References for Ethanol Production and Sweet Sorghum Information

- National Sorghum Producers
- Oklahoma State University
- Texas A&M University
- US Department of Energy
- Nimbkar Agricultural Research Institute
- International Crops Research Institute for the Semi-Arid Tropics
- EcoPort Foundation
- Latin America Thematic Network on Bioenergy
- Chinese Academy of Science
- Food and Agriculture Organization of the United Nations
- US Grains Council
- Renewable Fuels Association
- ECHI-T Large Bio-ethanol Project from Sweet Sorghum in China and Italy
- Tamil Nadu Centre for Plant Breeding and Genetics
Objectives

• Summarize methods in which a portion of the sweet sorghum plant is used in ethanol production
• Highlight chemistry of the various portions of the sweet sorghum plant
• Review the basics of the ethanol production
• Compare current status of ethanol production in various locations around the world using sweet sorghum
Sweet Sorghum in the Field
Characteristics of Sweet Sorghum in India and China

- Can be grown in temperate climates
- “More Crop Per Drop” or “Camel of Crops” - Low irrigation needs of 1/2 that of maize and 1/3 that of sugarcane
- Low fertilizer needs
- Days to flowering: 75-85 days
- Days to maturity: 100-115 days
- Plant height: 280-340 cm
- Average cane weight: 380-528 g/plant
- Cane yield: 35-50 MT/ha
- Grain yield: 1,700-2,800 kg/ha
Comments from Others
(ICRISAT, 2006 & FAO, 2002)

• Sweet sorghum (SS) can grow like no crop has grown before: in drylands, acidic or basic soils, waterlogged fields
• SS grows faster than sugarcane, 200 days (2 crops) vs 365 days
• SS needs 4.5 times less water than sugarcane, 8,000 (2 crops) vs 36,000 cubic meters with no irrigation necessary
Comments from Others
(ICRISAT, 2006 & FAO, 2002)

- Cost of cultivation of SS is 3 times less than that of sugarcane.
- SS is easily planted, 5 kg of seeds/ha; sugarcane requires the handling of 5,000 cuttings.
- Ethanol production process from SS is eco-friendly; that from sugarcane is not.
- Ethanol from SS is better than from sugarcane for two reasons: it has lower sulphur content (is less polluting) and higher octane (yields more power).
Relative Amount of Each Part in a Sweet Sorghum Plant

- Kernels – up to 7%
  - Mainly starch (~60-65%)
- Stalk – up to 75%
  - Contains sucrose and cellulose
- Leaves – 10-15%
- Roots – ~10%
Glucose is Necessary for Ethanol Fermentation

\[ \text{C}_6\text{H}_{12}\text{O}_6 \xrightarrow{\text{Yeast}} 2 \text{CH}_3\text{CH}_2\text{OH} \quad \text{and} \quad 2 \text{CO}_2 \]
Where Does Glucose Come From?

- From kernel where polymers of starch are first hydrolyzed to disaccharides (maltose molecules) before further hydrolysis to monosaccharides of glucose molecules
- From juice in stalk (or stem) where disaccharides of sucrose molecules are hydrolyzed to monosaccharides of glucose and fructose (isomer of glucose) molecules
- From dry matter in stalk where polymers of cellulose are first hydrolyzed to disaccharides (cellubiose molecules) before further hydrolysis to monosaccharides of glucose molecules
Hexoses, mainly glucose and fructose, are converted to ethanol, CO₂ and other minor compounds by yeast cells following the pathway on the right.
Figure 3: Simplified Diagram of Alternative Processes to Convert Sweet Sorghum to Energy Fuel.
Source: Chiaramonti, et al.
Typical Grain Sorghum Field in US
Grain Sorghum Kernel
Facts Concerning Grain Sorghum

- Grain sorghum has greater amounts of long-chained fatty acids, alcohols and aldehydes than maize; its bloom
- Kernel structure of endosperm, germ and bran
- Starch granules embedded in protein matrix
- Components of cereal grains can be separated using various methods
- Most common physical methods used in ethanol production are:
  - Wet Milling (traditional method)
  - Dry Milling
  - *Dry Grind (most common nowadays)*
Portion of Kernel Used for Ethanol

Starch Granules

Cell Walls

SG

CW
Dry Grind Process Flow Diagram

Corn → Grain Receiving → Corn Meal → Mash Preparation → Corn Mash → Fermentation → Beer → CO₂ → Distillation 190 Proof Ethanol → Dehydration 200 Proof Ethanol → Product Storage → Denaturant Fuel Ethanol → Whole Stillage → Centrifugation Wet Grains → Dryer → DDG’s Storage DDG’s → Thin Stillage → Evaporation → Process Condensate Syrup → Source: American Coalition for Ethanol www.ethanol.org
Dry Grind Process Flow Diagram

Corn → Grain Receiving → Corn Meal → Milling

Milling → Corn Mash → Mash Preparation

Mash Preparation → Fermentation → Beer → Distillation

Distillation → Whole Stillage → Centrifugation → Thin Stillage → Process Condensate

Centrifugation → Wet Grains → Dryer → DDG's

Dryer → DDG's Storage → DDG's

DDG's Storage → Product Storage

Product Storage → Denaturant → Fuel Ethanol

Fermentation → CO₂

Source: American Coalition for Ethanol
www.ethanol.org
Milling

Whole kernels are ground to approximately 20 mesh or 0.85 mm in diameter
Dry Grind Process Flow Diagram

Corn
- Grain Receiving
- Corn Meal
- Corn Mash
- Fermentation → CO₂
- Beer
- Distillation → 190 Proof Ethanol
- Whole Stillage
- Centrifugation → Wet Grains
- Thin Stillage
- Evaporation
- Process Condensate

Mash Preparation
- Ammonia Enzymes

Liquefaction and Saccharification

Dehydration
- 200 Proof Ethanol
- Dryer
- DDGs
- DDGs Storage
- Source: American Coalition for Ethanol
- www.ethanol.org

Product Storage
- Fuel Ethanol

Denaturant

Source: American Coalition for Ethanol
www.ethanol.org
Liquefaction

An enzyme called alpha-amylase is used to break 1-4 linkages of starch polymer resulting in dextran polymers at 91°C and pH of 6.5
A second enzyme called glucoamylase is used to break 1-6 & 1-4 linkages moving along starch polymer releasing glucose molecules at 60°C and pH of 4.5
Dry Grind Process Flow Diagram

- Corn
  - Grain Receiving
  - Corn Meal
  - Mash Preparation
    - Corn Mash
  - Fermentation
    - CO₂
    - Ammonia Enzymes
    - Denaturant
      - Fuel Ethanol
      - Product Storage
        - DDG's Storage
          - DDG's
          - Syrup
        - Dryer
          - Wet Grains
          - 200 Proof Ethanol
        - Dehydration
          - 190 Proof Ethanol
          - Distillation
            - Whole Stillage
            - Thin Stillage
            - Process Condensate

Source: American Coalition for Ethanol
www.ethanol.org
Fermentation

Saccharomyces cerevisiae (yeast) cell with bud working at 34°C and pH of 4.5
Dry Grind Process Flow Diagram

Corn

Grain Receiving

↓ Corn Meal

Mash Preparation

↓ Corn Mash

Fermentation

↓ Beer

Distillation

↓ Whole Stillage

Centrifugation

↓ Thin Stillage

Evaporation

↓ Process Condensate

Ammonia Enzymes

→ CO₂

190 Proof Ethanol

Dehydration

200 Proof Ethanol

Product Storage

Denaturant

Fuel Ethanol

DDGs

DDGs Storage

Source: American Coalition for Ethanol
www.ethanol.org
Aqueous ethanol (95%) is separated from “beer” by vaporizing it at 78°C in a column with numerous plates and then condensing the ethanol vapors that come over.
Dehydration

Removal of residual water in 95% ethanol to increase ethanol content to 100% using a preferential absorbing apparatus known as a molecular sieve.
Dry Grind Process Flow Diagram

Corn → Grain Receiving → Corn Meal → Corn Mash → Mash Preparation → Ammonia Enzymes

Fermentation → CO₂ → Beer → Distillation → 190 Proof Ethanol → Dehydration → 200 Proof Ethanol → Product Storage → Denaturant → Fuel Ethanol

Distillation → Whole Stillage → Centrifugation → Wet Grains → Dryer → DDGS → DDGS Storage

Evaporation → Process Condensate → Syrup
Denaturing

Blending of 100% ethanol with up to 5% gasoline to render the fuel ethanol undrinkable
Dry Grind Process Flow Diagram

Corn
- Grain Receiving
  - Corn Meal
  - Mash Preparation
    - Ammonia Enzymes
    - Corn Mash
  - Fermentation
    - CO₂
    - Beer
- Distillation
  - 190 Proof Ethanol
  - Whole Stillage
- Centrifugation
  - Wet Grains
  - Thin Stillage
- Evaporation
  - Process Condensate
  - Syrup
- Dehydration
  - 200 Proof Ethanol
  - Dryer
  - DDGS Storage
- Product Storage
  - Denaturant
  - Fuel Ethanol

Co-product Processing

Source: American Coalition for Ethanol
www.ethanol.org
Co-product Processing

- Spent beer or whole stillage is pulled off bottom of distillation column
- Centrifugation separates wet distillers grains from remaining solubles in aqueous solution
- Wet distillers grains can be dried and solubles can be concentrated
- CO$_2$ is captured
Grain Used in Ethanol Production in 2007 in US

- 12-18% of all maize and grain sorghum is used for ethanol production
- >85 million metric tons of maize
- >1.2 million metric tons of grain sorghum
Grain Sorghum Production in South America
Grain Sorghum Production in Colombia

Histórico de Producción (1950-2006)
2007 US Ethanol Plants

Biorefineries in Production (115)

Biorefineries under Construction (79)

Source: Renewable Fuels Association
4.3.07
2007 Nebraska Ethanol Plants

Source: http://www.ne-ethanol.org/industry/ethplants.htm
Refinement of Process Technology

- In 1982, it was considered good to produce a gallon of ethanol using 55,000 Btu with capital costs of $2.25/gal of annual production
- In 2004, on average, a gallon of ethanol can be produced for 30,000 Btu with capital costs of <$1.25/gal of annual production
- Refinement came from improvements in process efficiency and greater return from increased used of by-products
Figure 3: Simplified Diagram of Alternative Processes to Convert Sweet Sorghum to Energy Fuel.
Source: Chiaramonti, et al.
Sugarcane Method for Ethanol Production from Sweet Sorghum

• Presently a 5.7 million L/year facility is under construction in Louisiana to use sugarcane
Enzymatic Hydrolysis of Sucrose in Sweet Sorghum Juice

Source: U.S. Department of Energy Genome Program's Genome Management Information System (GMIS)
Mechanical Seeding in China of Sweet Sorghum
Sweet Sorghum Stalk Cutting and Hauling from Field
Sugarcane Method for Ethanol Production from Sweet Sorghum

• Presently a 5.7 million L/year facility is under construction in Louisiana to use sugarcane
In-Field Stationary Press for Sweet Sorghum
Centrally-Located Sweet Sorghum Presses
Pressed Sweet Sorghum Juice
Productivity and Quality of Sweet Sorghum Juice in China and India

• Quality of juice is slightly inferior to sugarcane
• Trash content is high due to crushing leaves and stalks
• High fiber in juice up to 21.17%
• 14-20% directly fermentable sugar (i.e. no starch to convert)
• Juice extractability: 40-50%
• Brix: 16°-19°
• Total soluble solids: 13-15.2%
• Reducing sugars: 1.3-2.1%
• Sucrose: 9.6-13.6%
• Ethanol yield: 2,500-4,000 L/ha
Sugarcane Method for Ethanol Production from Sweet Sorghum

- Presently a 5.7 million L/year facility is under construction in Louisiana to use sugarcane
Fermenters Used in China
Fermentation

Saccharomyces cerevisiae (yeast) cell with bud working at 34°C and pH of 4.5
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Distillation

Aqueous ethanol (95%) is separated from “beer” by vaporizing it at 78°C in a column with numerous plates and then condensing the ethanol vapors that come over.

Ethanol

Spent Beer
Or Whole Stillage
Dehydration

Removal of residual water in 95% ethanol to increase ethanol content to 100% using a preferential absorbing apparatus known as a molecular sieve
Denaturing

Blending of 100% ethanol with up to 5% gasoline to render the fuel ethanol undrinkable.
Table 1. Potential Ethanol Yield (L/ha) from Sweet Sorghum Juices of Different Sugar Contents

Source: Bellmer and Huhnke, 2006

<table>
<thead>
<tr>
<th>Biomass Yield (metric tons/ha)</th>
<th>Sorghum Juice Sugar Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>56.25</td>
<td>3,357</td>
</tr>
<tr>
<td>78.75</td>
<td>4,703</td>
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<tr>
<td>101.25</td>
<td>6,040</td>
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</tbody>
</table>

Assumes 0.65 juice expression ratio and 95% conversion efficiency
Fermentation of Sweet Sorghum Juice in Field

On-Farm

- Juice → Fermentation → Distillation
  - Heat Energy
  - Bagasse → Silage
  - Field Residue

Central Facility

- Dehydration

Sorghum → Press
In-Field Fermentation Studies by Oklahoma State University

• Production Yields for Sweet Sorghum in OK
• Potential Harvest Window in OK
• Feasibility of In-Field Pressing and Fermentation
• Full/Partial On-Farm Distillation
Mechanical Cutting of Sweet Sorghum Stalks
Stalk Sugar Content over 5-Month Harvest Period at 4 Locations
In-Field Stalk Crushing Rolls
Typical In-Field Fermentation in OK

Superstart Distillers Yeast/pH5.4/NoUrea

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Total Sugar (g/L)</th>
<th>Ethanol (g/L)</th>
<th>Cell Count (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>161.52</td>
<td>0.01</td>
<td>0.54</td>
</tr>
<tr>
<td>24</td>
<td>107.16</td>
<td>9.93</td>
<td>1.56</td>
</tr>
<tr>
<td>48</td>
<td>60.70</td>
<td>33.90</td>
<td>3.52</td>
</tr>
<tr>
<td>72</td>
<td>33.45</td>
<td>56.17</td>
<td>6.07</td>
</tr>
<tr>
<td>96</td>
<td>11.92</td>
<td>68.54</td>
<td>5.76</td>
</tr>
<tr>
<td>120</td>
<td>0.00</td>
<td>76.95</td>
<td>6.36</td>
</tr>
</tbody>
</table>

Biomass, g/L
In-Field Fermentation Results

- Yeast cells were able to ferment sugars at extreme temperatures
- Reducing pH had no significant effect on ethanol yield
- Ethanol yield was not significantly affected by use of added urea
Remaining Questions for In-Field Ethanol Production

- Availability of in-field harvester/press
- Timely inoculum and acid addition
- Cycling and re-use of fermentation tanks and bladders
- Feasibility of on-farm ethanol dewatering, either fully or partially
Figure 3: Simplified Diagram of Alternative Processes to Convert Sweet Sorghum to Energy Fuel. 
Source: Chiaramonti, et al.
### Bagasse Remaining after Pressing

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>15-25%</td>
</tr>
<tr>
<td>Lignin</td>
<td>20-30%</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>35-50%</td>
</tr>
<tr>
<td>Ash</td>
<td>8-10%</td>
</tr>
</tbody>
</table>
Pretreatment Needed to Release Bagasse Components
Hydrolysis in Cellulosic Ethanol Production

Fragment of a cellulose molecule

Glucose

Celllobiose

Alternating glucose residues are in an inverted orientation so the celllobiose (a disaccharide) is the repeating structural unit.
1. Biomass is harvested and delivered to the biorefinery.

2. Biomass is cut into shreds and pretreated with heat and chemicals to make cellulose accessible to enzymes.

3. Enzymes break down cellulose chains into sugars.

4. Microbes ferment sugars into ethanol.

5. Ethanol is purified through distillation and prepared for distribution.
Status of US Cellulosic Conversion

• The Iogen Corporation (Ottawa, ON) currently produces more than 4 million liters annually of ethanol from wheat, oat and barley straw in its facilities.

• Several existing ethanol plants in the US are engaged in R&D projects with the US DOE utilizing the existing fiber in their facilities (e.g. Abengoa Bioenergy which uses sorghum).
Status of US Cellulosic Conversion

• Enzyme companies including Genencor International and Novozymes have led successful research projects with the US DOE to significantly reduce enzyme cost and increase enzyme life and durability

• Continued advancements in pretreatment technology, fermentation, and collection and storage logistics, the commercial production of cellulosic ethanol becomes more economical
Hemicellululosic Ethanol Production Remains Elusive

Hemicellulose hydrolyzes to xylose (a pentose) but is unfermentable by S. cerevisiae
Other Potential Sweet Sorghum Processing Scenarios

- Harvest entire crop with forage harvester, transport to central facility for pressing of juice and cellulosic conversion
- Utilize sorghum as a supplemental, seasonal feedstock in an existing grain ethanol facility; particularly for regions with very short harvest window
- Consider non-fermentation methods such as the MixAlco process
**Texas A&M MixAlco Process**

**Figure 4:** Schematic of the MixAlco Process  
How Much Ethanol Can We Get? Where Does It Come From?

**Figure 3:** Simplified Diagram of Alternative Processes to Convert Sweet Sorghum to Energy Fuel.
Source: Chiaramonti, et al.
Ethanol from *Sweet Sorghum Juice*

- Potential yield according to reports – 80-100 metric tons/ha
- Longer maturity yield surpasses 100 metric tons/ha
- Typical ethanol yields found through various research projects
  - 2,640 L/ha Brazil
  - 7,000 L/ha China *(includes grain?)*
  - 3,000 L/ha South Africa
  - 4,790 L/ha USA
  - 3,500 L/ha India
Yearly production of different products from 1 ha of Sweet Sorghum:

- Sweet sorghum: 75-100 T
- Stripped stalks: 60-80 T
- Grain: 2-4 T
- Leaves: 5-7 T (dry)
- Bagasse: 15-20 T (dry)
- Char: 4-5.4 T
- Fermentation:
  - Juice: 30-40 T
  - Effluent: 36-37 T
- Distillation:
  - Ethanol: 3000-4000 l (95% v/v)

- Biomass Gasification System:
  - Used as:
    - Soil conditioner
    - Briquetted fuel

- Flour mill:
  - Flour for bread
Sweet Sorghum Ethanol Facilities Planned for China

• Under its recently announced *Agricultural Biofuel Industry Plan*, the Chinese government said that 3.8 million metric tons of ethanol will be produced each year (4.6 billion L/yr) from the stalks of the sweet sorghum.

  – Under construction are a 490 kL/day pilot demonstration facility at the China Agriculture Engineering Institute in Anqiu City, Shandong Province and a 5,000 kL/day commercial demonstration facility in Huachuan County, Heilongjiang Province.

  – Other facilities are planned for the Hebei Province and the Mongolian and Xinjiang Regions.
Shandong Province Facility

Multi-stage solid fermentation equipment

Mixing of the fermentation bacteria cocktail
Rusni Distilleries Pvt, Ltd. in Hyderabad, India

ICRISAT works closely with Rusni to deliver on sweet sorghum's promise.
<table>
<thead>
<tr>
<th>Requirements</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol day(^{-1}) (kl)</td>
<td><strong>35-40</strong></td>
</tr>
<tr>
<td>SS stalks required day(^{-1}) (t)</td>
<td>800-875</td>
</tr>
<tr>
<td>Stalks required for 105 days (t) per season</td>
<td>84000-91875</td>
</tr>
<tr>
<td>Area required (rainy season) ha</td>
<td>2300-2600</td>
</tr>
<tr>
<td>Area required (postrainy season) ha</td>
<td>3700-4200</td>
</tr>
<tr>
<td>Total sweet sorghum area required (ha)</td>
<td>6000-6800</td>
</tr>
<tr>
<td>No. of small farmers(^1) to be involved</td>
<td>3000-3400</td>
</tr>
</tbody>
</table>

1. Small farmers: 2 ha holdings in India. Source: Rusni Distilleries.
Solar Powered Ethanol Facility at Nimbkar Ag Research Institute

- In Maharashtra, India
- Operates at 30-40 L/day
Current Problems to Address

- Transportation of materials from field to central processing facility
- Undesired bacterial fermentation in field
- Methods to limit lactic acid formation
- Methods for adjust pH to 4.3 and add yeast inoculum while in field
- Feasibility to squeeze and ferment on small scale and deliver ethanol or fermentation liquor to central facility
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Relavant Publications

Training Manual
For Sweet Sorghum
Under the FAO Project TCP/CPR/0066
Thanks for the Invitation and Support from