

Biological and Economic Feasibility of Pearl Millet as a Feedstock for Ethanol Production

J.P. Wilson, A.J. McAloon, W. Yee, J. McKinney, D. Wang, and S.R. Bean

Pearl millet (*Pennisetum glaucum* L.R. Br., Poaceae) has its origins as a cereal crop adapted to the harshest growing conditions in sub-Saharan Africa. Although currently used as a forage and cover crop in many regions of the US, Brazil, Australia, and Canada, grain hybrids have attributes that are of value in production systems of the southeastern United States. Successful integration of pearl millet into regional cropping systems requires identifying applications in which pearl millet has advantages compared to alternatives.

'Tifgrain 102' pearl millet is compatible in double-cropping systems in the southeast, and is resistant to nematodes that affect cotton and peanut, the region's mainstay crops (Timper and Hanna 2005). As a species of desert origins, it is inherently drought tolerant and adapted to acidic, sandy soils with low fertility characteristic of the southern Coastal Plain. The high quality grain is not prone to preharvest aflatoxins and fumonisins in dryland production (Wilson et al. 2006), and is proving to be a superior grain in rations for game birds in the recreational wildlife industry and for broiler production. Diversified marketing options will help growers secure a more stable price for their product.

One such market that has received little attention is the bioenergy industry. The development of the ethanol industry in the southeastern US has been limited by the amount of maize and other feedstocks produced in the region. As new facilities are being planned, information is needed on other potential feedstocks that might supplement maize grown locally or shipped in from other regions. Wu et al. (2006) have demonstrated that pearl millet might be a useful feedstock for ethanol production. These present studies were conducted to confirm prior research and to further assess the economic feasibility of using pearl millet as a supplemental feedstock.

MATERIALS AND METHODS

Fermentation Analysis

Fermentation experiments were conducted to assess the biological feasibility of using pearl millet as a feedstock. Experimental pearl millet cultivar '2304' was harvested from the 2005–2006 winter nursery grown in Juana Diaz, Puerto Rico.

The sample preparation, liquefaction, saccharification, and fermentation procedure used was a modified version of that used by Lemuz et al. (2005). Maize grain, variety unknown, was cleaned over a 12/64" RH screen to remove broken corn and foreign material. Pearl millet '2304' was used as received from Puerto Rico. Three hundred grams of maize were ground using a Romer 2A mill (Romer Labs, Union, Missouri) set as described in the manufacturer's operating instructions with the adjustment lever set to the finest grind setting. Three 300 g samples of pearl millet were ground in different manners. The first was identical to the maize setting, the second with the Romer 2A mill set at the coarsest setting, and the third using a Retsch ZM200 centrifugal mill (Retsch, Inc, Newtown, Pennsylvania) equipped with a 1 mm sieve. The Retsch produced the finest grind of the three methods. The coarse setting of the Romer mill was the coarsest, with some whole grain observed in the sample after grinding. The fine setting of the Romer mill was intermediate, with no intact grain. Moisture concentration of the samples was determined according to AACC Method 44-15A using approximately 2 g of ground sample heated at 130°C for 60 min.

Four flasks were used for the fermentation, while the fifth was a check flask for pH and temperature measurement. Twenty-five grams of each test material was added to each of the four 125 mL Erlenmeyer flasks used for fermentation, preweighed to the 0.1 mg, and also to the fifth flask with no weight recorded. The filled test flasks were again weighed accurately to 0.1 mg. Then, 75 ml of deionized water was added to the flasks, followed by gentle swirling to suspend the ground material with minimal adhesion to the flask wall to which 275 µL of diluted (1:10 by volume with deionized water) SPEZYME® FRED (Lot number 107-04143-001) alpha-amylase enzyme (Genencor International, Inc., Rochester New York) were added and flasks swirled by hand to mix. The pH of the slurry of the check flask for each sample was measured at this point using a calibrated electronic pH meter.

A thermocouple probe was placed in one of the check flasks. Flasks were placed in a hot water bath to achieve a temperature of 90–94°C with intermittent gentle swirling by hand during the heating process to prevent clumping of the gelatinizing material. The rise time to 90°C was approximately 30 min. The liquefaction process was allowed to continue for 60 min after reaching 90°C. At the end of this time, samples were removed from the hot water bath and cooled in cold tap water to less than 40°C.

Yeast (*Saccharomyces cerevisiae*) inoculum suspension was prepared by adding 7.2 g of Fleischmann's active dry yeast (ACH Food Companies, Inc., Memphis, Tennessee) to 100 mL of deionized water at room temperature (approx 24°C), then adding 100 ml of deionized water at 40°C. Inoculum was then placed in a shaking incubator set at 40°C for 1 hr and used soon thereafter.

The pH of the cooled check flasks was recorded again. Diluted hydrochloric acid [one part certified 37% HCl (Fisher Scientific, Hanover Park, Illinois):four parts deionized water by volume] was added to bring the pH to between 4.5 and 5.0. The required volume of the HCl solution was usually 325 μ L.

The required amount of acid for each sample was then added to each test flask and swirled by hand to mix. A solution consisting of 12.0 g of ammonium sulfate [(NH₄)₂SO₄] (Fisher Scientific, Hanover Park, Illinois) in 100 mL deionized water was prepared. Four hundred μ L of the ammonium sulfate solution was added to each test flask as a nitrogen source. Two hundred μ L of diluted (1:10 by volume with deionized water) G-ZYME® 480 (Lot number 107-04246-002) glucoamylase enzyme (Genencor International, Inc., Rochester New York) were added to the flasks and swirled by hand to mix.

Five mL of yeast inoculum (prepared earlier) was added to each test flask and swirled gently to mix. The residue on the wall of the flask was scraped into the slurry using a disposable weighing spoon. Minimal deionized water was used to rinse the weighing spoon for each flask. Flasks were plugged with a rubber stopper vented with an 18 gauge 1.5" single-use syringe needle (Becton Dickinson and Company, Franklin Lakes, New Jersey). The flasks with stoppers were immediately weighed to the 0.1 mg and placed in a shaking incubator at 32°C. Flasks were removed briefly, weighed, and replaced in the incubator after fermentation times of 18, 24, 40, 48, and 64 hr. Weight loss (as CO₂) was converted to grams of ethanol produced by multiplying by a factor of 1.0468. The sample weight and moisture concentration were used to convert ethanol yield to gallons of anhydrous ethanol per standard bushel of grain.

After final weighing, flasks were placed in a boiling water bath to evaporate off most of the ethanol. The stillage was then dried to a wet cake at 130°C, and then dried further at 50°C. Samples of the resulting dried distillers grains with solubles (DDGS) were analyzed for concentrations of protein, fat, crude fiber, ash, and moisture.

Economic Feasibility Analysis

The economic feasibility of using pearl millet as a feedstock was compared to maize (*Zea mays* L.) by using the Superpro Designer Dry Grind model (Kwiatowski et al. 2006). This process and cost analysis simulates the costs associated with the production of fuel ethanol, as affected by the composition of raw materials entering the process. These analyses used the assumption that pearl millet grain composition was 68.4% starch, 11.1% protein, 6.6% fat, 1.4% fiber, and 1.7% ash at 10.8% moisture. These values are the average composition of four pearl millets previously analyzed (Wu et al. 2006). The maize composition was assumed to be 59.5% starch, 8.3% protein, 3.4% fat, and 15% moisture content. For these analyses, the cost of maize was assumed to be \$2/bushel (\$0.078714 kg⁻¹). The cost of pearl millet as a feedstock was assumed to be 10% greater than maize. Other variables used in the model include the sizing of equipment, utility consumption, operating costs, capital costs required for a facility with a 151 million L per year capacity. Revenue was estimated based on the July 2006 market value of ethanol (\$0.65 kg⁻¹). Value of DDGS was valued at \$0.07 kg⁻¹ for maize and \$0.11 kg⁻¹ for pearl millet due to its higher protein content.

An additional source of cost savings from using pearl millet as a feedstock is in the cost of electricity required to grind the grain. In the process and cost analysis, 369,678 tonnes (t) of maize and 319,572 t of pearl millet were required for the desired plant output. Electricity requirements to grind maize and pearl millet (Dozier et al. 2005) and data for average retail price of electricity for industrial use in July 2006 (EIA 2006) was used to calculate net energy costs for grinding maize and pearl millet.

RESULTS AND DISCUSSION

Fermentation Analysis

Final ethanol yield from fermentation of pearl millet was about 8% less than the yield from maize (Fig. 1). Pearl millet fermented more quickly and reached 85% fermentation approximately 12 hr earlier than the maize treatment (data not shown), which confirms the earlier findings of Wu et al. (2006). There was no difference in ethanol yield or fermentation efficiency between the samples ground by the Retsch or the fine ground Romer samples. Yield and efficiency obtained by fermenting the coarse Romer samples were lower, likely due to the intact grain observed in these samples.

On an as-is basis, the DDGS from pearl millet had 6% lower moisture compared to DDGS from maize. On a dry basis, the DDGS from pearl millet had 16% greater protein, 53% greater fat, 45% higher ash, 19% lower crude fiber, and 20% lower nitrogen-free extract content compared to DDGS from maize (Table 1). These values are similar to data observed in an earlier study (Wu et al. 2006).

Economic Feasibility Analysis

The process and cost analysis estimated that the greater protein content of pearl millet would result in a greater protein content in the DDGS, and a 13% greater DDGS value income compared to maize DDGS. We assumed that the market value of the DDGS from pearl millet would be based solely on its protein content. The

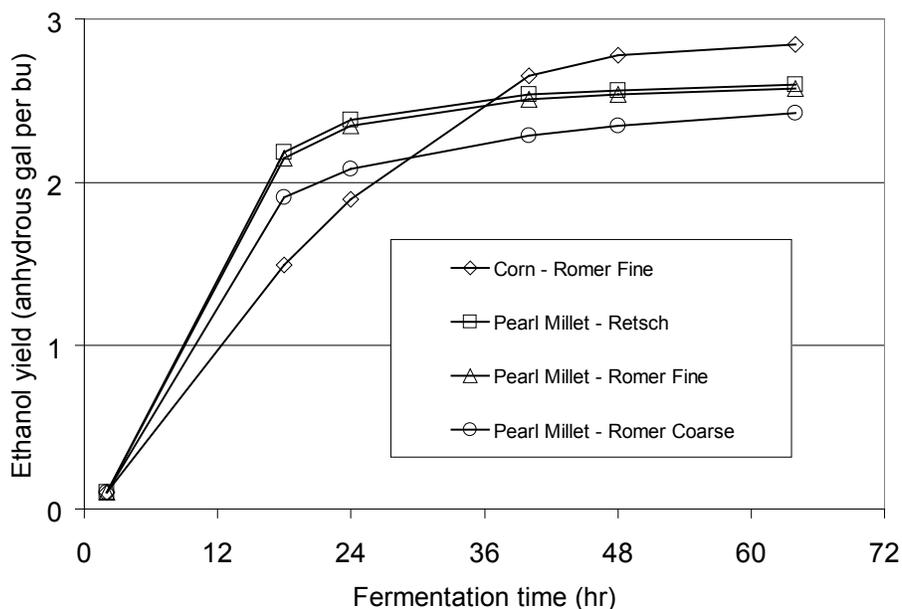


Fig. 1. Ethanol yield from pearl millet subject to three grinding treatments, and a maize standard.

Table 1. Composition² of distillers dried grains with solubles (DDGS) derived from fermented pearl millet and maize.

Feedstock	Protein (%)	Fat (%)	Crude fiber (%)	Ash (%)	Moisture (%)
Pearl millet	30.5	16.4	5.9	5.5	11.8
Maize	26.2	10.7	7.3	3.8	12.5

²Moisture values are as-is basis, proximate composition are on a dry basis. Proportions not accounted for are the nitrogen-free extract consisting of carbohydrates, sugars, starches, and hemicellulose.

process and cost analysis also estimated that the greater fat content of pearl millet would result in a greater fat content of the DDGS. This higher fat content was accounted for in the process and cost analysis, but did not enter into determining the DDGS value. The higher fat content in the DDGS might have advantages in some markets.

Within the limitations of this preliminary process and cost analysis, the results suggest that even with a 10% premium on the cost of pearl millet, the net cost of ethanol production is \$0.016 per L less than production using maize. Total net profit from a facility using pearl millet as the sole feedstock was \$25,175,000 per year compared to \$23,758,000 for maize feedstocks, a \$1.4 million advantage. Pearl millet with different compositions would produce different results.

Two additional sources of savings not captured in the process and cost analysis are the lower energy requirements to grind pearl millet, and a potentially faster batch processing allowed by the faster fermentation rate. Grinding rate of pearl millet is 53% faster and requires 40% less energy to grind than maize (Dozier et al. 2005). For grain quantities indicated by the process and cost analysis, electricity costs can be reduced an additional \$20,200 because of the lower energy requirements to grind pearl millet. The economic benefit of the faster fermentation rate could be significant, but may be difficult to capture if pearl millet is used as a supplement, rather than a principle feedstock. If pearl millet is used as a sole feedstock, analyses suggest the faster fermentation could increase gross returns by 25% (Wilson et al. in press).

Biologically and economically, pearl millet is a feasible supplemental feedstock for dry-grind maize-to-ethanol facilities in the southeastern US. Research to support profitable cropping systems that supply an adequate supply of feedstock are needed. Regionally grown pearl millet should benefit rural economies in the southeast that are planning to import feedstock for ethanol production.

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