farm co-ops is significant variation in the properties and quality of the biomass. Farmers use different techniques and equipment to harvest, collect, and bale agricultural residues, which lead to inconsistent biomass-feedstock quality. Large custom harvesters generally use the same equipment and can produce more-consistent quality feedstock (e.g., similar bale dimensions and density). However, both farmers and custom harvesters have little control over moisture and ash content as their main goal is to get residues off the field, and often their harvest schedule is tied to the grain operation. In comparison, the biomass integrators and feed aggregators pay more attention to the quality of biomass in terms of moisture, particle size, and soil contamination. It is difficult to obtain long-term feedstock-supply agreement with farmers because their concern over the availability of feedstock, which can be affected by weather and competitive uses for agricultural residue such as feed and animal bedding.

The shutdown of pioneer biorefineries reinforces farmers' hesitance in entering long-term supply contracts with cellulosic biofuel industry.

To reduce the risk of price and availability fluctuation, it is advisable to develop feedstock-supply logistics that produce stable, conversion-ready feedstock that can be stored for long periods of time. The feedstock supply should be a business separate from biofuel conversion. Additionally, a separate feedstock supply business could potentially produce multiple high-value products that would lower the cost of biofuel feedstock. Vertical integration with biomass supply can also ensure stable feedstock availability for biorefineries in the events of unexpected weather-related disruptions (e.g., drought, excessive precipitation).

2.2 Feedstock Preprocessing

Pioneer biorefineries process bales in the same biofuel-conversion facility. Milled biomass is generally stored in a bin with storage capacity less than one day of plant-design throughput. This approach of integrating feedstock preprocessing and conversion causes many operability issues for the whole facility. Because of the small storage capacity of preprocessed feedstock, operational difficulties in either the preprocessing or conversion area can cause process upsets and low plant throughput. It is advisable to separate feedstock preprocessing from conversion operations. Feedstock preprocessing can be performed in feedstock depots. The BALES project sponsored by the DOE-BETO demonstrated an advanced supply chain for lower cost, higher quality biomass feedstock delivery.[14] Additional work is required to provide preprocessed feedstock that meets the tight specifications for biochemical conversion and thermochemical conversion processes. The Feedstock Conversion Interface Consortium (FCIC), created by BETO, is an integrated and collaborative network of eight national laboratories dedicated to addressing technical risks and understanding how biomass properties influence collection, storage, handling, preprocessing, and conversion technologies with the goal of improving the overall operational reliability of integrated pioneer biorefineries.[15]

2.2.1 Depot concept: advantages of decoupling feedstock preprocessing from biorefinery operation

Pioneer biorefineries did not achieve designed plant throughput and product yields mainly because of difficulties in producing consistent quality feedstock from raw biomass (in bale format) with highly variable properties. Even if the bales were to have consistent properties, over a period of weeks and months of storage outdoors, properties will change due to moisture and soil pickup (through precipitation, wind) and degradation. To make matters worse, these changes in properties are neither consistent nor predictable. Pioneer biorefineries process feedstock onsite, with inadequate storage capacity for preprocessed feedstock (less than 12 hours). Decentralized biomass feedstock preprocessing depots may be necessary to achieve feedstock cost, quantity, and quality.[16]

The following sections contain brief descriptions of operability issues in the feedstock preprocessing area.

2.2.2 De-Stringing, Unwrapping, and Bale Breaking: Impact on Operability

The success rates of mechanical de-stringing of large square bales and unwrapping of round bales are less than about 95%. As a result, each preprocessing line requires the attendance of an operator full time to manually remove occasional stranded baling twine and net wrap. One type of de-stringer for square bales holds the bale stationery under a hydraulic press while a knife cuts the string across the bottom. A hook then travels across the top of the bale, pulling out the cut strings and dumping them on a conveyor (Figure 4). West Salem Machinery (https://www.westsalem.com/) and Warren & Baerg Manufacturing (https://www.warrenbaerg.com/?n=1&id=1) supply square-bale de-stringers. The West Salem de-stringer uses guillotine-type knife for cutting the strings. The Warren & Baerg Vermeer de-stringer uses a knife cutter similar the one shown in Figure 4. Vermeer has developed a prototype round guillotine-type bale slicing system that cuts the bale in half and removes the net wrap.[17]

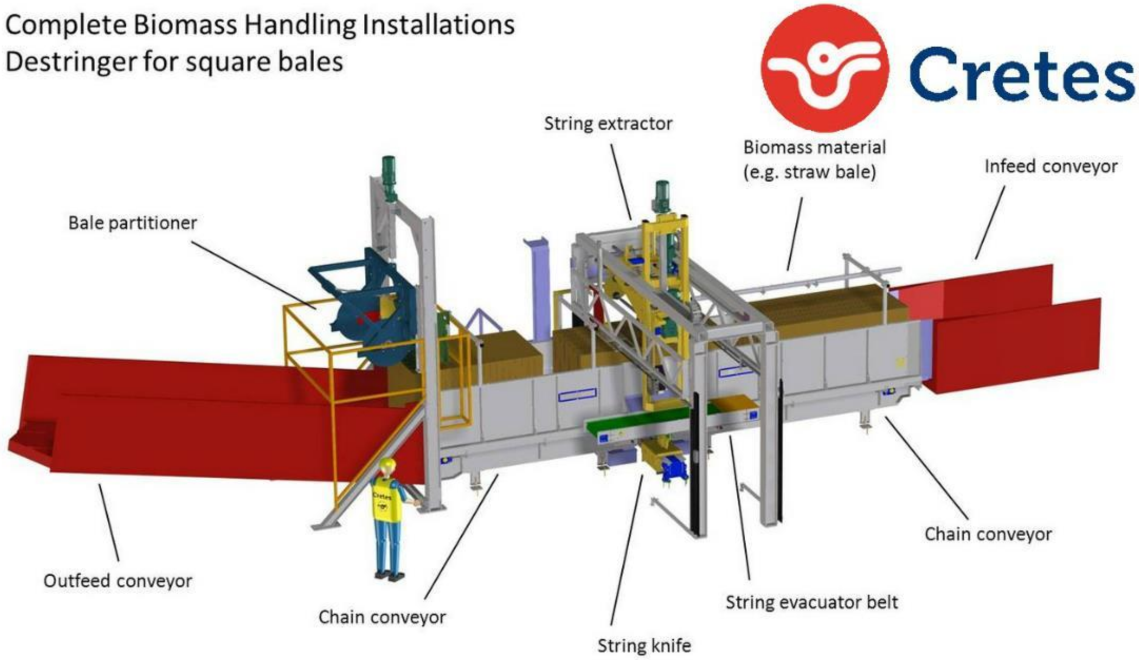


Figure 4. Diagram of a de-stringer for large square bales.[18] (Source: http://www.cretes.be/en/detail_211.aspx#ad-image-ctl00_ContentPlaceHolder1_ucPageManager_ctl00_Fotolist2_rptFoto_ctl01_lnk)

Following destringing of square bales or removing of net wrap of round bales, the bales are passed through the bale breaker. There are many options for bale breaking: tub or horizonal grinder with large opening screens (3–4-in. diameter), single-drum chopper without screen, bale processor with multiple-drum choppers, and vertical augers which break up the flakes without size reduction.

Horizontal bale grinders randomly peel large chunks of flakes from square corn stover bales because the knives or hammers strike the face of the bales tangentially. These large chunks cause surge flows and plugging in downstream equipment and variation in particle-size distribution.

Two major types of agricultural bale breakers (or bale processors) used in the U.S. are: 1) multiple-horizontal choppers operating at relatively low tip speed for square bales[19] and 2) vertical low-speed twin choppers for round and square bales.[20] Although effective in breaking up the bales, these bale breakers also reduce the size of corn stover and generate fines because the knives or tines impact the face of the flakes of the bale. Furthermore, these machines are not robust enough for industrial use 24 hours each day. Another type of bale-breaker design uses large vertical augers to buckle the flakes. This type of design does not reduce the particles size, but may result in small chunks of flakes. A downstream bulk mixer or fluffer should break up these small chunks.

2.2.3 Conveying: mechanical (screw, belt, drag chain), pneumatic

The performance of many mechanical conveyors and pneumatic conveying systems is negatively impacted by high moisture content. Figure 5 shows that the throughput of a 20-in. helical-screw conveyor reduced from 11.2 tons corn stover/hr (dry basis) at 6% moisture content to 2.2 ton/hr (dry basis) at 30% moisture. Furthermore, at 30% moisture content the operation of the conveyor was unstable, as indicated by frequent surges in the motor current. Conveyors designed for wood chips tend to be undersized and underpowered for agricultural residues. Agricultural-grade equipment, because of their flimsy construction, is not suitable for 24 hr per day industrial use. Integration of mechanical and pneumatic conveyors requires careful consideration for surge flows that can cause plugging as surge flows can often exceed the design capacity of the equipment. Fines can accumulate at transition points and cause plugging. A common design deficiency of long screw and paddle conveyors is the use of hanger bearings, which should be avoided because they cause buildup of stringy biomass materials, resulting in blockage. Long helical-screw conveyors can cause compaction and segregation of milled corn stover which may lead to uneven flow rate. To reduce compaction, cut-flight or paddle conveyors may be used.

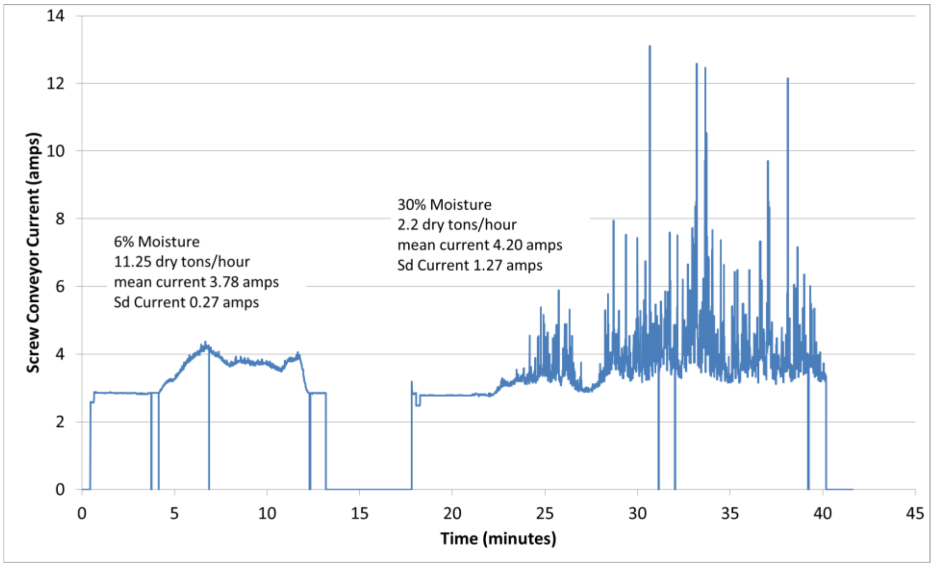


Figure 5. Effect of corn-stover moisture content on screw-conveyor performance. [21]

Drag chain and belt conveyors are used for large flows. Provision must be made for easy access to the drive systems to clear out accumulations of biomass materials, especially at the lower end. Loose biomass can spill from open drag chain and belt conveyors and cause expensive housekeeping issues. In certain areas, local fire codes may not allow sweeping and collecting spilled biomass from the plant floor to be put back onto a conveyor that feeds high-speed size-reduction equipment without first removing potential metal and rock contaminants. For this reason, drag chain and belt conveyors feeding grinding equipment should have a cover to contain spills and dust.

Tubular conveyors are used for low-flow application. These conveyors do not have a proven record on low-bulk-density and compactable biomass such as herbaceous materials. Stringy biomass, such as corn stover, can wrap around the sprockets at the transition points and cause plugging.

2.2.4 Size Reduction: Impact Vs. Shear, Equipment Types

Hammer mills and shredders are the most common biomass size-reduction equipment because of their high capacities and relatively low cost. Their major drawbacks include 1) throughputs that are severely affected by moisture content greater than about 20% and 2) high impact force by thick hammers that generate many fines.

Figure 6 shows that the operating capacity of a hammer mill was reduced from 15 ton/hr of corn stover at 7% moisture content to less than 8 ton/hr at 20% moisture content.

Tub grinders are used for coarse grinding of bales with little concern about precise control of particle-size distribution. Tub grinders can eject rock and metal contaminants upwards and should have a housing and heavy slat curtain at the feed entrance to contain these projectiles.

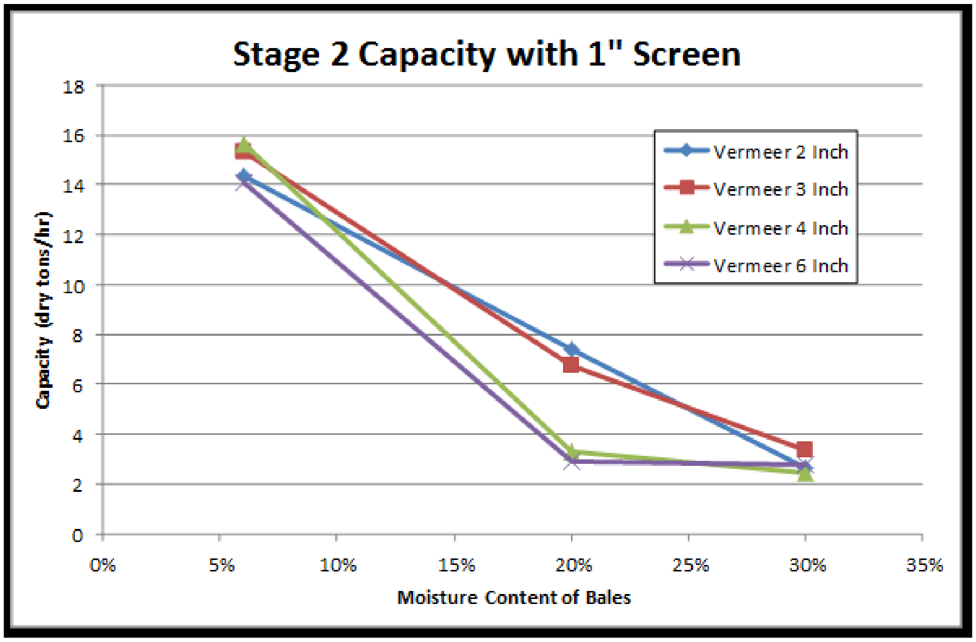


Figure 6. Impact of moisture content of corn stover on operating capacity of a hammer mill.[21]

Rotary shears generally have lower throughput than hammer mills. The positive aspects of rotary shears include 1) a throughput not impacted by high moisture, 2) generation of very little fines, and 3) clean cutting edges that enhance the flowability of size-reduced material. Rotary shears work well for wood chips. Forest Concepts has developed rotary shears that can produce small wood chips with uniform particle-size distribution.[22,23] However, feeding light and bulky biomass such as corn stover is a challenge. Bridging above the cutting rotors and low throughput (due to low bulk density) are major issues that need to be resolved.

Knife mills comminute biomass materials via mainly shearing between the rotor knives and the stationary knives. Knife mills operate at lower rotational speed than hammermills and generate less fines and narrower particle-size distribution (22).[24] Both hammer mills and knife mills utilize higher specific energy at higher moisture content of biomass.[25]

TORXX Kinetic Pulverizer (http://www.torxxkp.com/) is a new generation of size-reduction technology that use air vortexes to smash biomass materials against each other. In this way, there are no cutting knives or screens to wear out. The kinetic pulverizer appears to generate a high proportion of fines when generating smaller particle size.

Comminution of herbaceous materials in bale or loose form because of random orientation of the stalk and other components (leaf, husk, cobb), inevitably produces wide distribution of particle size unless the biomass materials are reduced to very small particle size. The most effective method of producing narrow particle-size distribution of herbaceous biomass while minimizing the production of fines is to gather, bundle, and chop the stalks of the standing crops using forage harvesters. A cutaway of a forage chopper (Figure 7) shows the precompression rollers continuously feed the stalks into the cylindrical chopper.

Figure 7. Cutaway view of CLAAS Jaguar Series 900 forage precompression rollers and drum chopper.[26]

2.2.5 Chutes

Chutes are used to transfer materials between equipment by gravity. Improper design of chutes can cause plugging. Chutes must have adequate height and appropriate angle to prevent backup of materials in cases of fluctuating flows and surges. Biomass fines can build up on the chute wall where scouring force by gravity is lower than particle-adhesion force to the wall. Coating and air blasters can be used to minimize fines buildup inside chutes.

2.2.6 Size Classification and Contaminant Removal: Screens, Air Density Separators

Air density separators and screens are used to remove contaminants such as rock, gravel, sand, and non-ferrous metal and to classify particle size of biomass materials.

Disc screens are generally used in conjunction with vibrating screens after the bale breaker or processor to separate corn stover into three fractions: over particles (which are forward to a hammer mill for further size reduction), accept fraction, and a fine fraction. The fine fraction is further screened to recover organic-rich material and reject high-ash material. Disc screens designed for wood chips are not suitable for corn stover because the smooth discs tend to drag the short- and medium-length stalks through the openings instead of conveying them forward.

2.2.7 Storage Issues: Moisture Migration, Freezing, Bale Shrinkage and Compaction

Moisture and soluble ash migration within a bale and between bales are a common problem for outdoor bale stacks.[27] The high-moisture bales more likely degrade faster than low-moisture bales. Bale degradation and compaction of bales near the bottom of a stack cause shrinkage and weakening of the bale integrity, which can lead to loss of entire bales when handling using a forklift. Another common problem with stacking round bales in cold-climate regions is potential interlocking of bales via ice formation across the net wraps which often leads to breakage of net wraps and loss of entire bales upon handling using the forklift. Ensiled pile storage of corn stover, on the other hand, is more stable in terms of moisture movement and low microbial degradation.[8]

2.2.8 Matters for Attention in Integrating Solid Handling Equipment

The pulp and paper, biomass power, and wood-pellet industries have extensive and proven experience in handling woody biomass. However, wood handling and processing techniques do not necessarily apply to herbaceous biomass. Pioneer corn stover-to-ethanol plants using equipment and systems designed to handle woody biomass inevitably encounter difficulties in achieving stable operation, design throughput, and achievement of feedstock specifications. These difficulties are primarily caused by the lack of information on herbaceous biomass regarding variability in the properties of incoming biomass, physical and mechanical properties, and lack of operating experience.

To be effective in developing robust herbaceous-biomass handling and preprocessing systems and to properly select and integrating equipment, the designers must have knowledge of properties—i.e., chemical composition and physical and mechanical properties—of biomass and understanding of the impact of these properties on the performance of equipment. Because the performance of most equipment is significantly affected by the variability of biomass properties (e.g., moisture, ash content, structure integrity, particle-size distribution), it is critically important to ensure consistent quality of incoming biomass materials. Surge flows of bulky and compactable herbaceous biomass are to be expected; therefore, conveyors, bins and chutes should have adequate capacity to handle surges. Pioneer biorefineries often found equipment plugging or underperforming because the motor and gear box on conveyors, live bottom, and grinder cannot handle sudden-surge flows of biomass. Another requirement for achieving stable operation is to match the turndown ratio capability of integrated equipment as this affects system performance during the startup period when equipment does not operate at design capacity. Additionally, predictive and feed-forward control should be utilized where applicable.

2.2.9 Fire and Explosion Risks

Fire of bale stacks is inevitable. The causes of stack fire include lighting, self-heating, and human agency. No effective methods are known for extinguishing fire in a large bale stacks, and the fire is often allowed to burn out, which can take several weeks. The risk of fire spreading between bale stacks is high if the stacks are placed close together, as was practiced by pioneer biorefineries. Spacing the bale stacks far apart results in higher cost of storage and handling. In contrast, fire in high-moisture, ensiled biomass piles is very rare because of the low oxygen content within the pile.

Smoldering and fire in preprocessing equipment of dry biomass, especially with dusty materials such as corn stover, can be a serious problem. Smoldering in dust collected outside of the screen and inside the housing of hammer mills has been observed. Air blasters and proper design can minimize buildup of fines inside equipment. Size reduction using impact equipment like a hammer mill can create significant dust, which leads to fire and explosion risks. Housekeeping costs are high for handling and processing corn stover if the equipment does not contain spills and dust. Access points should be provided to clean out buildup of loose biomass and fines inside covered-belt and drag-chain conveyors, especially at their lower points. Local fire codes may impact how spilled biomass is handled and recycled. Dust, if not contained, can also cause issues with particulate emissions. Containing dust and preventing fires and dust explosions can add significant capital and operating costs.

2.3 Pretreatment

2.3.1 Steam Explosion Pretreatment

Steam explosion is an effective pretreatment for herbaceous- and some hardwood-biomass materials. Hardwood requires higher severity (higher temperature and/or longer time) than most herbaceous biomass. Steam explosion reduces particle size to a uniform distribution and sterilizes biomass. Highly bioactive materials such as biowaste, corn fiber, and brewery waste may not be properly sterilized by steam-explosion pretreatment at a large scale because pockets of material may not be exposed to high-steam temperatures. One issue with steam explosion and other thermochemical-pretreatment methods is that prehydrolyis of hemicellulose occurs at a lower severity than that required for effective cellulose pretreatment. This leads to selecting a compromised pretreatment condition that generally results in higher enzyme dosage for both hemicellulose and cellulose hydrolysis.

2.3.2 Dilute-Acid Pretreatment

Dilute-acid pretreatment is used to overcome the bimodal prehydrolysis of hemicellulose and cellulose observed in steam explosion. The use of acid catalysis with steam explosion results in high enzymatic hemicellulosic sugars and glucose yields at relatively low enzyme dosage.[28] The major drawbacks of dilute-acid steam-explosion pretreatment are that it requires an expensive-alloy reactor, has a high risk of generating inhibitors if precise process control is not attained, and causes condensation of lignin, which may make material less valuable as a chemical feedstock. Tar deposits inside a pretreatment reactor can be an issue, depending on the reactor design and process conditions.

2.3.3 Alkali Pretreatment

Alkali pretreatment is less effective than dilute-acid pretreatment in terms of prehydrolysis yield of hemicellulose and improving the digestibility of cellulose in herbaceous and hardwood biomass. Severe alkali pretreatment conditions could lead to degradation of hemicellulose. Alkali-pretreated biomass generally requires higher enzyme dosage than acid-pretreated materials. The advantages of alkali pretreatment over dilute-acid pretreatment are that stainless steel reactors are adequate and there are lower inhibitors and a more reactive lignin co-product.

2.3.4 De-acetyl Mechanical Refining (DMR)

DMR can be considered as a form of improved alkali pretreatment with the alkali extraction of a portion of hemicellulose and lignin prior to mechanical refining.[29,30] In this way, the inhibitory effect of acetyl group and lignin are significantly reduced and result in lower cellulase enzyme loading. Because DMR does not hydrolyze a significant amount of hemicellulose, the xylanase loading for DMR-treated biomass is higher than that of dilute acid pretreated material. Another advantage of DMR is low level of fermentation inhibitors which should lead to higher-fermentation product yield. One challenge facing DMR is to recover the soluble extract without using excessive water. It is relatively simple to wash wood chips, but washing corn stover at industrial scale requires development and optimization work, especially when alkali is used because the resultant swelling of fiber and pith causes poor water drainage.

2.3.5 Pretreatment Reactors: Batch, Continuous Horizontal and Vertical, Slurry, Mechanical Refining

Steam-explosion pretreatment can be carried out in batch or continuous reactors where steam is directly injected into the reactor.

- Batch reactors: the solid loading in these reactors is generally about 40–60% solids prior to steam injection. Masonite Corp. used batch steam-explosion reactors to produce fibers from wood chip for medium density fiber board since the 1920s. Wood chips are loaded by gravity into vertical cylindrical digesters. The wood chips are cooked by direct steam injection. Discharge of the cooked chips is sudden, through a die, by opening the blow valve at the bottom of the reactor. The steam-exploded fibers are directed into a cyclone, where flashed steam is separated from the fibers. Batch steam explosion technology is more suitable for low-throughput (less than about 750 ton/day) processing because of the practical limit in the size of a batch reactor. Loading a very large batch reactor can take some time. Discharging a large reactor requires a large flash cyclone. Multiple bath reactors discharging into a common flash cyclone will result in continuous flow of materials downstream. The advantages of batch steam explosion reactors over continuous reactors include: (i) they are more reliable as there are less moving parts, (ii) they produce very little tar deposit as the reactor self-cleans upon each discharge, (iii) they are more flexible in operation as the residence time can be precisely adjusted. In fact, one reactor can be taken out of service without seriously impacting plant operation. Figure 8 shows a bank of six batch steam explosion reactors at the Zilkha pellet mill in Selma, AL.[31] The design capacity of this mill is 240,000 metric ton/year.

- Continuous horizontal steam treatment reactor: the first commercial continuous horizontal steam-explosion reactors were the Pandia reactors, which were introduced around the mid-1940s. A plug screw feeder compresses wood chips into a dense plug that seals the steam pressure inside a vertical Tee piece, which connects to a horizonal screw-conveyor reactor (Figure 9). Cutaway views of a plug screw feeder are shown in Figure 10. Steam is injected into the Tee piece as well as the reactor. Vent nozzles are located along the top of the reactor and the Tee piece to vent non-condensable gas that, if allowed to build up inside the reactor, can lower the reaction temperature. Chemicals can be added with the steam at the top of the Tee piece directly above the biomass as it exits the plug pipe. The feed rate and the rotational speed of the reactor screw are adjusted to control the throughput and residence time. The reactor is generally operated at less than half-full (i.e., the level of biomass is at or below the horizontal reactor shaft) to prevent back flow, and this can affect the residence-time distribution and potential plugging at the transition with the Tee piece. The cooked fibers exit the horizontal section of the reactor and drop into the discharge assembly which has a sweeper at the bottom. The sweeper ensures fibers are swept to the discharge port. A valve throttles the discharge rate of the slurry. There were several drawbacks of horizontal steam-pretreatment reactors, which led to their replacement by the vertical reactors in the mid-1980s. The major drawbacks of continuous horizontal steam pretreatment reactors include:

  a) Wild residence-time distribution due to slippage, increase in bulk density, and change of rheological properties of biomass material as it is conveyed down the length of the reactor, and stickiness of certain biomass materials as the sugar and lignin are dissolved. The National Renewable Energy Laboratory has extensively investigated the residence-time distribution of continuous horizontal reactors.[32,33] Just conveying wood chips (i.e., without steam pretreatment), the residence-time distribution is rather wide, probably because of slippage of chips (Figure 11). With dilute-acid steam pretreatment, the residence-time distribution in a horizontal reactor can vary widely (Figure 12). Because of the wide residence-time distribution, it would be difficult to achieve high product yield using Pandia-type reactors.

  b) Severe tar buildup on the conveyer flights (especially for low pH pretreatment).

  c) Expensive to purchase and maintain. The reactor can only be filled to less than 50% of the nominal volume.

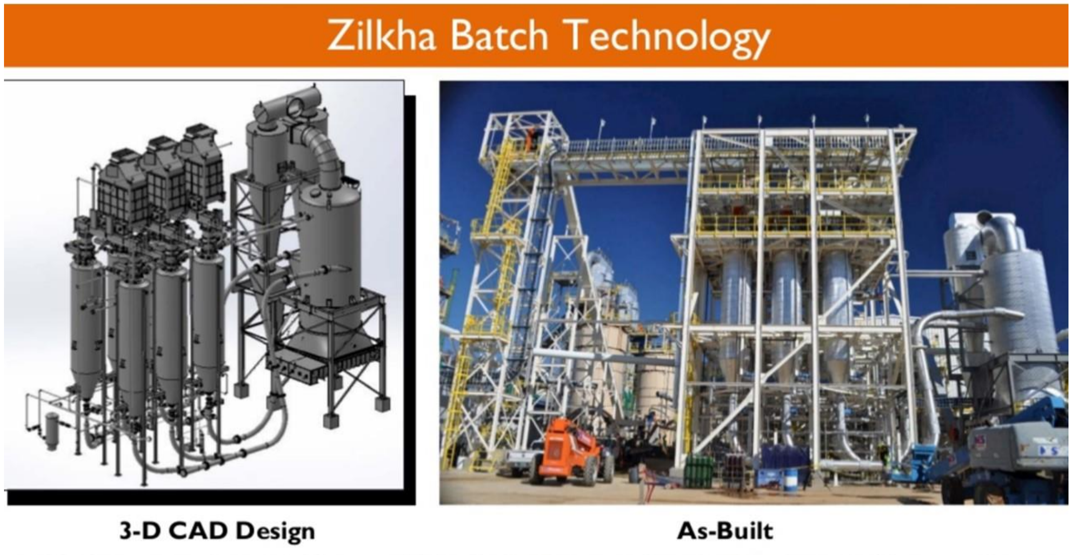


Figure 8. Batch steam explosion reactors for wood pellet production.[31] Zilkha Pellet Mill, Selma, AL, design capacity = 240,000 metric ton/yr.

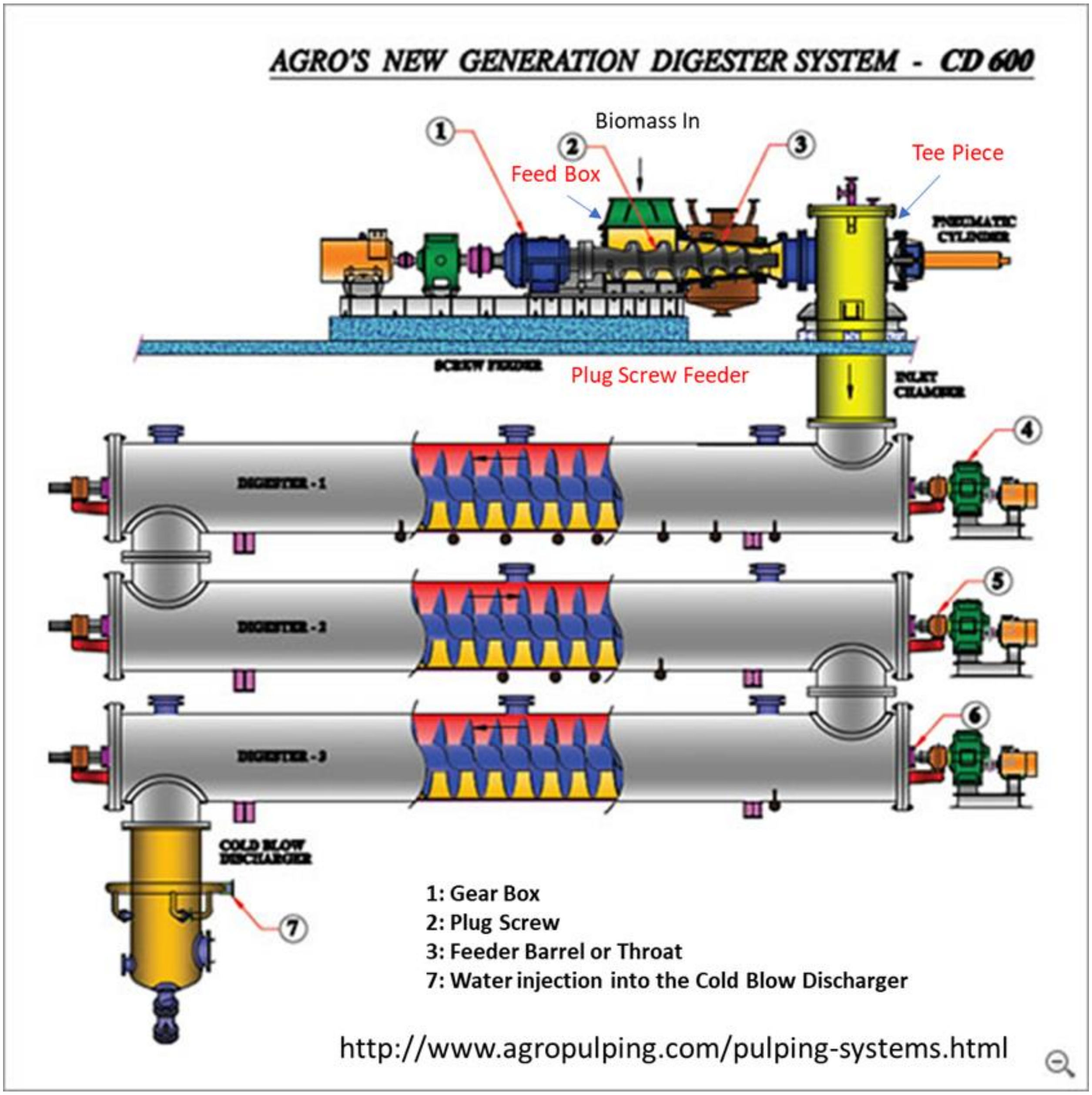


Figure 9. Pandia-type reactors.

Figure 10. Valmet FeedMax plug screw feeder.

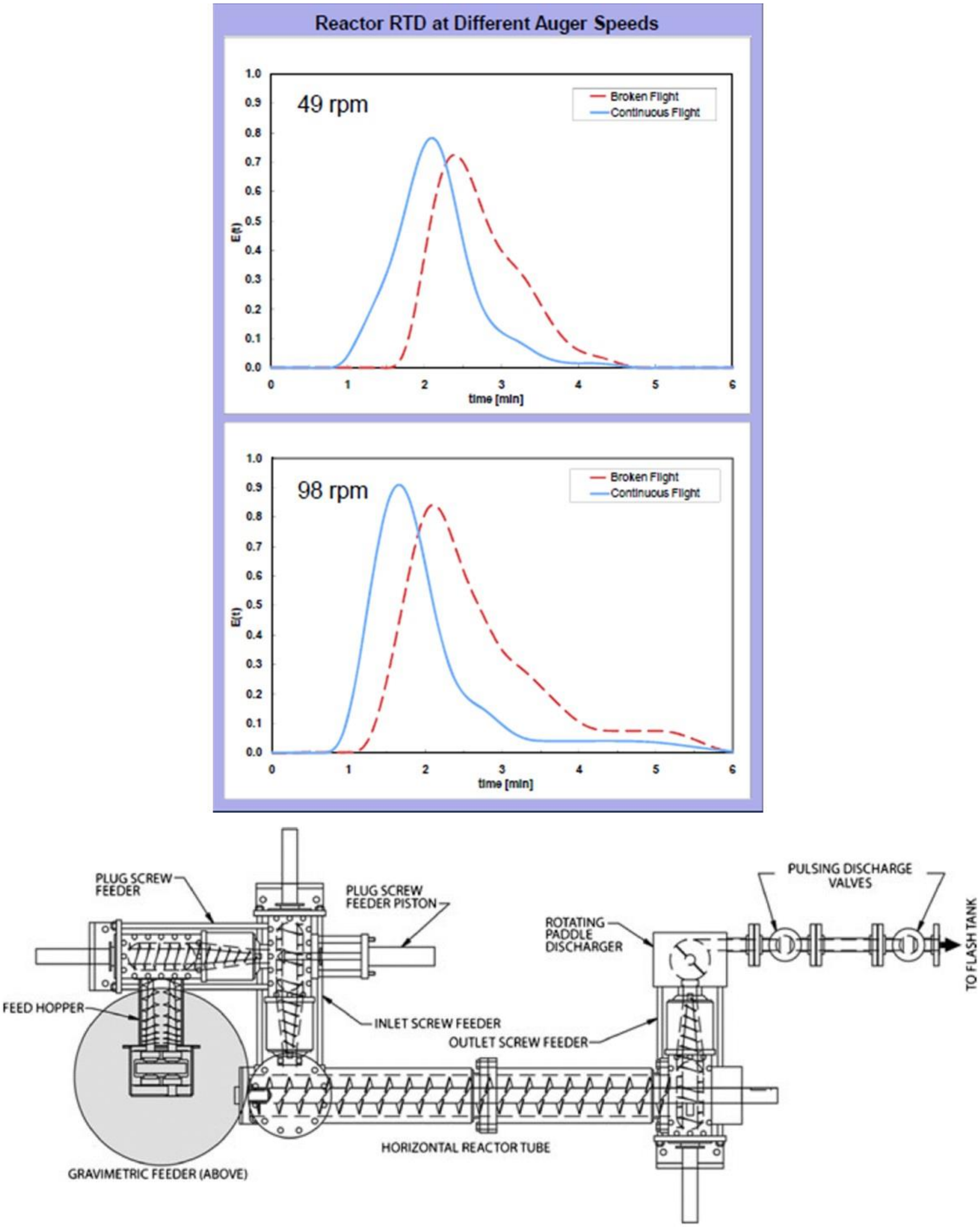
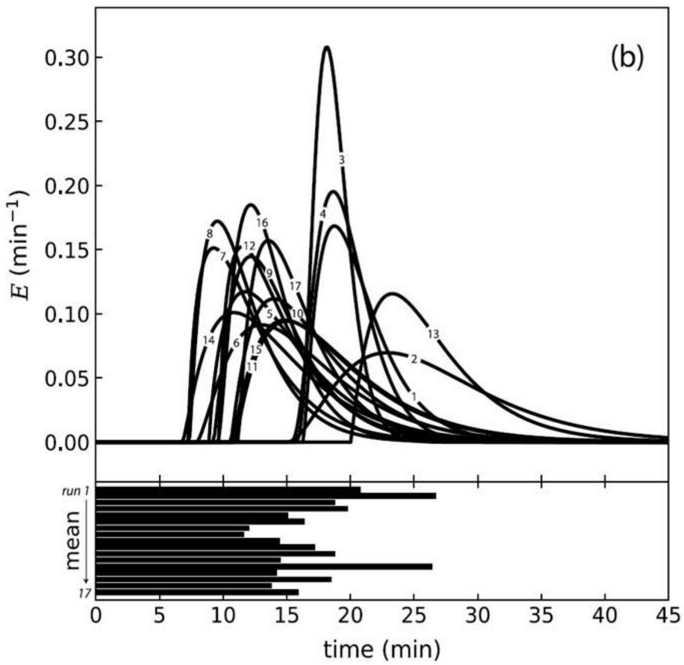


Figure 11. Residence time distribution of wood chips conveyed in a 200 kg/day continuous horizontal pretreatment reactor.[32]



- Gamma distribution fit of RTD of 17 Dilute Acid Steam Pretreatment Runs using 2 Reactor Tubes
- Run numbers are identified on the curves.
- Mean-time bars are given in ascending run number from top bottom.

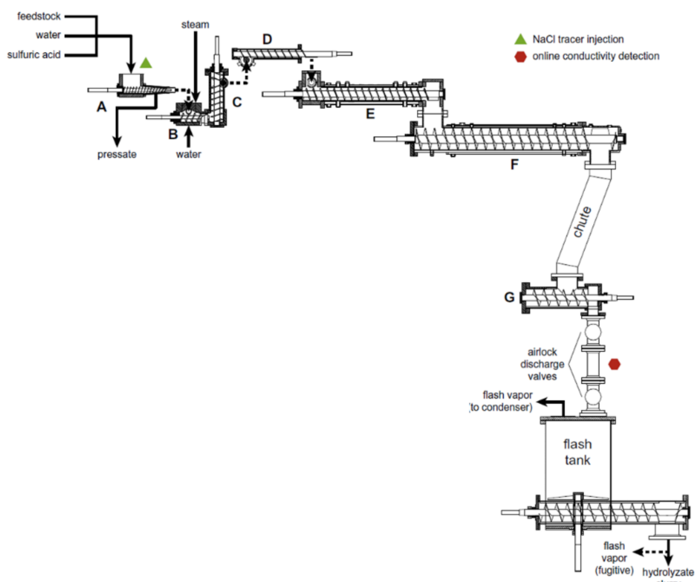


Figure 12. Residence time distribution of dilute acid steam pretreatment in continuous horizontal pretreatment reactors.[33]

- Continuous vertical steam-treatment reactor: because of the many deficiencies of the continuous horizontal reactor mentioned above, and with the availability of reliable and accurate on-line level and density measurement sensors based on gamma-ray technology, Kamyr-type vertical reactors were commercialized in the mid-1980s. This design continues to be used today in the manufacturing of pulp, medium-density fiberboard (MDF), and for steam-explosion pretreatment reactors for ethanol and wood-pellet production. The residence time can be more-accurately controlled (compared to the Pandia-type reactor) by controlling the feed rate and the level of biomass inside the reactor. A plug screw feeder, similar to that used in the Pandia reactor, feeds biomass into the top of the vertical reactor (Figure 13). The discharge system comprises a sweeper, extract screw conveyor, and either a disc refiner or a discharge valve.

Figure 13. Valmet continuous vertical steam explosion reactor, Biotrac system.[34]

- Slurry reactors: these reactors are custom designed according to process specifications. Slurry reactors are considered when feeding biomass into high-pressure reactors poses difficulties. Biomass material is milled to small particle size (usually less than 2 mm) and slurried using water. Acid or alkali is optionally added. The slurry is then pumped through a tubular reactor. Steam is injected into the slurry via a hydroheater.[35] The residence time is controlled by controlling the feed rate. Discharge is via a flow-control valve. Tar buildup is a common problem. High water and heat usage are also issues.

- Mechanical refining: mechanical refining is another form of pretreatment. Biomass is generally thermally pretreated (using hot water or steam) with alkali or acid to soften the structure of the biomass or disrupt the lignin-carbohydrate bonds prior to mechanically defibration (see DMR above). Flat-disc refiners are commonly used in thermomechanical pulping. The plate pattern and the gap between the plates are selected, depending on the extend of defibration. Pressure disc refiners can reduce the moisture content of fiber via steam flash. Two roller mills are used in the sugar-cane industry to crush the cane stalk, extract the sugar, and dewater the fiber. Extruders have been used at pilot scale to pretreat cellulosic biomass.[36,37,38] High abrasion wear and high energy consumption are the main concerns.

2.3.6 Feeding and Discharging Continuous Pressurized Biomass Reactors

Pioneer biorefineries encountered difficulties in feeding and discharging continuous pressurized steam pretreatment reactors. Bridging of bulky biomass, such as corn stover, in the plug screw feed box is frequently observed. Biomass with high ash content can quickly wear out the forward flights of the plug screw feeder. Fines can cause plugging of the drain (weep) holes on the feeder barrel (i.e., the throat, see Figure 14) leading to flooding of the feed box and a stopping of the feeding. Adequate flushing of the weep holes using external spray nozzles should prevent buildup of fines on the feeder barrel. Valmet has developed a precompression screw to increase the bulk density of bulky biomass materials before introducing the biomass into the plug screw feeder. This device should reduce the bridging problem and improve the performance of the plug screw feeder.

Pioneer biorefineries experienced severe erosion problems of the discharge vale and piping of continuous steam-pretreatment reactors. The probable cause was extremely high velocity and improper design of equipment and piping. This is an area that needs attention when integrating pretreatment reactors with downstream equipment. An alternate design uses a cold-blow discharger, in which cold water is mixed with pretreated biomass to form a slurry which is pumped out (Figure 9). The cold-blow method, however, negates the steam-explosion effect.

Figure 14. Weep holes of a plug screw feeder covered with fines.

2.4 Conditioning of Pretreated Biomass Materials

For high-temperature and high-solids pretreatment, one major challenge is to cool down the pretreated biomass and adjust the temperature and pH to meet a rather narrow range of values prior to adding enzyme to avoid potential denaturing of the enzyme. Heat exchangers cannot be used because of the high-solid slurry. One method of cooling and adjusting the pH of steam-exploded biomass is to mix the material with chilled, pH-adjusted water in a high-shear mixer. Because steam exploded biomass material is shear thinning, high-shear mixing reduces the viscosity of the slurry and improve the mixing. Progressive cavity pumps can be used to pump slurry of dilute-acid pretreated corn stover up to about 22% total solids.

2.5 Enzymatic Hydrolysis

2.5.1 Viscosity Reduction of High-Solid Slurry

Conveying or pumping high-viscosity pretreated biomass slurry over long distances is difficult. Therefore, it is desirable to reduce the viscosity of high-solid pretreated biomass slurry quickly. Viscosity reduction can be performed in a liquefaction tank using enzyme. The viscosity of pretreated biomass slurry can be reduced from over 100,000 cP to a pumpable 5,000 cP in less than 30 minutes if the biomass is properly treated (e.g., by dilute acid in corn stover). During the viscosity-reduction operation, cellulose hydrolysis into glucose is usually less than 2%, which suggests that the addition of endoglucanase alone may be enough to reduce viscosity. Other enzymes can be added later in the hydrolysis reactors to preserve their activities from potential loss due to high shear mixing during the enzyme-addition step.

2.5.2 Batch vs. Continuous

Most dry-grind corn-ethanol plants in the U.S. use batch hydrolysis and fermenters. These are proven technologies, with fermenter sizes up to about 1.2 million gallons, working volume. Continuous hydrolysis and fermentation save capital costs, but are more difficult to operate from the aspect of contamination control and cleaning. The use of batch fermenters in cellulosic ethanol is also predominant, except for the liquefaction step because the residence time is short.

2.5.3 Contamination Control: Clean in Place

Pioneer cellulosic ethanol plants generally follow the practice of the dry-grind corn-ethanol industry in its contamination-control strategy of using clean in place (CIP) and antibiotics. The effluent of cellulosic ethanol plants is normally sent to a wastewater treatment facility. With the presence of phenolic compounds in lignocellulosic hydrolysates, the use of chlorine compounds in CIP systems should be curtailed to avoid the potential formation of organo-chlorine compounds.

2.5.4 Heat Exchangers for Slurry

Heat exchangers for slurry are required for process streams between the hydrolysis and fermentation step because hydrolysis is generally carried out at about 50°C, and fermentation at about 32–35°C (for *Saccharomyces cerevisiae*) and in the distillation heat-recovery system.

Pioneer biorefineries had many operational issues with wide-gap plate-and-frame heat exchangers due mainly to fibers clogging the exchangers. In some cases, the undigested fibers (due to under-pretreatment or upset in the enzyme hydrolysis steps) are tightly compacted into large chunks of wavery boards, taking on the pattern of the plates. Plugging is common at heat-exchanger pass inlets, where the slurry streams make abrupt turns.

Shell-and-tube heat exchangers are better suited for handling pretreated biomass slurries than are wide-gap plate-and-frame heat exchangers. However, plugging at the head plates can occur in improperly designed units.

Spiral heat exchangers are another option for handling slurry. Proper velocity must be maintained to ensure self-cleaning of the channels and to avoid dead spots. If slurry flow is stopped for extended periods of time, the heat exchanger must be flushed clean with water. Cleaning of spiral heat exchangers is easier than is cleaning of shell-and-tube heat exchangers.

Tube-in-tube heat exchangers works best for slurry. However, they have low heat-exchange efficiency and are therefore costly. In area where reliable operation is critically important, it is recommended that tube-in-tube heat exchangers or spiral heat exchangers be the first choice.

2.6 Fermentation

2.6.1 Strategy for Handling Inhibitors: CIP vs. Organism Adaptation

For most researchers, fermenting inhibitors (e.g., organic acids, lignin and carbohydrate degradation products) should be avoided completely. However, for some plant operators, inhibitors can sometimes be an ally so long as they do not cause significant reduction in product yield.

An example of some level of inhibitors being beneficial is the fermentation of spent sulfite liquor. These plants rarely experience contamination issues because the spent sulfite liquors contain high levels of inhibitors. The plant operators adapt the yeast to the inhibitors to achieve ethanol yields from hexose in the 80–90% range, depending on the cooking conditions.

Bacterial contamination in a dry-grind corn-ethanol plant is not a significant issue because high ethanol concentration can be achieved quickly, which suppresses contamination. On the other hand, the long period of cellulose hydrolysis (usually 72 hours) can promote growth of bacteria. If the hydrolysate contains certain level of inhibitors to effectively suppress bacterial contamination, less frequent CIP and lower antibiotic doses are required.

2.6.2 Fermenter Design: Startup Consideration

For new cellulosic ethanol facilities, startup periods are expected to be long, and the initial biomass throughput is significantly lower than the design rate. Heat exchangers, pumps, and agitators should be designed to operate at low flow rates and low tank levels during startup. Auxiliary startup loops may be beneficial. For very large fermenters, adequate agitation or mixing must be maintained to avoid settling of fibers. Sand will settle out in fermenters. Provision must be installed to remove sand from the fermenter bottom to avoid erosion of pumps and piping. Provision for air sparging into the ethanol fermenter (e.g., via the recirculation or cooling loop) could be helpful in preventing stuck-yeast fermentation.

2.6.3 Seed Train

The seed train should include an option for adapting the fermenting organism to inhibitors in biomass hydrolysates and for storing the adapted strains.

2.7 Distillation System

2.7.1 Tray Design for handling Slurry

Fibers can deposit on sieve trays and cause plugging. Deposit of soluble compounds (e.g., low-molecular-weight lignin, unfermented sugars, salts, and extractives) can cause tray fouling. Fixed-valve trays are better than sieve trays in handling insoluble solids. An example of fixed valve tray design is shown in Figure 15.

Figure 15. Fouling-resistant Koch-Glitsch FFEXIPRO valve tray.[39]

2.7.2 Solid Liquid Separation

If dry cake (>45% total solids) is required (e.g., for use in a biomass boiler), a membrane filter press would be the primary choice; however, these are expensive to purchase and operate. Decanter centrifuges may produce cake up to 40% solids. With addition of flocculants, screw presses and belt filters could be alternatives. Dewatering of biomass stillage requires further development and testing.

3. ENGINEERING PROCUREMENT AND CONSTRUCTION

3.1 Lump Sum vs. Cost-Plus Contract for Pioneer Plants: Pros and Cons

The two most common construction contracts for new technologies are lump sum and cost plus. Lump-sum or fixed-price contracts are appropriate if the scope and schedule of the project are well defined, and the contractor has the proper experience in executing the project. These are often not the case for designing and building the first plant using new technologies. Cost-plus contracts are often used for construction of pilot and commercial-demonstration facilities using new technologies and custom-designed equipment. Experience with both types of contracts indicates that facilities built using cost-plus contracts have fewer operational issues and shorter startup periods, possibly because of close interaction between the owner's engineers and the EPC engineers. Table 5 lists the characteristics of both contract types based on experience in design, construction, and startup of lignocellulosic-ethanol plants (three pilot plants, one commercial demonstration plant, and two commercial plants).

Table 5. Comparison of lump-sum and cost-plus construction contracts for lignocellulosic ethanol plants.

Characteristics	Lump sum contract	Cost-plus contract	Comment
Technologies	Well defined. Pilot plant test data and known properties of process streams available	Technologies less well defined, with some missing properties data	
Cost to owner	Fixed. However, the contractor may inflate the price to ensure profitability.	Can be higher than lump-sum contract if not well managed	Could include a guaranteed maximum price for the cost-plus contract
Potential risks to owner	If technologies turn out to be not well defined, potential escalation of cost, which can cause the contractor to cut corners to maintain profitability. As a result, inferior substitutes or omissions may negatively affect the operability and performance of the plant.	Higher administrative and audit costs. Higher overall cost than anticipated. Contractor has little incentive to keep cost down and maintain schedule.	For both contract types, it is critically important to the owner's engineers to work closely with the contractor throughout the design, procurement, and construction phases of the project to avoid costly surprises.

3.2 Permits for New Technologies (Federal, State, County, and City)

Knowing the requirements of applicable permits at all level of governments is critically important for ensuring the project can be carried out on schedule and meet its budget. Some permits can take months to obtain, especially if they involve public hearings. Appropriate data should be available.

3.3 HAZOP Analysis (Roles of R&D, Engineering, Operation and Maintenance): Is It Effective and Sufficiently Thorough?

It is critically important to carry out thorough Hazard Operability (HAZOP) analysis in the engineering design phase to avoid potential escalation in costs, delay in construction and startup, and operational issues. Thorough HAZOP analysis of a typical lignocellulosic-ethanol facility will take about one week or possibly longer. The review team should include key members from the following departments of both the owner and contractors: R&D, process engineers, design and construction, plant operation and maintenance, environmental, safety, and health (ES&H), and an experienced HAZOP analysis consultant who is familiar with the technologies (and could also serve as moderator). Any major changes in the plant design should require additional HAZOP analysis.

3.4 Owner Engineers' Role During Design, Procurement and Construction Phases

To reduce the risks in designing and constructing a biofuel facility utilizing new technologies, it is critically important for the owner to assemble a team of experts in the field to work closely with the engineering construction and procurement (EPC) firm that designs and builds the facility. If the EPC firm is new to the technologies, it will need data—including equipment and pilot-plant test data, properties of raw materials and intermediate process streams, product specifications—to properly select and integrate the equipment for robust operation.

The owner's engineer team should include the experts mentioned as part of the HAZOP analysis team. One of their key roles is to develop detailed and accurate datasheets for equipment in key process areas with which the EPC firm is not familiar. If important material and process-stream properties are missing, those data need to be generated. An example is the terminal and saltation velocity of milled biomass materials and the effect of particle size, moisture, and ash content. Because raw biomass, such as corn stover, has variable properties, data sheets should specify the typical range of these properties and not a single value. A common mistake found is that process parameters are specified in datasheets rather than product specifications. As an example, the screen size of a grinder may be specified instead of the particle-size distribution of the comminuted biomass, which is one of the key output specifications.

BETO established the Feedstock Conversion Interface Consortium (FCIC)[40] to address technical risks and understanding how biomass properties affect collection, storage, handling, preprocessing and conversion technologies with the goal of improving the overall operational reliability of integrated pioneer biorefineries. The FCIC applies the "quality by design" approach in identifying critical attributes of product output and material input and critical process parameters of biomass-preprocessing equipment. This approach should apply well in developing specifications and datasheets for biomass conversion facilities.

The owner's team should review the layout and three-dimensional drawings of the plant during the design phase to ensure the integration of equipment will lead to efficient and safe operation and maintenance. Easy access must be provided to sampling points, equipment, and instruments that require periodic maintenance. Compatibility of equipment and control systems must be verified prior to purchase, especially when integrating systems from different suppliers. For example, the integration of a mechanical conveying system from one vendor to a pneumatic conveying system from another must be carefully evaluated. The turn-down capabilities of the systems are not likely be similar; therefore, the transition (e.g., transfer chutes and plenums) and the control logics must be designed accordingly. Nozzle placement and orientation on vessels must be carefully reviewed to ensure the best routing of piping, electrical, and instrument wiring. Sequencing of site preparation, road and civil work, and equipment installation must be carefully planned to avoid potential delays. The impact of weather on the operation of outdoor equipment must be evaluated. If necessary, enclosures should be provided.

3.5 Process and Equipment Guaranty Pitfalls

One common mistake several pioneer biorefineries made was relying too much on equipment suppliers to provide performance guaranties without adequate testing or testing with on-spec biomass only. As mentioned above, the variability in biomass properties was identified as a major cause of operational difficulties of pioneer cellulosic-ethanol plants. Many equipment suppliers have little industrial experience in processing difficult-to-handle biomass, such as corn stover. A piece of equipment that processes wood chips well may not handle milled corn stover effectively.

To avoid uncertainty regarding equipment performance, extensive testing using biomass materials with the range of properties expected to be delivered to the plant is vital. For corn stover, the properties that have major impact on the performance of preprocessing equipment are moisture content, total ash content, and fiber integrity (e.g., brittleness). A non-degraded bale behaves differently from a degraded bale with the same moisture content during size reduction and conveying

3.6 Process Control, Instrumentation, In-Line-Sensors

Another major cause of operability problem in pioneer cellulosic ethanol plants is the lack of proper process and equipment control. Most equipment suppliers will provide interlocks that are designed primarily to protect equipment. For example, if the current draw on a grinder exceeds the safe operating current of the grinder motor, the interlock sends a signal to slow down or stop the feed conveyor. This type of feedback control is not effective because either a blockage occurs or the grinder operates close to the upper limit of the motor current. Equipment control using interlocks and feedback alone often leads to unsteady operation and surge flows.

An adaptive and predictive control logic should be used in addition to interlocks or feedback control to minimize surges in flow rate and prevent unexpected stoppage. However, to attain a steady flow rate of feedstock, the properties of input biomass must be consistently maintained, which is not feasible for the bale logistics because the properties of biomass vary within a bale and between bales. Ensiled storage of sized and moisture-adjusted biomass should provide feedstock with more consistent properties. Or better yet, conversion-ready feedstock in uniform format (e.g., pellets) should provide robust operation of the biorefineries and lower the capital and operating costs as well.

Figure 16 illustrates the application of the quality-by-design approach to biomass-feedstock preprocessing and pretreatment. Although the blocks are connected, it is highly recommended that a biomass-feedstock preprocessing operation be completely decoupled from pretreatment to increase the operational reliability of each area. Feedstock preprocessing can be carried out in depots located near the source of raw biomass. The densified feedstock can then be transported to the conversion facilities.

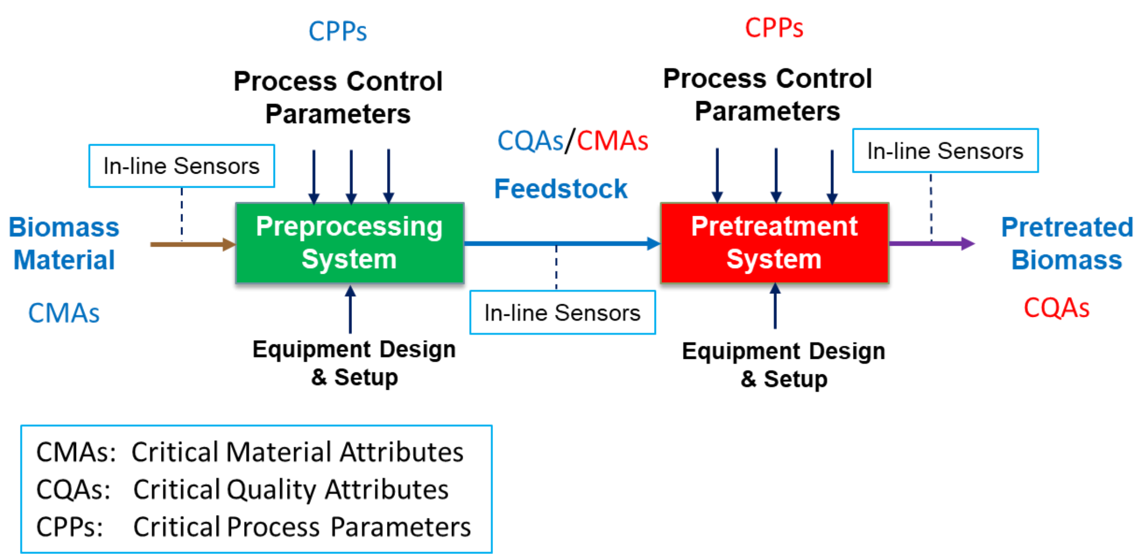


Figure 16. Quality-by-design approach to biomass-feedstock preprocessing and pretreatment.

To achieve the desired critical quality attributes (CQAs, e.g., particle size distribution) for a specific hammer-mill design (e.g., screen size and knife design) and setup (which normally cannot be adjusted during operation) the critical process parameters (e.g., feed rate, tip speed of the knives, air flow) must be adjusted according to the critical material attributes (CMAs, e.g., moisture content, ash content, bulk density, fiber brittleness). Both predictive, feed forward and feedback controls should be used. In-line sensors measuring the CQAs and CMAs are required to achieve effective process and equipment control. Specifically, in-line sensors for measuring particle shape, particle size distribution, composition, moisture content and brittleness of biomass need to be developed.

Figure 17 illustrates the application of an adaptive control system that uses predictive models (e.g., empirical models of machine performance based on historical data, first principles models of physical properties) and on-line biomass property measurements for feed-forward control of the unit operation. The empirical models are continually strengthened with on-line data collection (i.e., machine learning).

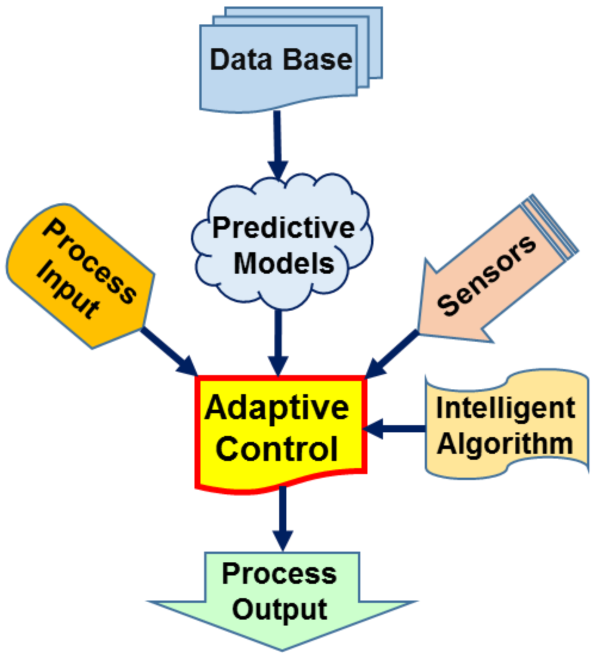


Figure 17. Adaptive control system.[21]

3.7 Freeze protection

Facilities in cold weather regions require proper freeze protection. Contractors facing cost overrun often skim freeze protection such as heat tracing. The consequence can be devastating when pipes freeze and split. A dedicated (steam or electric) heat-supply system should be provided for freeze protection.

4. PLANT COMMISSIONING, STARTUP, AND OPERATION

4.1 Operating and Maintenance Manuals

Equipment suppliers should provide up-to-date installation, operating, and maintenance manuals for individual equipment or a package system. The EPC firm and owner's engineers should develop operating and maintenance manuals for all integrated systems. Draft copies of these manuals, if feasible, should be available prior to installation of equipment, piping, valves, and instruments so that the system and the manuals can be verified in the field during construction.

4.2 Operator Training (Classes and Hands On)

It is critically important to train operators and technicians in biomass-preprocessing operations and equipment maintenance prior to commissioning the plant. Training can be carried out at the owner's pilot plant, equipment vendor's facility, or a research facility that has commercial-scale equipment, as does the Biomass Feedstock National User Facility (BFNUF) operated by INL in Idaho Falls, Idaho. The BFNUF has equipment for processing bales and forest residues ranging from bale breaking, size reduction, air-density separation, screening, drying, and densification.

Classroom presentations to give an overview of the process, plant and equipment design, characteristics of feedstock, intermediate and final products should be provided prior to hands-on training.

4.3 Spare Parts and Maintenance

An inventory of critical spare parts for equipment should be maintained to ensure quick changeout of worn or broken parts. A preventative-maintenance program should be developed and implemented to prevent unexpected outages of equipment. Operation logs should be used to inform the preventative maintenance program. For example, the knives of a hammer mill should be replaced after *x* tons of biomass were processed at a given set of properties (e.g., moisture content, ash content) and process parameters (e.g., screen size, knife tip speed, air flow).

4.4 Fabrication Support

During commissioning and startup periods, it is expected that some modifications to equipment and piping will be necessary, and these activities will often involve fabrication work. It is important that the plant have a list of nearby fabricators that can quickly turn around work on short notice.

4.5 Plant Lab's Role

Improper use of laboratory resources is common in many pioneer biorefineries. One example is that a lab is often inundated with feedstock samples waiting for measurement of particle-size distribution using traditional sieve analysis methods. These analyses take laboratory resources from other potentially critical analyses. Furthermore, the sieve analysis results invariably come too late for the plant operators to make effective process adjustments. This points to the need for developing in-line sensors for particle-size distribution. Better yet, the solution is to supply the biorefineries with conversion-ready feedstock which have uniform particle size (e.g., pellets) and other critical properties such as ash and moisture content and chemical composition.

The plant laboratory's primary role should be to maintain quality control and quality assurance of the products and incoming feedstock. Another function of the lab could be to solve process chemistry and biological issues, such as identifying unusual contaminants in feedstock and products, analyzing deposits in process equipment, and monitoring the activity of enzymes and fermenting organism.

4.6 Pilot Plant Support for Key Unit Operations

Having pilot-plant support during commissioning and startup periods could be valuable as certain unit operations in the pilot plant are scaled versions of the commercial plant's. Test results of these unit operations could help guide the commercial plant operators to find the optimal operating conditions more quickly.

4.7 R&D Support

Having R&D support during commissioning and startup periods is valuable in solving unexpected process-performance deviations from design. An example is that recycled streams could concentrate inhibitors not observed in pilot test results. Methods may need to be developed to neutralize or remove these inhibitors to improve product yield.

5. CONCLUSION

Based on industrial experience and published information related to pioneer biofuel operations the following observations are made:

1. The failure to achieve design production rate of pioneer biorefineries can be attributed to:
    a) Bale logistics for harvesting, collection and storage of corn stover cause wide variation in biomass properties delivered to the biorefineries.
    b) The inability of the biorefineries to produce consistent quality in feedstock from biomass with varying properties leads to low on-stream time and low product yield.
    c) The integration of biomass feedstock preprocessing and conversion processes in the same facility leads to low operational reliability of the integrated facility.
    d) Unstable operation of many equipment and systems due to lack of in-line sensors for measuring biomass properties and lack of knowledge on the impact of biomass properties on the performance of biomass preprocessing equipment prevents achievement of design throughput.
    e) Lack of robust process control—i.e., of interlock and feedback controls—prevent the maintenance of steady operation of biomass-preprocessing and conversion systems).
    f) The long commissioning and startup periods are due partly to inexperienced operators. Many operators of the startup teams were drawn from dry-grind corn-ethanol plants. Their operating experience and approach did not help in the operation of biomass preprocessing systems.
2. Equipment designed for processing woody biomass may not work for processing herbaceous materials. For example, hammer mills create a lot of fines and dust from corn stover.
3. Bale logistics lead to high dry-mater loss due to microbial degradation and processing (i.e., spillage, fines).

The following research and development activities (many of which are being performed by the FCIC) should lead to more-robust biofuel process and plant design and improve the economic viability of lignocellulosic biofuel production:

- Single-pass, chopped-biomass harvest and ensiled/anaerobic storage should reduce the variability of biomass properties.
- Knowledge on the impact of the physical, mechanical, thermal, and chemical-composition biomass properties will have a beneficial effect on the performance of preprocessing equipment.
- Development in-line sensors for measuring critical properties of biomass and intermediate streams and application of the Quality by Design and adaptive control approaches will improve process design.
- Expanding the feedstock depot concept to include fractionation of biomass for producing multiple products (including conversion-ready feedstock) and minimizing waste may obviate pretreatment at the conversion facility.
- Improving feedstock logistics to produce multiple products (for different high-value applications), including conversion-ready feedstocks, improves the economics of the industry.
- The use of conversion-ready feedstock should significantly reduce the technical and economic risks of biorefineries.

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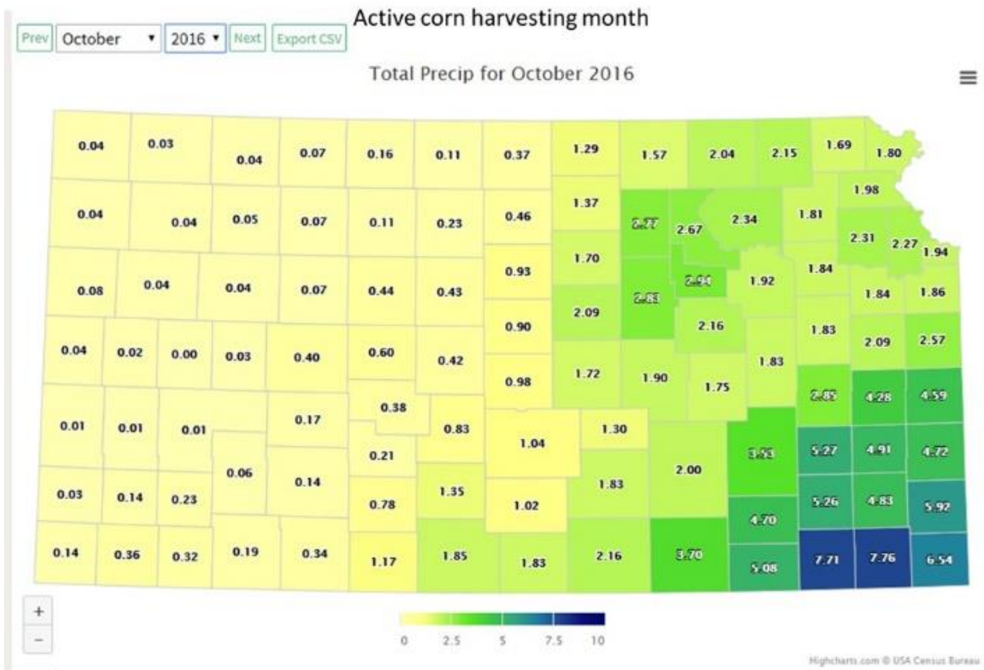
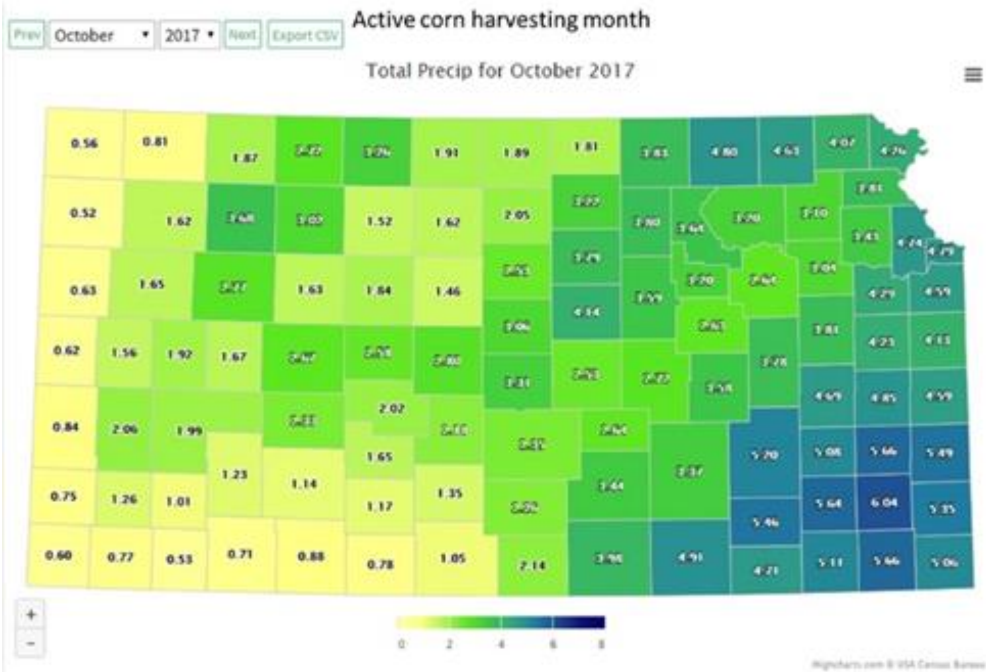
Appendix A

Precipitation in Active Corn and Wheat Harvesting Months



October precipitation in Kansas in 2016 and 2017. Note: Most active corn harvest in Kansas occurs in October. Source: http://climate.k-state.edu/precip/county/.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Active corn harvesting month
Total Precip for October 2017
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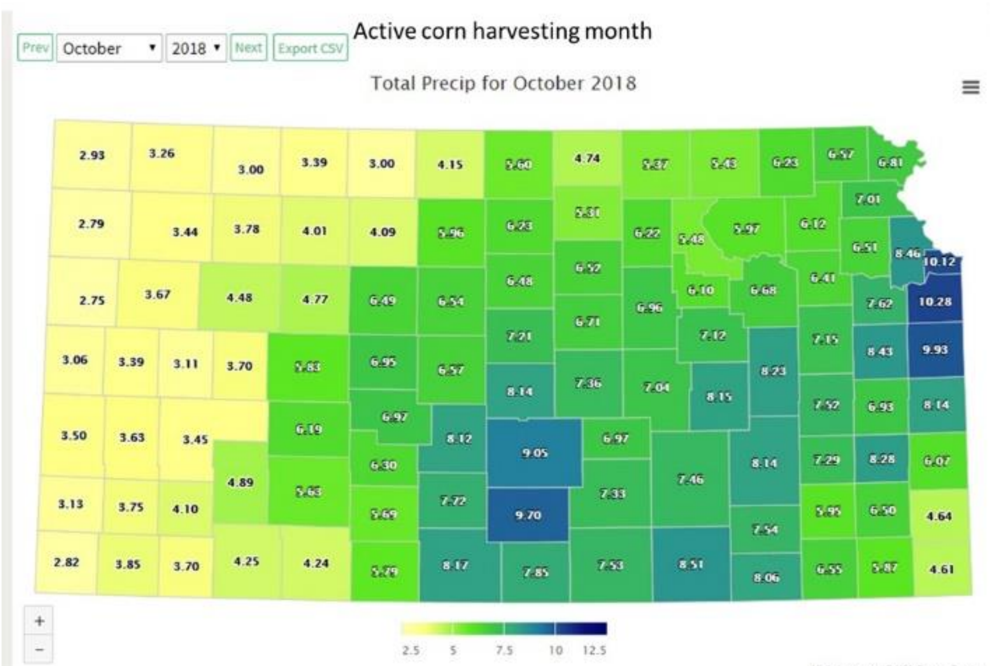
2
4
6
8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Active corn harvesting month
Total Precip for October 2018
2.5
5
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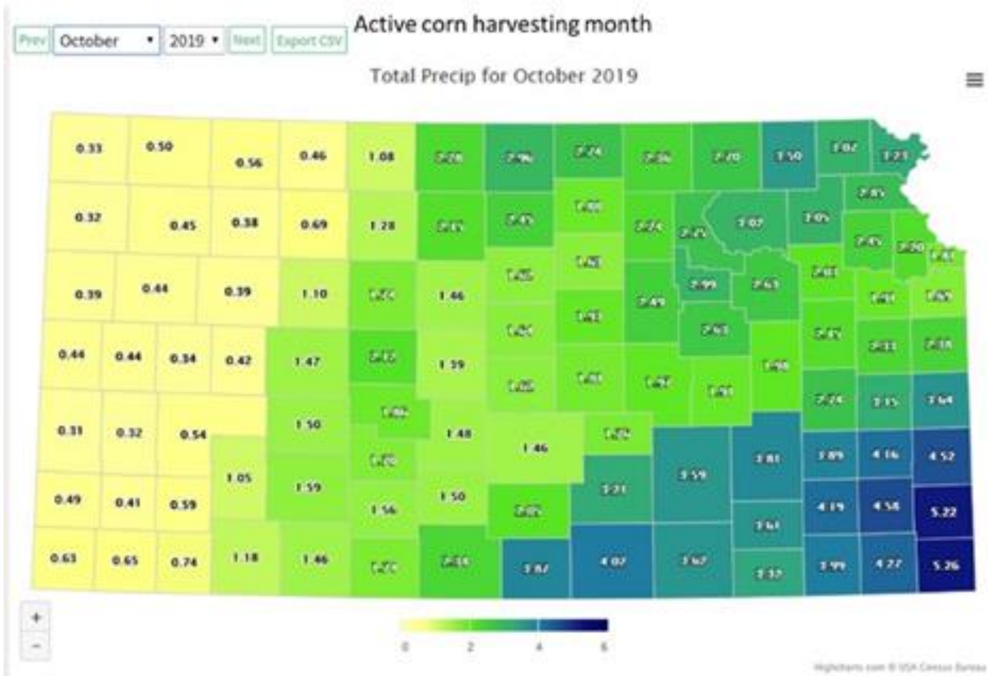
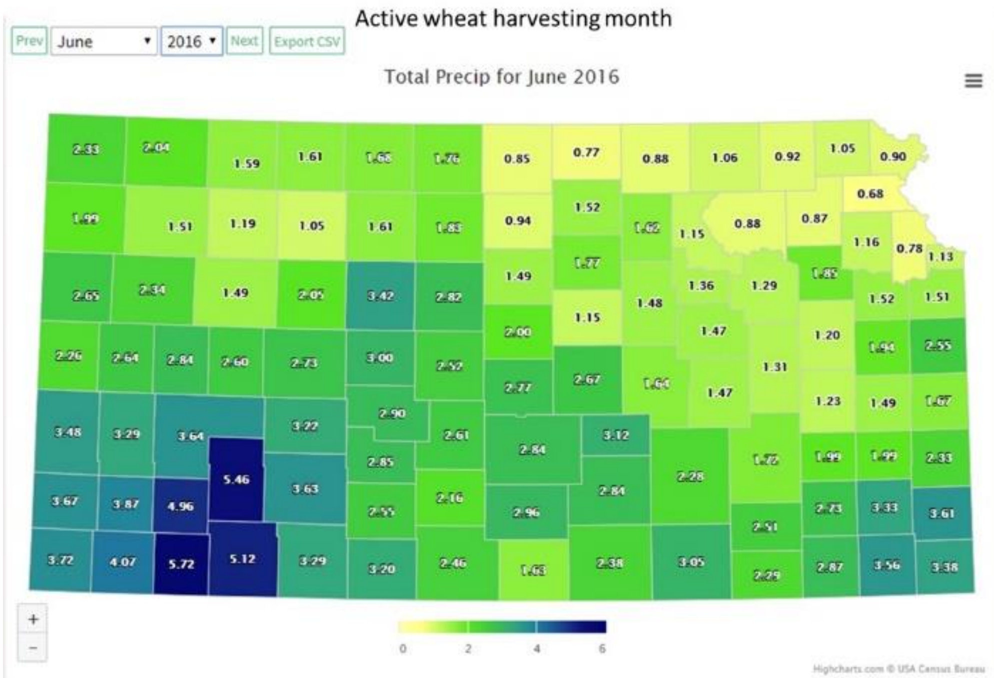
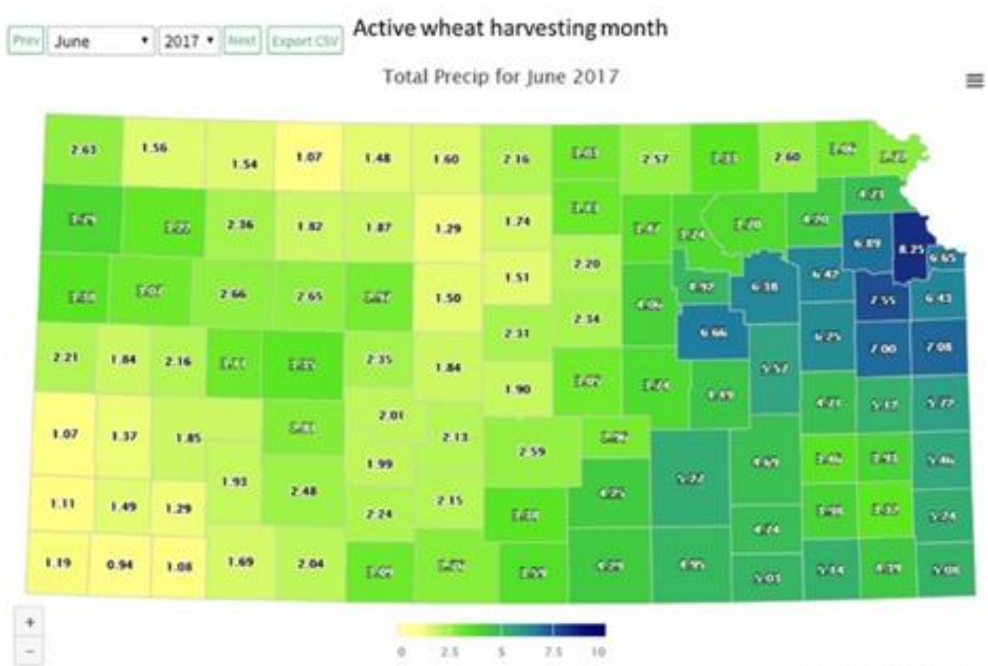
12.5
Highcharts.com © USA Census Bureau

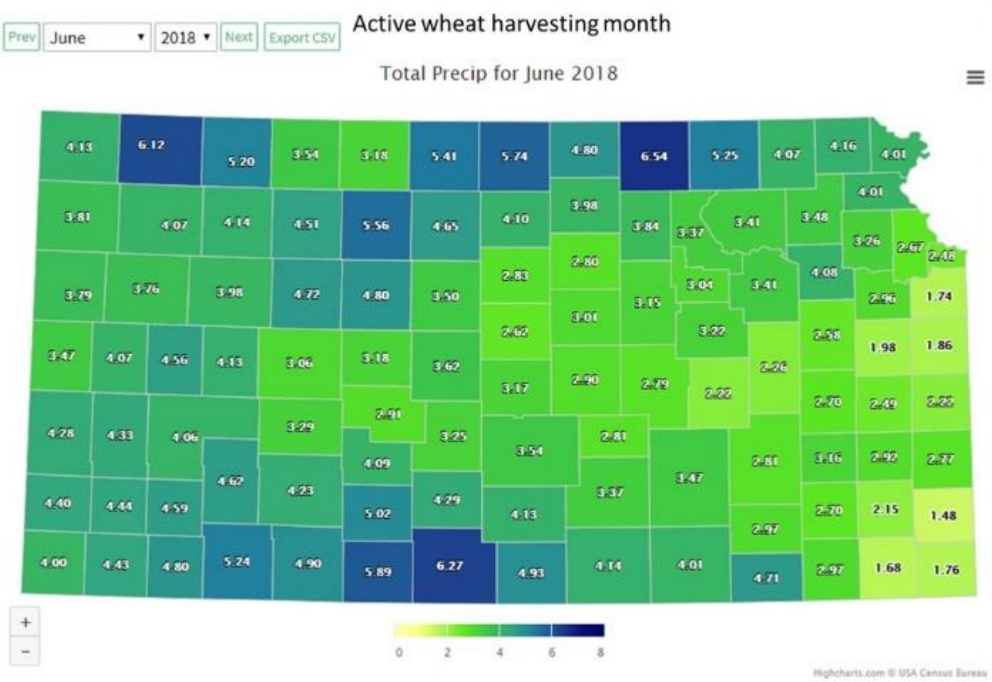


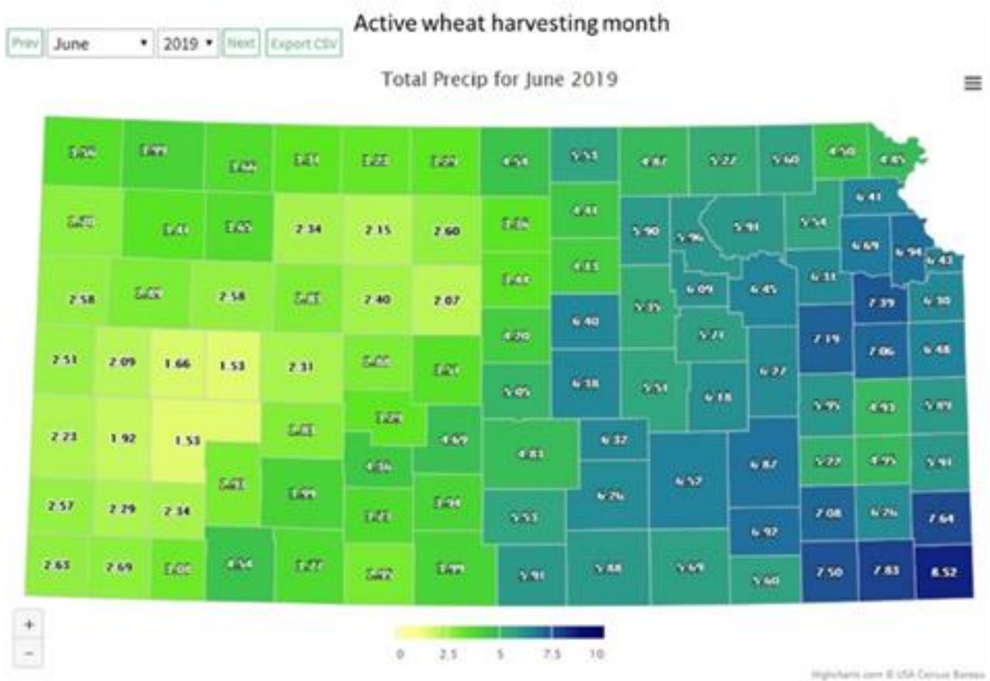
October precipitation in Kansas in 2017, 2018, and 2019. Note: Most active corn harvest in Kansas occurs in October. Source: [http://climate.k-state.edu/precip/county/.](http://climate.k-state.edu/precip/county/)



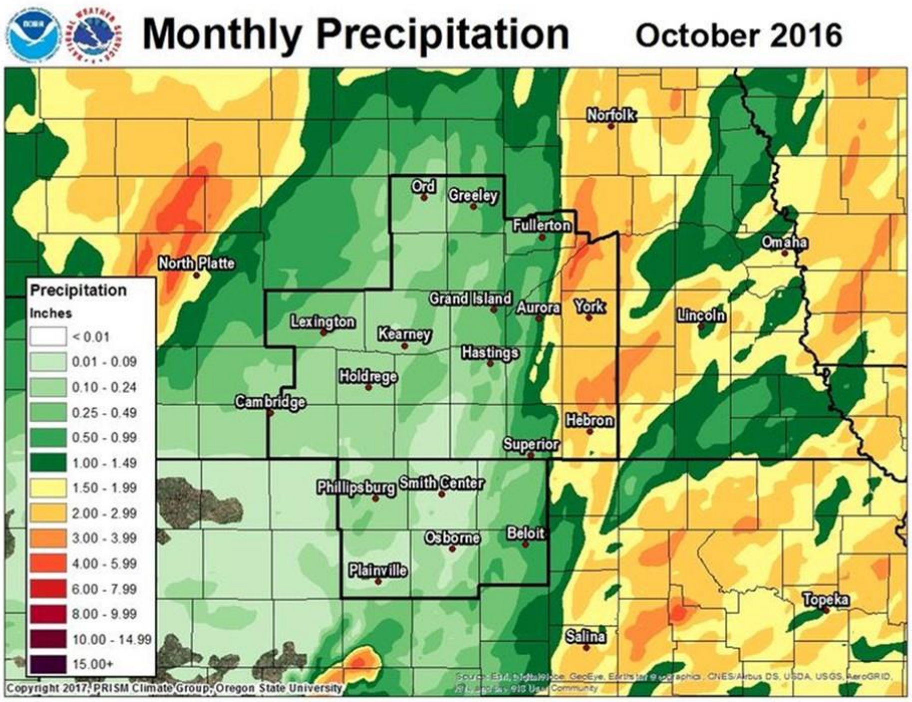


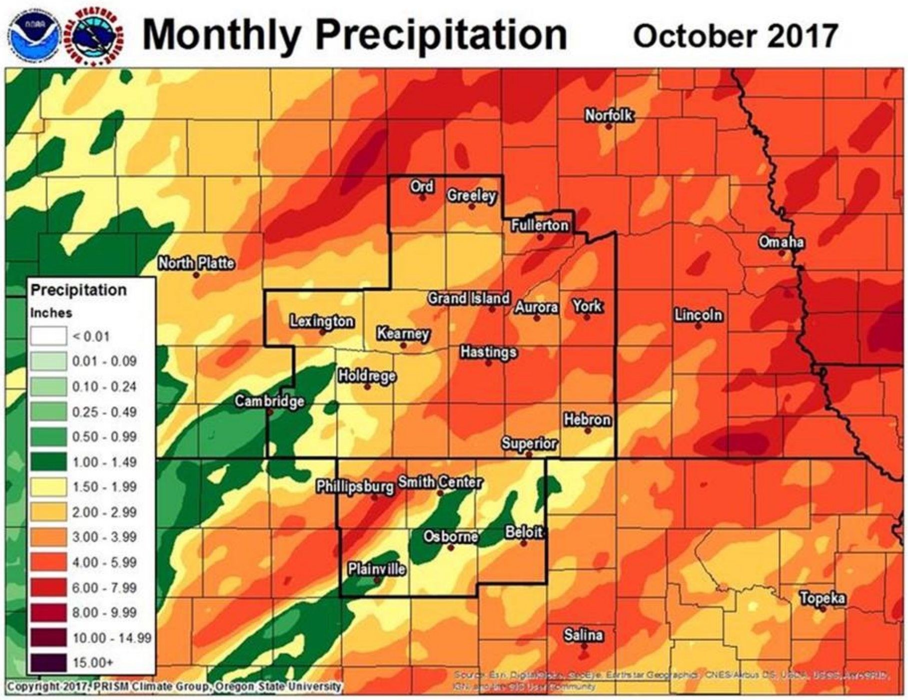
June precipitation in Kansas in 2016 and 2017. Note: Most active wheat harvest in Kansas occurs in June. Source: http://climate.k-state.edu/precip/county/





June precipitation in Kansas in 2018 and 2019. Note: Most active wheat harvest in Kansas occurs in June. Source: [http://climate.k-state.edu/precip/county/.](http://climate.k-state.edu/precip/county/)





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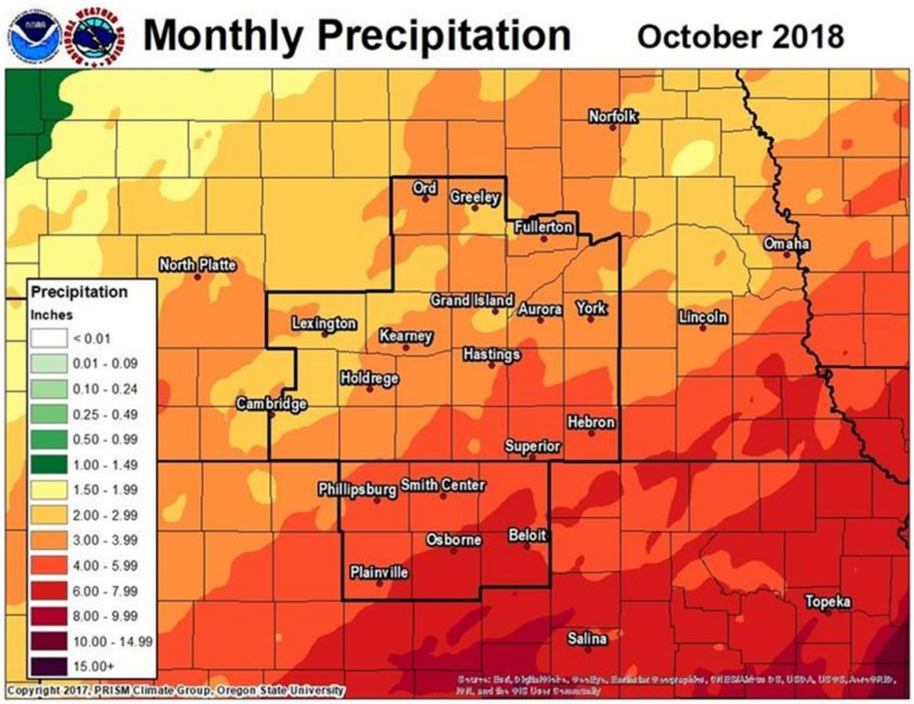

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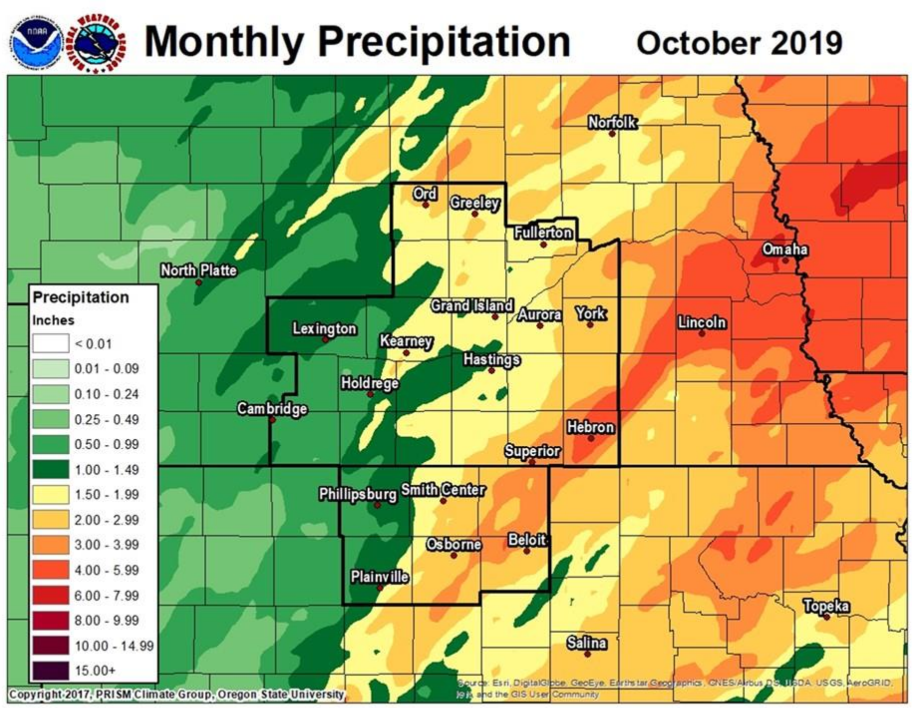
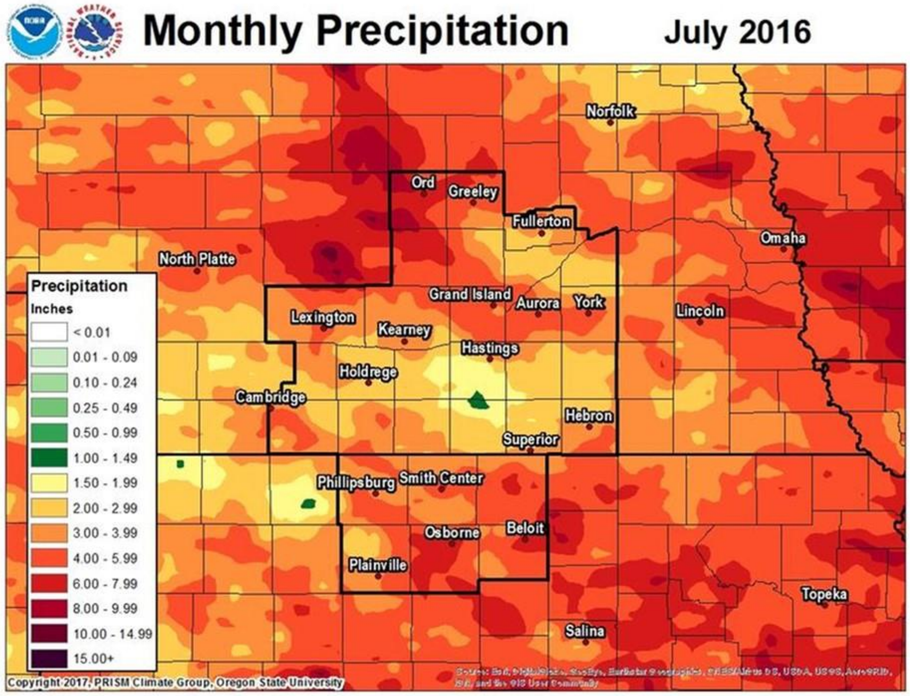


October precipitation in Nebraska in 2018 and 2019. Note: Most active corn harvest in Nebraska occurs in October. https://www.weather.gov/images/gid/climate/MonthlyPrecipitationMaps/2017.10.jpg



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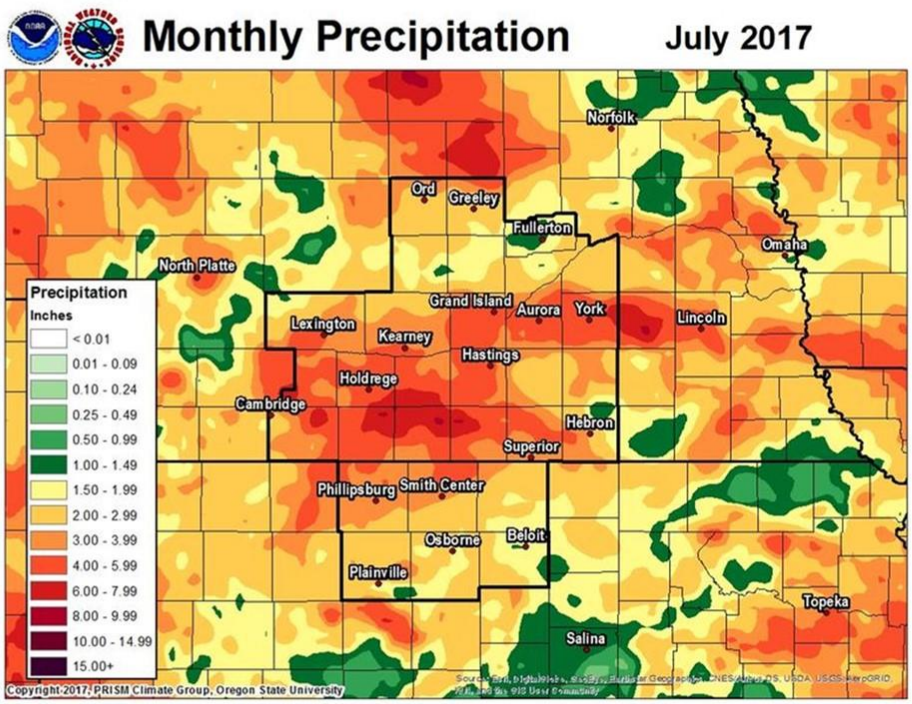
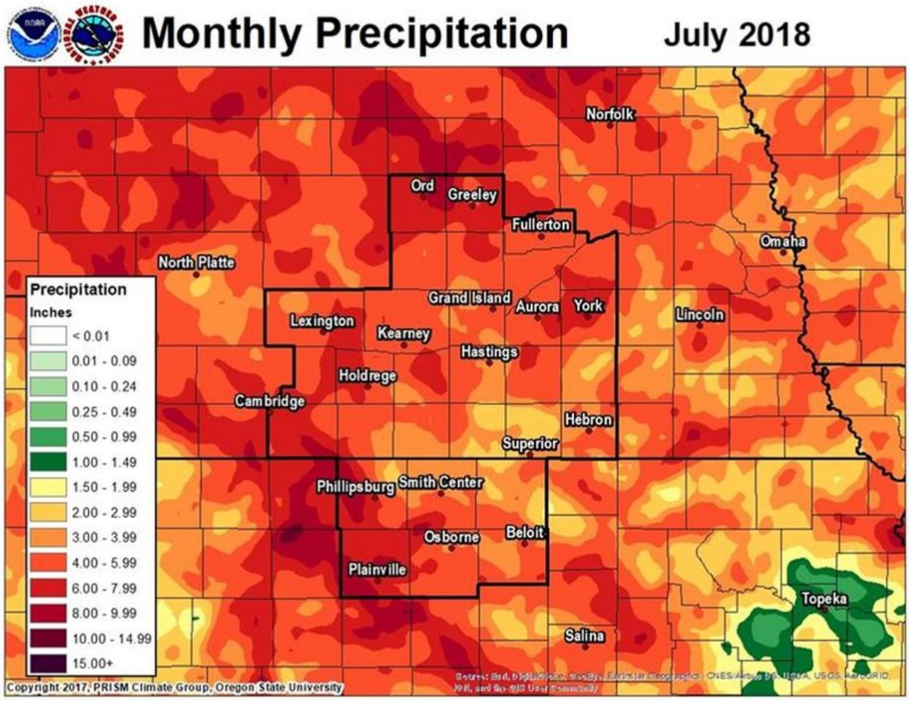


July precipitation in Nebraska in 2016 and 2017. Note: Most active wheat harvest in Nebraska occurs in July. https://www.weather.gov/images/gid/climate/MonthlyPrecipitationMaps/2019.10.jpg



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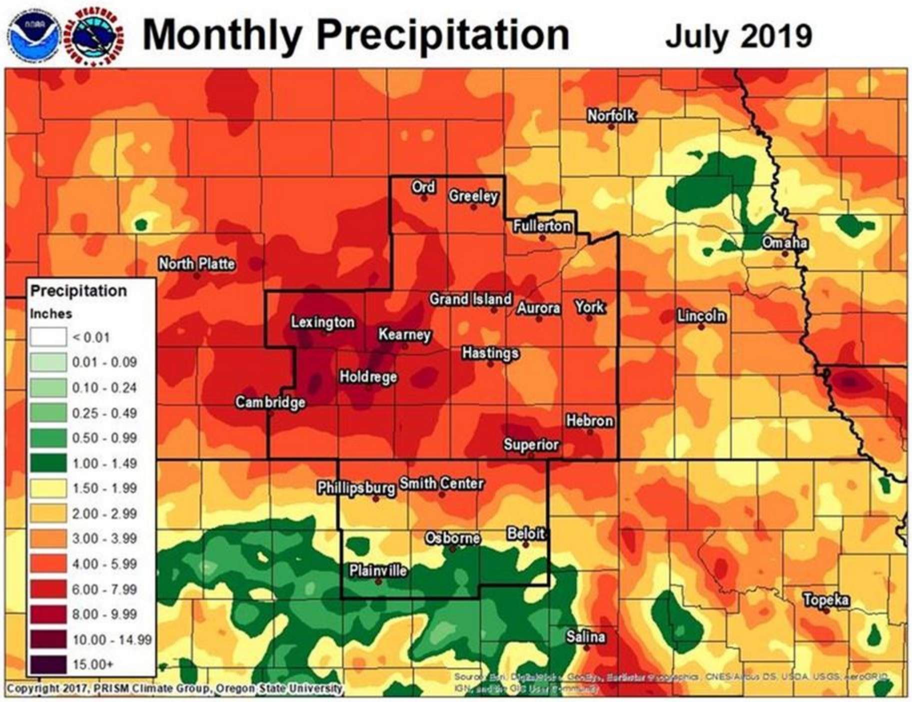


July precipitation in Nebraska in 2018 and 2019. Note: Most active wheat harvest in Nebraska occurs in July. https://www.weather.gov/images/gid/climate/MonthlyPrecipitationMaps/2017.07.jpg.

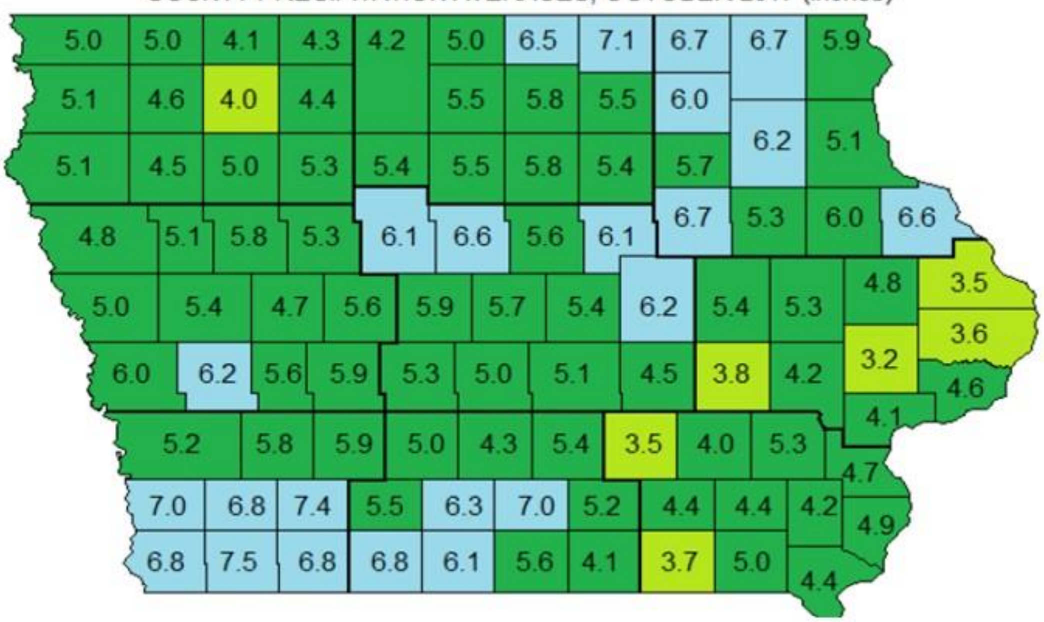
October 2017											
WEATHER BY DISTRICTS											
	TEMPERATURE (F)		HEATING DEGREE DAYS				PRECIPITATION (inches)				
DISTRICT	October 2017 Average	Departure*	October 2017 Average	Departure*	Since Jul., 1, 2017 Average	Departure*	October 2017 Average	Departure*	Since Jan.1, 2017 Average	Departure*	SNOWFALL Oct 2017 Average
Northwest	50.2	+1.2	452	-52	559	-133	4.77	+2.53	29.47	+1.51	T
North Central	51.3	+2.4	423	-83	530	-173	5.48	+3.10	33.63	+2.43	T
Northeast	52.8	+3.2	379	-105	491	-174	5.83	+3.25	36.76	+4.27	T
West Central	52.1	+1.6	398	-59	486	-126	5.36	+2.95	34.52	+4.27	T
Central	53.5	+2.8	360	-92	433	-171	5.68	+3.06	30.97	-1.92	T
East Central	54.7	+3.0	330	-93	412	-146	4.29	+1.40	32.03	-0.48	T
Southwest	54.9	+2.5	319	-84	371	-147	6.87	+4.26	35.42	+2.97	T
South Central	54.9	+2.6	321	-85	370	-162	5.19	+2.34	29.64	-4.43	T
Southeast	56.1	+2.5	295	-74	342	-129	4.84	+1.78	27.52	-6.74	T
STATE	53.2	+2.4	368	-81	450	-152	5.35	+2.74	32.25	+0.37	T

* Departures are computed from 1981-2010 normals.

The weather data in this report are based upon information collected by the U. S. Dept. of Commerce, NOAA National Weather Service.

State Climatologist, Iowa Dept. of Agriculture & Land Stewardship

COUNTY PRECIPITATION AVERAGES, OCTOBER 2017 (inches)



October precipitation in Iowa in 2017. Note: Most active corn harvest in Iowa occurs in October. Source: Iowa monthly weather summary: October 2018. Harry J. Hillaker, State Climatologist
https://iowaagriculture.gov/climatology-bureau/monthly-weather-report

WEATHER BY DISTRICTS

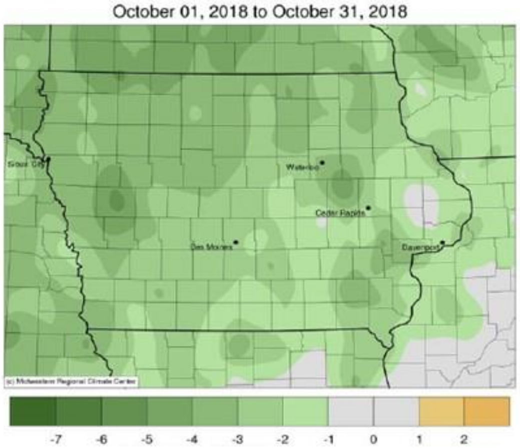
DISTRICT	TEMPERATURE (F) October 2018 Average	Departure*	HEATING DEGREE DAYS October 2018 Average	Departure*	Since Jul., 1, 2018 Average	Departure*	PRECIPITATION (inches) October 2018 Average	Departure*	Since Jan.1, 2018 Average	Departure*	SNOWFALL Oct 2018 Average
Northwest	45.7	-3.3	598	+103	741	+45	2.66	+0.42	40.28	+12.32	1.3
North Central	45.9	-3.0	592	+93	733	+30	3.79	+1.42	45.95	+14.75	0.8
Northeast	46.7	-2.9	567	+73	703	+5	5.74	+3.16	50.30	+17.81	0.3
West Central	47.8	-2.7	533	+90	644	+36	3.36	+0.95	37.23	+6.98	1.5
Central	48.6	-2.1	508	+65	608	+8	4.34	+1.72	42.79	+9.90	0.3
East Central	49.6	-2.1	477	+47	560	-9	5.61	+2.72	42.00	+9.49	T
Southwest	49.8	-2.6	471	+74	557	+24	4.65	+2.04	37.19	+4.74	1.1
South Central	50.3	-2.0	460	+62	534	+7	5.55	+2.70	35.16	+1.09	T
Southeast	50.9	-2.7	442	+61	510	+18	5.37	+2.31	34.81	+0.55	0.1
STATE	48.2	-2.6	510	+67	611	+11	4.49	+1.88	40.93	+9.05	0.6

* Departures are computed from 1981-2010 normals.

The weather data in this report are based upon information collected by the U. S. Dept. of Commerce, NOAA National Weather Service.

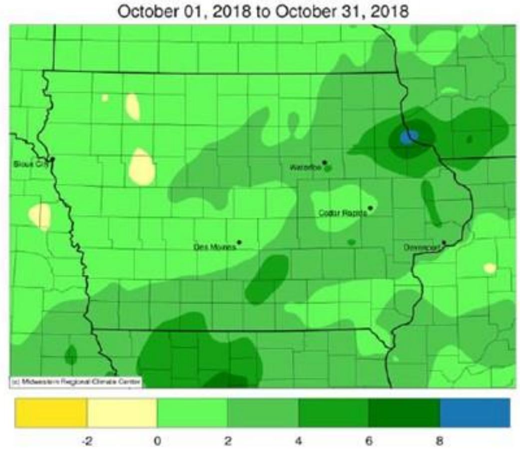
Average Temperature (°F): Departure from 1981-2010 Normals

October 01, 2018 to October 31, 2018



Accumulated Precipitation (in): Departure from 1981-2010 Normals

October 01, 2018 to October 31, 2018



October precipitation in Iowa in 2018. Note: Most active corn harvest in Iowa occurs in October. Iowa monthly weather summary: October 2018. Justin M. Glisan, Ph.D. Source: https://iowaagriculture.gov/climatology-bureau/monthly-weather-report

WEATHER BY DISTRICTS

DISTRICT	TEMPERATURE (F) October 2019 Average	TEMPERATURE (F) October 2019 Departure*	HEATING DEGREE DAYS October 2019 Average	HEATING DEGREE DAYS October 2019 Departure*	HEATING DEGREE DAYS Since Jul., 1, 2019 Average	HEATING DEGREE DAYS Since Jul., 1, 2019 Departure*	PRECIPITATION (inches) October 2019 Average	PRECIPITATION (inches) October 2019 Departure*	PRECIPITATION (inches) Since Jan.1, 2019 Average	PRECIPITATION (inches) Since Jan.1, 2019 Departure*	SNOWFALL Oct 2019 Average
Northwest	44.8	-4.2	626	+132	746	+50	4.62	+2.38	35.95	+7.99	0.1
North Central	45.3	-3.6	611	+112	732	+29	5.60	+3.23	36.66	+5.46	0.6
Northeast	46.1	-3.5	586	+92	710	+11	6.05	+3.47	42.55	+10.06	3.1
West Central	47.2	-3.3	552	+109	636	+28	4.43	+2.02	33.53	+3.28	0.3
Central	47.2	-3.5	552	+109	632	+33	5.81	+3.19	37.42	+4.53	1.8
East Central	48.2	-3.5	521	+91	583	+13	4.15	+1.26	41.85	+9.34	5.2
Southwest	48.4	-4.0	515	+118	574	+41	4.73	+2.12	38.88	+6.43	0.7
South Central	48.7	-3.6	505	+107	559	+30	3.79	+0.94	41.82	+7.75	2.5
Southeast	49.4	-4.2	484	+103	532	+40	2.45	-0.61	42.41	+8.15	4.3
STATE	47.1	-3.7	547	+104	628	+27	4.70	+2.09	38.77	+6.89	2.3

* Departures are computed from 1981-2010 normals.

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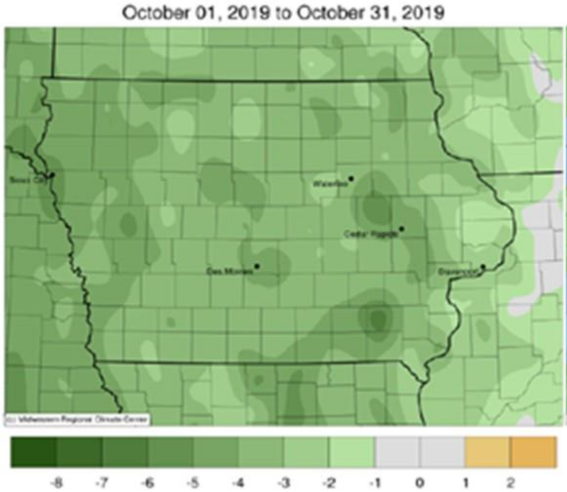
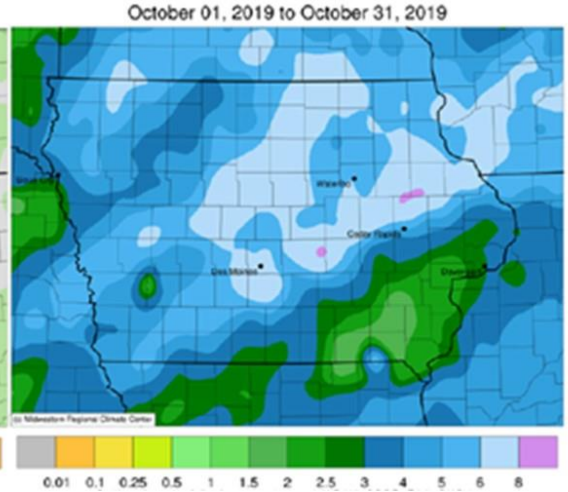
Average Temperature (°F): Departure from 1981-2010 Normals

October 01, 2019 to October 31, 2019



Accumulated Precipitation (in)

October 01, 2019 to October 31, 2019



Above: October precipitation in Iowa in 2019. Note: Most active corn harvest in Iowa occurs in October. Below: Iowa monthly weather summary: October 2019. Justin M. Glisan, Ph.D. Source: https://iowaagriculture.gov/climatology-bureau/monthly-weather-report