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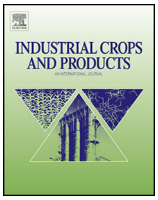

Agronomic productivity, bioethanol potential and postharvest storability of an industrial sweetpotato cultivar

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ABSTRACT

An industrial sweetpotato cultivar, CX-1, offers several advantages as an alternative crop for bioethanol production, including high agronomic productivity and high starch content as well as viable coproducts for additional bioenergy recovery. A two-year agronomic field trial resulted in a root yield of 12.3 dry $\mathrm{t\,ha^{-1}}$ after optimization of planting strategy and improved site drainage. Starch content (73.5% dry matter (DM) for Year 1 and 72.1% DM for Year 2) exceeded that of any other industrial variety grown in the Southeastern USA. In contrast to other industrial cultivars, starch concentrations were maintained over a six-month storage period, making this a favorable year-round feedstock. The bioethanol potential of the CX-1 ($4.2\,\mathrm{t\,ha^{-1}}$ or $5300\,\mathrm{L\,ha^{-1}}$) was determined based on the conversion of CX-1 dry biomass into ethanol by simultaneous saccharification and fermentation combined with the agronomic root yield from the Year 2 field trial. The cull rate was 36% of the overall root yield, as determined based on United States Department of Agriculture culinary grades. However, assessment of the culls from an industrial processing perspective would significantly reduce the cull rate. Approximately 45% of the culls were classified as cull material (i.e. secondary rootlets) that could feasibly be converted into ethanol. The remaining 55% of the culls could be used for biogas recovery to offset the energy required to produce ethanol from sweetpotatoes.

1. Introduction

Industrial sweetpotatoes (*Ipomoea batatas* L.) are a high-yielding crop that can be grown on marginal lands and used in the production of bioethanol. Sweetpotatoes thrive in tropical to sub-tropical climates and are known for their resistance to extreme weather conditions such as droughts and flooding. Minimal fertilization, irrigation and weed control favor this crop as a sustainable agricultural system; however, cultivation and harvesting practices need further mechanization and improvement. Industrial sweetpotato cultivars can be differentiated from standard table varieties by their high dry matter (DM) and starch content (Mussoline and Wilkie, 2015). A life cycle assessment (LCA) that evaluated all agronomic and biotechnological aspects of converting an industrial sweetpotato into ethanol resulted in a positive net energy ratio of 1.48 and a net energy gain of $6.55\,\mathrm{MJ\,L^{-1}}$ (Wang et al., 2013). Thus, from agronomic and energetic perspectives, industrial sweetpotatoes are a viable alternative crop for bioethanol production.

Corn (maize, *Zea mays* L.) is currently the primary feedstock for bioethanol production, despite its limited agronomic productivity in warm climates. Approximately 60% of the world's ethanol is produced in the USA (Renewable Fuels Association, 2015) and 90% of US biorefineries use corn as a feedstock (Ethanol Producer Magazine, 2015). Corn, however, has limitations as an ethanol feedstock, particularly with regard to agronomics and land-use controversies. In warmer climates such as the Southeastern USA, sweetpotatoes had twice the bioethanol yields than corn primarily due to superior agronomic yields (Ziska et al., 2009). From a societal perspective, corn is a staple food that has a dominant nutritional role in most of the world's diet and its use as an energy crop is controversial. In China, for example, recent regulations have directed the ethanol industry toward non-grain-based feedstocks (Qui et al., 2010). This decision was largely motivated by food security issues, but reduced greenhouse gas emissions ($263{,}000\,\mathrm{t}$ CO_2 predicted

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for 2015) was found to be an important environmental benefit of using sweetpotatoes rather than grain-based feedstocks (Li et al., 2010). Of the non-grain-based feedstocks considered (namely sweet sorghum (*Sorghum bicolor* (L.) Moench), cassava (*Manihot esculenta)*, molasses, agricultural straw and sweetpotato), sweetpotato was also the most economical (3840 Yuan t^{-1}) for bioethanol production (Li et al., 2010). Thus, in addition to the agronomics, the industrial sweetpotato has a socioeconomic advantage as an alternative crop for bioethanol production.

The process of converting starch into bioethanol is a well-established technology that involves the following steps: 1) gelatinization or solubilization of the starch molecules; 2) liquefaction or the conversion of long-chain glucose polymers into dextrins; 3) saccharification or the hydrolysis of dextrins to fermentable sugars; 4) fermentation or the conversion of sugars into alcohol and carbon dioxide using yeast; and 5) distillation or the concentration of the alcohol through evaporation and condensation. The initial gelatinization of starch requires a certain temperature that is best determined by the ratio of linear starch polymers (amylose) to branched starch polymers (amylopectin) (Power, 2003). Common corn and sweetpotatoes have relatively the same proportion of amylose (20 to 25%) to amylopectin (75 to 80%) and thus the optimal gelatinization temperature will be essentially the same (Power, 2003; Walter et al., 2000). Once the starch is gelatinized into a highly viscous liquid, hydrolysis is carried out by two specific enzymes, namely *α-amylase* (liquefaction) and *amyloglucosidase* (saccharification) (Power, 2003). The enzymatic hydrolysis is the only additional step required for starch feedstocks compared with sugar feedstocks, but these procedures are common in the biorefinery industry. Lignocellulosic feedstocks, such as corn stover and sugarcane bagasse, can also be converted into fuel ethanol; however, the pretreatment required for these feedstocks is often energy intensive and cost prohibitive (Wilkie et al., 2000).

Another benefit of the industrial sweetpotato crop is the associated coproducts, including aerial vines, culls and stillage, that can be used to produce substantial quantities of biogas via anaerobic digestion (Mussoline and Wilkie, 2015). As determined by LCA, the most significant improvement for converting sweetpotatoes to ethanol was displacing the fossil fuels used to generate steam with a cleaner-burning fuel such as natural gas (Wang et al., 2013). Biogas from the coproducts can be used directly to heat boilers and generate the steam for the distillation process. Successful bioenergy recovery and utilization from sweetpotato distillery waste in the Shochu industry has been demonstrated (Kanai et al., 2010; Kobayashi et al., 2014). The energy recovery from the coproducts not only reduces fossil fuel demand and associated greenhouse gas emissions, but also promotes the industrial sweetpotato as a new potential feedstock for advanced biofuels that could be considered under the US EPA's Renewable Fuel Standard Program (USEPA, 2015).

The objectives of this research were to determine the agronomic yield, starch content, bioethanol yield, and postharvest storability of a newly developed industrial sweetpotato. The CX-1 has a light yellow flesh color and was specifically selected for fuel ethanol production because of its high DM and starch content. Roots with high DM content promote more efficient handling processes including harvest, transport, curing and storing, and contain a higher starch content (Hall and Smittle, 1983; Hamilton et al., 1986; Martin and Jones, 1986). Site conditions and planting strategies were established during a preliminary trial in Year 1 and optimized agronomic yields are reported for Year 2. As part of the agronomic study, cull rates were determined to quantify the biomass that would be available for bioenergy recovery processes. Definitions of culls based on culinary practices were used; however, further delineation of the culls for industrial processing is discussed. Carbohydrate concentrations were determined for the roots and feedstock-specific ethanol yields were combined with agronomic yields to determine the bioethanol yield in tonnes per hectare ($t\,ha^{-1}$). Finally, the postharvest storability of the CX-1 industrial sweetpotato was investigated in order to assess its potential for utilization as a year-round ethanol feedstock.

Table 1
Classification used for grading sweetpotato roots.

Grade	Diameter (cm)	Length (cm)	Fresh Weight (kg)
No. 1	4.5 to 9.0	7.6 to 23.0	<0.6
No. 1 petite	3.8 to 5.7	7.6 to 18.0	ND
No. 2	>4.0	ND	0.6 to 1.0
Jumbo	ND	ND	1.0 to 3.0

Source: Johnson et al., 1992; USDA, 2005.
ND – Not defined.

2. Materials and methods

2.1. Agronomic field trials

An exploratory field trial was conducted in Gainesville, Florida (29° 37′ 38.32″ N, 82° 21′ 40.37″ W) from June to December 2014 (referred to herein as Year 1), to optimize the planting strategy and site conditions for the industrial CX-1 sweetpotato crop. Plant material was propagated in South Carolina and provided by CAREnergy, LLC, North Charleston, South Carolina, USA. Rooted plants were established in trays for 30 days prior to planting while non-rooted cuttings were stripped from recently harvested vines and planted directly in the ground. A total of 96 rooted plants and 96 non-rooted cuttings were initially planted in two plots on 6 June 2014. Each plot consisted of three replications of raised beds with an inter-row plant spacing of 30 cm. Raised beds were 50 cm wide by 30 cm high and formed on 1-m centers. The beds were oriented in a North-South direction. The soil type was a loamy Blichton sand, gently sloping and somewhat poorly drained (USDA, 2013). A compound fertilizer (N:P:K 6:6:6) was applied at a rate of 88.5 kg N ha^{-1}. Total rainfall was measured onsite during the growing season and no additional irrigation was applied.

A second field trial was conducted in the same location in the following year (2015), which is referred to herein as Year 2. During the Year 2 field trial, the initial planting material consisted of rooted plants only and the rows were oriented in an East-West direction rather than the previous North-South direction to promote better soil drainage. All other experimental conditions remained the same. There was some variation in climatic conditions such as rainfall and temperature.

The roots from both the Year 1 and Year 2 field trials were harvested by hand, 182 days after planting (DAP). The roots were graded by hand and weighed fresh in the field immediately following harvest. The roots were graded into four categories, namely No. 1, No. 1 petite, No. 2, and Jumbo, as defined in Table 1 (Johnson et al., 1992; USDA, 2005). Although not defined by the United States Department of Agriculture (USDA) for marketable sweetpotatoes, the Jumbo category is necessary to classify industrial sweetpotatoes since they can be larger than edible varieties. Root yields were determined on both a fresh matter and DM basis.

Culls from both Year 1 and Year 2 were separated by hand during the harvest. According to the USDA, a cull is defined as a root with evidence of soft rot, black rot, internal discoloration, bruises, cuts, growth cracks, damage from insects such as sweetpotato weevil or wireworm, or other diseases (USDA, 1997). Cull material includes fragments, root crowns, and secondary rootlets (USDA, 1997). Culls and cull material were separated from the graded roots and weighed to determine the cull rate for both years.