Research Article

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Feed and fuel: the dual-purpose advantage of an industrial sweetpotato

Wendy A Mussoline and Ann C Wilkie*

Abstract

BACKGROUND: Sustainable agricultural systems must support nutritional requirements, meet the energy demands of a growing population, preserve environmental resources and mitigate climate change. The sweetpotato (*Ipomoea batatas* L.) is a high-yielding crop that requires minimal fertilization and irrigation, and the CX-1 industrial cultivar offers superior potential for feed and fuel.

RESULTS: CX-1 had the highest agronomic fresh vine yield (51.5 t ha^{-1}), averaged over two cropping seasons, compared with Hernandez (33.7) and Beauregard (21.8) varieties. CX-1 vines were more nutritional than the table varieties, specifically in regard to relative feed value (205), water-soluble carbohydrates (171 g kg^{-1} dry matter (DM)), total digestible nutrients (643 g kg^{-1} DM), metabolizable energy (10.2 MJ kg^{-1} DM) and organic matter digestibility. Their lower fiber and lignin concentrations contributed to their freshness and digestibility throughout maturity. Significantly higher iron concentrations make the CX-1 vines a valuable, low-fat iron supplement for animal feed. The CX-1 roots also showed the highest bioethanol potential (82.3 g ethanol kg^{-1} fresh root) compared to Hernandez (64.5) and Beauregard (48.1).

CONCLUSION: The CX-1 industrial sweetpotato is an ideal dual-purpose crop for tropical/subtropical climates that can be utilized as a non-grain-based feedstock for bioethanol production while contributing a valuable, high-yielding nutritional supplement for animal feed.

Keywords: sweetpotato; bioethanol; animal feed; vines; roots; industrial cultivar

INTRODUCTION

A delicate balance between food and fuel must be accomplished through innovative agricultural practices and careful crop selection in order to provide sufficient resources to sustain the rapid increase in global population. The availability of fertile land is decreasing and strategic planning for sustainable agricultural land-use systems that significantly contribute to the surrounding communities without wasting environmental resources and damaging the ecological footprint of the land is essential. While biofuels can help support the energy needs of the future and displace some of our dependence on fossil fuels, they must not hinder the necessary requirements for basic nutrition. Food security must remain a top priority within the discussion of sustainable energy crops, especially for vulnerable populations. Africa, for example, is seen as having the world's largest potential for producing bioenergy crops in terms of acreage and productivity, and investors are purchasing millions of acres to grow bioenergy crops.[1] However, the declining supply of edible crops is inflating food prices and leaving rural communities in Africa starving.[1] A novel approach to this dilemma is to grow a dual-purpose crop with high biofuel potential as well as value-added potential from co-products.

The sweetpotato (*Ipomoea batatas* L.) crop is an attractive choice because of its high productivity on low-quality, arable lands and minimal demands for fertilization and irrigation. Although the primary target of the crop harvest is the storage root, which has biofuel potential, the sweetpotato vines contribute a substantial fraction of the overall crop yield. The nutritional value of the vines is recognized in some parts of the world as they are harvested for human food in many parts of Asia and the developing world.[2,3] Several studies have also demonstrated their effective use as a protein-rich supplement for livestock, including cows, pigs, goats and poultry.[4–8] Unfortunately, sweetpotato vines are not currently utilized in the USA and most producers discard them at harvest.[9] Therefore, complete utilization of this dual-purpose crop (including the roots and the vines) has not been globally recognized.

The decision on whether to grow sweetpotatoes for food, fuel or manufactured products is dependent on the needs of the surrounding community. China, for example, has the highest population in the world and they are the largest producer of sweetpotatoes, responsible for 70% of the global production.[10] In some parts of China, the sweetpotato is grown for biofuel production because recent regulations have directed the ethanol industry toward non-grain-based feedstocks.[11] The shift to using sweetpotatoes (rather than corn) for ethanol production is chiefly motivated by food security issues, but other environmental benefits have also been realized. It was estimated that greenhouse gas emissions in the form of CO_2 could be reduced by 263 000 t in

* Correspondence to: AC Wilkie, Soil and Water Sciences Department, University of Florida – IFAS, PO Box 110960, Gainesville, FL 32611-0960, USA. E-mail: acwilkie@ufl.edu

Soil and Water Sciences Department, University of Florida – IFAS, Gainesville, FL 32611-0960, USA

China in 2015 by utilizing sweetpotatoes for ethanol production rather than grain-based feedstocks.[12]

Nearly all (99.4%) of the ethanol currently produced in the USA is from corn or corn/sorghum rotations, with the remaining fraction from cellulosic feedstocks and beverage waste.[13] However, highly productive alternatives such as sweetpotatoes are under consideration. The higher dry matter (DM) and starch content associated with industrial sweetpotatoes grown for biofuel production compared with table varieties[14] is an aspect of this crop that increases its agronomic efficiency and promotes a sustainable future for the production of renewable fuels. Although most of the sweetpotatoes grown in the USA are currently used for human consumption,[9] they are a highly competitive feedstock for bioethanol production in the southeastern USA.[15] Florida, for example, needs a replacement crop for citrus groves that have recently been lost to the citrus greening bacterium, and the subtropical climate is suitable for growing sweetpotatoes as a feedstock for ethanol production.

The dairy cattle industry is quite large in the USA and it has successfully incorporated by-products from other agricultural industries such as citrus pulp, brewer's grains and cottonseed as supplements to feed.[16] As a supplement to Guinea grass, sweetpotato vines were found to be an effective substitute for dried brewer's grains and cottonseed meal in the diet of lactating dairy cows.[17] Thus sweetpotato vines could provide a valuable dietary supplement to the dairy cattle industry in the USA, particularly in Florida, which houses the largest number of dairy cows in the southeastern USA.[18] If the vines of industrial sweetpotatoes can be shown to be superior to those of common table varieties, then this crop can be promoted as a viable source of nutrition as well as an energy crop for bioethanol production.

The fundamental differences between the roots of sweetpotato cultivars grown for biofuel *versus* those grown for human consumption have been documented.[14] However, physiological, compositional and nutritional differences among the associated vines have not been documented. The overall goal of this research was to demonstrate the dual-purpose advantages of industrial sweetpotatoes as a viable crop that can supply biofuel from the roots and a nutritional animal feed supplement from the vines. The primary objective was to compare the vines from three different sweetpotato cultivars, including an industrial variety (CX-1) and two table varieties (Hernandez and Beauregard) in regard to agronomic yields over two growing seasons and extensive analyses pertaining to animal diets such as cell wall components, non-structural carbohydrates, macro- and micronutrients, and metabolic energy values. For complete synthesis of the crop, the roots of each cultivar were also evaluated to verify that the CX-1 starch content and bioethanol potential are superior to the common table varieties for biofuel production.

MATERIALS AND METHODS

Agronomic field trial

An agronomic field trial was conducted for two growing seasons (i.e. Year 1 and Year 2) in Gainesville, Florida (29° 37′ 38.32″ N, 82° 21′ 40.37″ W) to determine agronomic vine yields of the three different sweetpotato cultivars CX-1, Hernandez and Beauregard. Plant material for all the cultivars was propagated in South Carolina and provided by CAREnergy LLC, located in North Charleston, SC, USA. The CX-1 cultivar is a distinct derivative from the Chinese variety 'Xushi 18', and CX-1 was specifically selected for starch production and fuel ethanol production because of its large roots and high DM content. The Hernandez and Beauregard cultivars are two popular table varieties developed by the Louisiana Agricultural Experiment Station that are commonly grown in the USA.

Thirty-two plants were planted 30 cm apart in a raised bed with three replications for each cultivar, in a random block design, giving a total of 96 plants per cultivar each year. Raised beds were 50 cm wide by 30 cm high and formed on 1 m centers. The soil type was a loamy Blichton sand, gently sloping and somewhat poorly drained.[19] A compound fertilizer (N:P:K 6:6:6) was applied at a rate of 88.5 kg N ha^{-1} each year. Rainfall was measured using an on-site rain gauge over the entire growing season and no additional irrigation was applied. In addition to the climatic conditions, there were two variations between the Year 1 and Year 2 planting efforts. During Year 1, the initial planting material was non-rooted vine cuttings and the rows were oriented in a north–south direction. During Year 2, the initial planting material consisted of rooted plants that had been established approximately 30 days prior to placement in the ground and rows were oriented in an east–west direction to promote better drainage in the field trial plot. The modifications in Year 2 were an attempt to improve the overall vine and root yields for all the cultivars.

The vines were harvested by hand and weighed fresh in the field immediately following harvest. The vines were harvested 165 days after planting (DAP) during Year 1 and 172 DAP during Year 2. Vine yields were determined on both a fresh matter and DM basis, and they are expressed in terms of both kilograms per plant and tonnes per hectare (t ha^{-1}). Roots were harvested a couple of weeks after the vines (182 DAP for each year) and weighed in the field to determine fresh and dry root yields for each cultivar. These data were used to calculate the harvest index (HI) for each cultivar, which is defined as the root biomass divided by the total plant biomass (on a DM basis).

Sample collection and preparation

Vine samples were collected during the Year 1 growing season for laboratory analyses. Representative vine samples of each cultivar were collected at two different maturity stages: 112 and 165 DAP. The representative vine samples consisted of approximately twenty 60 cm lengths cut from the distal end of the vine. Vine samples were chopped with garden clippers and then placed in a drying oven at 60 °C for 72 h and milled to pass through a 0.85 mm sieve using a Wiley mill (Arthur H Thomas Co., Philadelphia, PA, USA).

Representative root samples of each cultivar were collected at harvest during the Year 1 growing season. The roots were first graded according to USDA standards, with the addition of a Jumbo category for any roots exceeding 1 kg.[20] Ten roots were then selected for each cultivar, with at least two roots from each grading category, and prepared for starch analyses. Excess soil was removed from unpeeled roots and they were chopped with a knife and processed in a Sunbeam food processor. The processed material was dried at 60 °C for 72 h and milled to pass through a 425 μm sieve using a Wiley mill. After milling, the sweetpotato flour (SPF) was stored in sealed polyethylene bags inside a desiccator at room temperature for further analyses.

Laboratory analytical methods for the vines

Upon harvest, the fresh vines from both seasons were immediately analyzed for DM according to standard methods[21] to determine DM yields. Dried and ground samples of all the vine cultivars from Year 1 harvested at 165 DAP were evaluated for several parameters by Dairy One Forage Testing Laboratory (Ithaca, NY, USA).

The DM and organic matter (OM) were analyzed according to standard methods.[21] The acid detergent fiber (ADF) and neutral detergent fiber (NDF) concentrations were determined according to Van Soest *et al.*[22] using a ANKOM 200 fiber analyzer (ANKOM Technology, Macedon, NY, USA) and F57 mesh bags. ADF and NDF were used to calculate the relative feed value (RFV) index according to hay grading standards.[23] Acid detergent lignin (ADL) was determined from the ADF residue digested in 72% (w/w) sulfuric acid for 3 h in an ANKOM DaisyII incubator at ambient temperature. Crude fat analysis was performed according to the Association of Official Analytical Chemists (AOAC) Method 2003.05, with extraction by Soxtec HT6 system using anhydrous diethyl ether.[24] Water-soluble carbohydrates (WSC) and ethanol-soluble carbohydrates (ESC) were partitioned according to Hall *et al.*[25] and results were measured using a Thermo Scientific Genesys 10S Vis spectrophotometer.

For starch analysis on the vines, samples were pre-extracted for sugar by incubation in a 40 °C water bath and filtration on Whatman 41 filter paper. Residues were thermally solubilized using an autoclave, then incubated with glucoamylase enzyme to hydrolyze starch to produce dextrose (glucose). Prepared samples were injected into the sample chamber of a YSI analyzer, where dextrose diffused into a membrane containing glucose oxidase. The dextrose was immediately oxidized to hydrogen peroxide and D-glucono-4-lactone. The hydrogen peroxide was detected amperometrically at the platinum electrode surface. The current flow at the electrode is directly proportional to the hydrogen peroxide concentration, and hence to the dextrose concentration. Starch was determined by multiplying dextrose by 0.9. Soluble proteins (SP) were determined according to the Cornell sodium borate–sodium phosphate buffer procedure.[26]

Non-fiber carbohydrates (NFC), total digestible nutrients (TDN), digestible energy (DE) and metabolizable energy (ME) values were estimated for the vines. NFC was estimated from NDF, crude protein (CP), crude fat and ash content.[27] TDN, DE and ME were predicted according to the 2001 National Research Council (NRC) approach for ruminants.[28] Macro- and micronutrients, including calcium (Ca), phosphorus (P), magnesium (Mg), potassium (K), sodium (Na), sulfur (S), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn) and molybdenum (Mo), were analyzed using a Thermo ICAP 6300 inductively coupled plasma (ICP) radial spectrometer after microwave digestion.

Dried and ground samples of all the vine cultivars (prepared as triplicate samples) from Year 1 at two different stages of maturity (112 and 165 DAP) were evaluated for DM, OM, *in vitro* organic matter digestibility (IVOMD) and total nitrogen (N) by the University of Florida Forage Evaluation Support Laboratory (FESL; Gainesville, FL, USA). DM and OM were analyzed according to standard methods.[21] The IVOMD concentration was determined by a modification of the two-stage technique.[29] For N analysis, samples were digested using a modification of the aluminum block digestion procedure.[30] Sample weight was 0.25 g, catalyst used was 1.5 g of 9:1 K_2SO_4:$CuSO_4$, and digestion was conducted for at least 4 h at 375 °C using 6 mL H_2SO_4 and 2 mL H_2O_2. N concentration in the digestate was determined by semi-automated colorimetry.[31] The N concentration was converted to CP by multiplying by a factor of 6.25.

Laboratory analytical methods for the roots

Upon harvest, the fresh roots from Year 1 and Year 2 were analyzed immediately for DM according to standard methods[21] to determine DM yields. After drying and grinding, the SPF from Year 1 was also analyzed for DM according to standard methods.[21] Total starch for the SPF from Year 1 was determined with a total starch assay kit (K-TSTA, Megazyme, Ireland) based on the use of thermostable α-amylase and amyloglucosidase.[32] This method has been adopted by the AOAC (Official Method 996.11) and the American Association of Cereal Chemists (Method 76.13). All analyses were done in triplicate and results are reported on a DM basis. The theoretical ethanol yield for 1 kg fresh roots was calculated based on the DM content measured in each respective cultivar and the theoretical conversion of starch into ethanol during fermentation (0.567 g ethanol g^{-1} starch).[33]

Statistical analyses

Laboratory analyses were performed in triplicate and the results are expressed as mean ± standard deviation. The data were subjected to analysis of variance using single-factor ANOVA in Microsoft Excel and the means were separated using Tukey–Kramer's test at the 0.05 probability level (i.e. $P < 0.05$).

RESULTS AND DISCUSSION

Agronomic yields of sweetpotato vines

Although the use of sweetpotato vines for animal feed is not new, the agricultural utilization of the vines from an industrial sweetpotato cultivar with both feed and fuel potential is novel. There are currently no reported values of vine yields from industrial sweetpotato cultivars, and vine yield determination is necessary to promote the utilization of this agricultural biomass. Generally speaking, the quantity of aerial vines produced from table sweetpotato cultivars varies widely depending on the cultivar, geographic region, fertilization rate and time of harvest. Five cultivars grown in different regions of Ghana had fresh vine yields ranging from 8 to 28 t ha^{-1}, with an average of 12 t ha^{-1} in the coastal region and 22 t ha^{-1} in the forest region.[34] Four cultivars grown in Swaziland had fresh yields ranging from 24 to 57 t ha^{-1} at 90 DAP, while the same four cultivars produced 52–144 t ha^{-1} at 110 DAP.[4] Yields reported on a DM basis include two cultivars grown in the Turrialba Valley of Costa Rica, which produced 3–4 dry t ha^{-1}.[35] A total of 18 varieties grown in the forest region of southeastern Nigeria had vine yields ranging from 3.9 to 8.1 dry t ha^{-1}, and the highest vine yields were observed at the time of harvest (140 DAP) rather than 56, 84 or 112 DAP.[36] These varying results demonstrate the importance of determining specific vine yields for cultivars of interest within the particular region where they are intended to be grown.

Fresh and dry vine yields for this study were measured during the final vine harvest for Years 1 and 2 (see Table 1). Of the three cultivars grown in the Gainesville field trial, CX-1 had the highest fresh matter vine yield during both seasons, and similar yields (t ha^{-1}) were obtained each season. Observations made at the time of harvest indicated that the CX-1 vines were the most robust, maintaining their structure and green leaves. The vine diameters over both seasons measured at the base of the stems were an average of 2.8 cm for CX-1, 1.3 cm for Beauregard, and 1.3 cm for Hernandez. Visual observation and lower DM content in the CX-1 vines indicates that they maintain their freshness throughout the entire growing season, which positively influences their nutritional value.

The survival rate of the plants (all cultivars) was lower during the Year 2 growing season, as depicted in Table 1. Despite the fact that there were fewer plants contributing to vine production, the fresh and dry vine yields on a tonnes per hectare basis for the

Table 1. Agronomic vine yields for both Year 1 and Year 2 of sweetpotato field trial[a]

	CX-1 vines		Hernandez vines		Beauregard vines	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Initial plants (#)	96	96	96	96	96	96
Harvested plants (#)	95	70	95	70	86	69
Growing season (DAP)	165	172	165	172	165	172
Fresh vine yield (kg per plant)	1.60	2.34	1.54	0.86	1.02	0.66
Fresh vine yield (t ha^{-1})	49.5	53.5	47.6	19.7	28.7	14.9
Dry matter (g kg^{-1} fresh wt)	131 ± 6	141 ± 2	165 ± 18	154 ± 5	151 ± 9	156 ± 3
Dry vine yield (dry t ha^{-1})	6.5	7.6	7.9	3.0	4.3	2.3
Harvest index[b]	0.38	0.62	0.40	0.55	0.60	0.70

DAP, days after planting.
[a] Rainfall during Year 1 = 76 cm; Rainfall during Year 2 = 95 cm.
[b] Harvest index equals total dry weight of roots divided by total dry weight of both roots and aerial vines.

CX-1 were higher during the Year 2 field trial (Table 1). Thus the CX-1 vine yield on a kilograms per plant basis was much higher in Year 2 (2.34) compared to Year 1 (1.60). CX-1 vine productivity may have been positively influenced by the improved site conditions in Year 2, namely the increased rainfall (see Table 1) and improved drainage at the site. The starting material in Year 2 (rooted plants *vs.* non-rooted vine cuttings) also likely contributed to higher vine yields for CX-1. In contrast, the vine yields for the Hernandez and Beauregard cultivars were substantially lower in Year 2 compared to Year 1 (see Table 1). These data suggest that despite seasonal changes such as site conditions, climate and the influence of pests, the CX-1 cultivar is a persistent crop that can provide substantial vine biomass from year to year.

Harvest index (HI) is a measure of the partitioning and assimilation of biomass into various parts of the plant. Since the roots are generally the target of the harvest, a high root HI is sought to promote higher fermentables. However, the biomass from the vines represents another potentially marketable product which can contribute significantly to the complete utilization of this crop. Therefore, HI values near 0.50 would be ideal to promote the use of both the roots and the vines of the CX-1 sweetpotato crop. The HI is highly variable for sweetpotatoes as it is affected by soil type, rainfall, fertilization, length of growing season and genotype. The HI for 15 different sweetpotato cultivars grown in Norfolk sandy loam in Fort Valley, GA, ranged from 0.31 to 0.75 after 143 DAP.[37] Since all the cultivars were grown simultaneously in the same location, this wide range can be attributed primarily to genetic differences. HI increased as the growing season progressed from 60 to 105 to 143 DAP for all but two of the cultivars,[37] demonstrating continual root growth over this period.

The HI values of the cultivars grown in this field trial in both Year 1 and Year 2 are within the range observed by Bhagsari and Ashley,[37] although there is substantial variability between Year 1 and Year 2 (see Table 1). The longer establishment period (i.e. rooted plants) in Year 2 essentially extended the growing period and promoted root biomass, which in turn increased the HI for each cultivar. The improved drainage conditions in Year 2 may have also positively influenced the root biomass. Thus, even among the same genotypes, HI values can vary significantly depending on site conditions. To optimize the utilization of the CX-1 as a dual-purpose crop for feed (vines) and fuel (roots), an ideal HI value of 0.50 should be targeted. The average HI value of the CX-1 cultivar over Year 1 and Year 2 was 0.50, which indicates that this target should be relatively easy to attain by establishing the appropriate length for the growing season.

Table 2. Proteins, fats and structural carbohydrates in sweetpotato vines (g kg^{-1} dry matter)

	CX-1 vines	Hernandez vines	Beauregard vines
Organic matter	883 ± 1a	896 ± 0b	886 ± 1c
Crude protein	134 ± 1a	124 ± 2b	141 ± 2c
Crude fat	32 ± 1a	24 ± 1b	31 ± 1a
Neutral detergent fiber	316 ± 5a	354 ± 3b	369 ± 2c
Acid detergent fiber	244 ± 7a	259 ± 1b	275 ± 5c
Acid detergent lignin	42 ± 1a	48 ± 2b	75 ± 0c
Relative feed value	205 ± 5a	181 ± 1b	170 ± 1c

Data are means ± standard deviation ($n = 3$).
Values within the same row with different lower-case letters are significantly different ($P < 0.05$).

Nutritional value of sweetpotato vines

Sweetpotato vines from table varieties have been determined to be a valuable supplement in forage diets, mainly owing to their high agronomic yield, palatability and relatively high protein concentrations.[5] However, the nutritional value of the vines from industrial varieties grown primarily for biofuel has not been previously reported. For potential use as animal feed, the nutritional value of the three sweetpotato vine cultivars was evaluated to determine whether there was a notable difference between the industrial and table varieties. The forage quality of the CX-1, Hernandez and Beauregard vines was determined by comparing the cell wall components (Table 2), non-structural carbohydrates (Table 3), energy values (Table 4), and macro- and micronutrient concentrations (Table 5) of each cultivar.

Cell wall components

From a nutritional perspective, carbohydrates are the primary source of energy in ruminant diets and generally comprise 60–70% of the total diet.[38] Carbohydrates can be categorized as either structural (part of the cell wall) or non-structural (inside the cell wall). Structural carbohydrates consist mainly of fiber and are less digestible than non-structural carbohydrates. Although

Table 3. Non-structural carbohydrates in sweetpotato vines (g kg^{-1} dry matter)

	CX-1 vines	Hernandez vines	Beauregard vines
Non-fiber carbohydrates	405 ± 4a	396 ± 2b	346 ± 5c
Water-soluble carbohydrates	171 ± 2a	153 ± 2b	112 ± 5c
Ethanol-soluble carbohydrates	101 ± 3a	97 ± 3a	86 ± 3b
Starch	25 ± 1a	16 ± 0b	11 ± 0c

Data are means ± standard deviation ($n = 3$).
Values within the same row with different lower-case letters are significantly different ($P < 0.05$).

Table 4. Energy values[a] associated with different sweetpotato vines

	CX-1 vines	Hernandez vines	Beauregard vines
Soluble protein (g kg^{-1} DM)	53.2 ± 1.6a	38.1 ± 1.9b	52.2 ± 0.0a
Total digestible nutrients (g kg^{-1} DM)	643 ± 6a	630 ± 0b	597 ± 6c
Digestible energy (MJ kg^{-1} DM)	11.97 ± 0.09a	11.70 ± 0.09b	11.15 ± 0.09c
Metabolizable energy (MJ kg^{-1} DM)	10.22 ± 0.09a	9.95 ± 0.09b	9.40 ± 0.09c

DM, dry matter; data are means ± standard deviation ($n = 3$).
Values within the same row with different lower-case letters are significantly different ($P < 0.05$).
[a] Energy values were determined specifically for ruminants.

some fiber is beneficial in an animal's diet, too much fiber can lead to lower feed intake, energy and production.[27] Fiber can be partitioned further into NDF, which encompasses cellulose, hemicellulose, lignin, insoluble minerals and fiber-bound nitrogen, and ADF, which excludes hemicellulose. NDF is correlated with animal intake whereas ADF is correlated with digestibility, and lower NDF and ADF values are preferred to improve forage quality.[39] ADL represents the indigestible portion of the cell wall and negatively affects the energy potential of the forage.

The CX-1 vines had significantly lower NDF and ADF concentrations than the other cultivars ($P < 0.05$), which in turn resulted in the highest RFV, as shown in Table 2. RFV is used to compare cool-season forages to a standard alfalfa hay in full bloom, which is assigned a value of 100.[39] Mature sweetpotato vine cultivars in this study had higher nutritive values than mature alfalfa hay, with the CX-1 vines in particular exhibiting the highest RFV (205), followed by Hernandez (181) and Beauregard (170), and differences among the cultivars were significant ($P < 0.05$). The CX-1 vines also had significantly lower ADL concentrations than the other cultivars ($P < 0.05$), which contributes to more efficient digestion and a higher energy potential.

Proteins and fats are also an important part of the cell wall contents. CP represents nitrogen in the feedstock and essentially provides energy and promotes digestion. Adequate CP concentrations for ruminants are approximately 80 g kg^{-1} DM and higher values do not viably contribute to the animal's digestive capacity.[40] Vine CP concentrations in all three cultivars met the minimum CP requirements for ruminants, ranging from 124 to 141 g kg^{-1} DM, with the Beauregard vines having the highest CP of the three cultivars after 165 DAP (see Table 2). Sweetpotato vines are generally considered to be a low-fat supplement to animal diets, but fats are a source of energy and they increase the absorption capacity of several nutrients. The crude fat concentrations ranged from 24 g kg^{-1} DM for Hernandez to 32 g kg^{-1} DM for CX-1 (Table 2), which aligns well with the average fat content measured from 40 different cultivars of sweetpotato leaves (37 g kg^{-1} DM).[41] Crude fat concentrations were significantly higher for CX-1 and Beauregard when compared to Hernandez ($P < 0.05$).

Non-structural carbohydrates (NSC)

NSC consist mainly of simple sugars, starches and fructans. Simple sugars (ESC) include mono-, di- and oligosaccharides, and they represent the most degradable fraction of NSC, whereas WSC incorporate both ESC and fructans. Certain forages such as perennial ryegrasses have been bred specifically for higher WSC content to improve N utilization in the rumen and thus prevent N loss through urine in ruminants.[42] Improved lactation was observed within dairy cattle, resulting in higher milk protein yields, when the cattle were fed ryegrasses with higher WSC concentrations (165 g kg^{-1} DM) compared to the control (126 g kg^{-1} DM).[43] Further partitioning showed that N was more efficiently utilized in lactation and less N (25% *vs.* 35% of intake) was excreted with the higher WSC ryegrass compared to the control ryegrass.[43] Among the three cultivars, the CX-1 vines had significantly higher concentrations of WSC ($P < 0.05$) and the concentrations were comparable to the high-WSC ryegrass (see Table 3). Although further studies should be conducted with the vines, similar benefits including improved utilization of N in the rumen can be anticipated if the CX-1 vines are fed as forage. This results in more sustainable livestock productivity and a reduction of nutrient pollution in the environment.

Non-fiber carbohydrates (NFC) yield values that are not synonymous with NSC, mainly because they also contain pectin and organic acids.[38] These types of carbohydrates provide a major source of energy for ruminants as they are easily digestible. The NFC concentrations for the CX-1 and Hernandez vines (Table 3) are relatively high when compared with alfalfa hay (220 g kg^{-1} DM) but are similar to corn silage (410 g kg^{-1} DM) and beet pulp (360 g kg^{-1} DM).[38] Also, the CX-1 vines had significantly higher NFC concentrations than the table varieties ($P < 0.05$). It is important to note that the starch fraction of the NFC was very low for all the cultivars, which indicates that the NFC concentrations represent mostly sugars and organic acids that are easily fermentable. The relatively high concentrations of easily degradable carbohydrates in the sweetpotato vines make them a valuable source of energy.

Energy values

The nutrients within a particular forage are only useful in the context of animal nutrition if they can be digested and metabolized by the animal. Readily available nutrients, including soluble protein (SP) and TDN in the vines, and associated energy values are shown in Table 4. TDN concentrations were significantly higher in the CX-1 vines compared to the table varieties ($P < 0.05$) and they are also higher than those reported for many other forages including barley silage (600 g kg^{-1} DM), rye silage (600 g kg^{-1} DM), triticale silage (570 g kg^{-1} DM), Bermuda grass (530–550 g kg^{-1} DM), Sudan sorghum (540 g kg^{-1} DM) and mature hay from a variety of

Table 5. Macro- and micronutrients in different sweetpotato vines

	CX-1 vines	Hernandez vines	Beauregard vines
Macronutrients (g kg^{-1} dry matter)			
Ca	11.7 ± 0.1a	11.6 ± 0.1a	15.9 ± 0.5b
P	4.1 ± 0.1a	4.3 ± 0.0b	3.6 ± 0.1c
Mg	2.9 ± 0.1a	3.3 ± 0.0b	4.3 ± 0.1c
K	36.1 ± 0.3a	32.1 ± 0.1b	31.4 ± 0.7b
Na	0.94 ± 0.02a	0.04 ± 0.00b	0.13 ± 0.01c
S	3.5 ± 0.0a	3.1 ± 0.1b	4.1 ± 0.1c
Micronutrients (mg kg^{-1} dry matter)			
Fe	75.7 ± 2.3a	58.3 ± 0.6b	58.0 ± 1.7b
Zn	17.0 ± 0.0a	17.0 ± 0.0a	14.3 ± 0.6b
Cu	6 ± 0a	7 ± 0b	4 ± 0c
Mn	49.3 ± 0.6a	37.0 ± 0.0b	51.7 ± 2.1a
Mo	1.1 ± 0.0a	1.0 ± 0.0b	1.0 ± 0.0b

Data are means ± standard deviation ($n = 3$).
Values within the same row with different lower-case letters are significantly different ($P < 0.05$).

cool-season grasses (560 g kg^{-1} DM), which were all determined using the same approach.[38]

Digestible energy (DE) represents the gross feed energy minus the energy lost in feces, whereas metabolizable energy (ME) also accounts for losses from methane and urine. The energy values reported herein (see Table 4) are based on the measured values for digestible protein, fats, fibers and NFC, and are estimated according to the 2001 NRC approach specifically related to ruminants.[38] This approach is helpful for comparative purposes among the different cultivars as it demonstrates that the CX-1 vines have significantly higher energy values when compared to the Hernandez and Beauregard vines ($P < 0.05$). The ME value for CX-1 (10.2 MJ kg^{-1} DM) was also higher than other cultivars, namely TIS-87/0087, TIS-8164 and TIS-2532.OP.1.13, which ranged from 6.7 to 7.9 MJ kg^{-1} DM.[17] Etela *et al.*[17] also measured the actual ME intake when the vines were fed to lactating dairy cows and found that, although the intake was lower than with other supplements (dried brewer's grains and cottonseed meal), the efficiency of ME utilization for milk production was up to 3.5 times higher with the sweetpotato vine supplemental diet. Since the estimated ME values of the CX-1 vines are higher than those measured by Etela *et al.*, it is anticipated that CX-1 vines used as a dietary supplement would enhance ME utilization for milk production in lactating dairy cows.

Macro- and micronutrients

The macro- and micronutrient concentrations of the vines were evaluated for all three cultivars at their harvest maturity stage (165 DAP) and the results are summarized in Table 5. The most abundant nutrient in the vines was potassium (K), and this is consistent with previous mineral studies conducted on various cultivars of sweetpotatoes leaves.[41,44] Dairy cattle require more K than any other cation nutrient, and it is required on a daily basis since the animal does not have much storage capacity for K.[38] The K concentrations were significantly higher ($P < 0.05$) in the vines from the CX-1 cultivar (36.1 g kg^{-1} DM) compared to the table varieties, and they were also relatively high compared to 40 different cultivars of sweetpotato leaves from China (4.79–42.81 g kg^{-1} DM)[41] and 11 different cultivars of sweetpotato leaves from Japan (19–40 g kg^{-1} DM).[44] The leaves are the site of photosynthetic exchange and typically have a higher level of nutrients than the other components of the vine such as the stems and petioles. The K concentration, in particular, is higher in sweetpotato leaves than in the stems and petioles.[45] Since the vines analyzed in this experiment consisted of leaves, petioles and stems (i.e. 60 cm vine tips), this contributes to the relatively high K concentration of the CX-1 vines compared to other cultivars in China and Japan.[41,44]

The most variable nutrient measured in the vines was sodium (Na), and this phenomenon was also observed in the Chinese and Japanese cultivars.[41,44] The Na concentration was lowest in the Hernandez and highest in the CX-1 vines, and significant differences were determined ($P < 0.05$; Table 5). Dairy cattle evolved with minimal dietary Na and thus have an efficient absorption and storage capacity for this macronutrient.[38] The proper balance of K and Na is important for acid–base equilibrium, fluid and electrolyte balance, heart function and nutrient transport in dairy cattle.[38] The K:Na ratio for Hernandez (802) was exceptionally high because of the low Na concentration, but the K:Na ratios for Beauregard (241) and CX-1 (38) were consistent with the leaves from the Chinese and Japanese cultivars and all were higher than that of spinach (18).[41,44]

The most abundant micronutrient in the vines was iron (Fe), which plays an important role in hemoglobin and oxygen transport, and Fe deficiencies in calves can cause anemia and depressed immune responses.[38] Fe was significantly higher in the CX-1 vines compared to the table varieties ($P < 0.05$; Table 5), supporting their use as a valuable, low-fat Fe supplement for animal feed. As for the other nutrients, Mo concentrations were significantly higher ($P < 0.05$) in the CX-1 vines, while Ca, Mg and S concentrations were significantly higher ($P < 0.05$) in the Beauregard vines (Table 5). The Mn concentrations in the CX-1 and Beauregard vines were similar, but significantly higher ($P < 0.05$) than in Hernandez (Table 5). The Hernandez vines exhibited significantly higher ($P < 0.05$) P and Cu (Table 5). The Zn concentrations were the same in the CX-1 and Hernandez vines, which were significantly higher ($P < 0.05$) than the concentrations in the Beauregard vines (Table 5).

Effects of maturity on sweetpotato vines

The length of the growing season significantly influences the root yield from the sweetpotato crop. Although there are variations in storage root development rates with different cultivars, roots generally enlarge and accumulate mass the longer they remain in the ground, and root yields increase linearly until 200 DAP.[37,46] Extended growing seasons are suitable for industrial sweetpotatoes because the marketable product is not limited to a USDA No. 1 grade (as with table varieties) but the focus is rather on higher DM yield to improve handling efficiency.[47] Therefore, a growing season that ranges from 180 to 220 DAP is appropriate for the CX-1 roots to maximize DM yields and bioethanol potential, especially in tropical and subtropical climates where freezing temperatures will not damage the crop. Thus, for CX-1 in particular, it is important to determine the impact that maturity will have on the major nutritional components of the vines.

There are several physical and chemical changes that occur during the maturity stages of the sweetpotato vine. In the planting stage, vine cuttings from the preceding harvest are planted to produce a new sweetpotato crop. Vines initially grow upwards like a bush to approximately 0.5 m and then begin to extend laterally to form a dense canopy. This canopy serves as weed control and provides protection for the storage roots. The canopy contributes to the low-maintenance aspect of the crop by eliminating the need to hand-weed or apply herbicides and by preventing fertilizer

Table 6. Changes in digestibility and crude protein of sweetpotato vines with maturity

	IVOMD (g kg^{-1} OM)[a]		Crude protein (g kg^{-1} DM)	
	112 DAP	165 DAP	112 DAP	165 DAP
CX-1 vines	790 ± 2aA	750 ± 8aB	179 ± 3aA	134 ± 1aB
Hernandez vines	706 ± 2bA	620 ± 13bB	156 ± 5bA	124 ± 2bB
Beauregard vines	787 ± 2aA	643 ± 5cB	172 ± 3aA	141 ± 2cB

IVOMD, *in vitro* organic matter digestibility; OM, organic matter; DM, dry matter; DAP, days after planting. Data are means ± standard deviation ($n = 3$); values within the same column with different lower-case letters represent significant differences among cultivars ($P < 0.05$); values within the same row with different upper-case letters represent significant differences among analyses at different DAP ($P < 0.05$).
[a] Represents the concentration of organic matter digested.

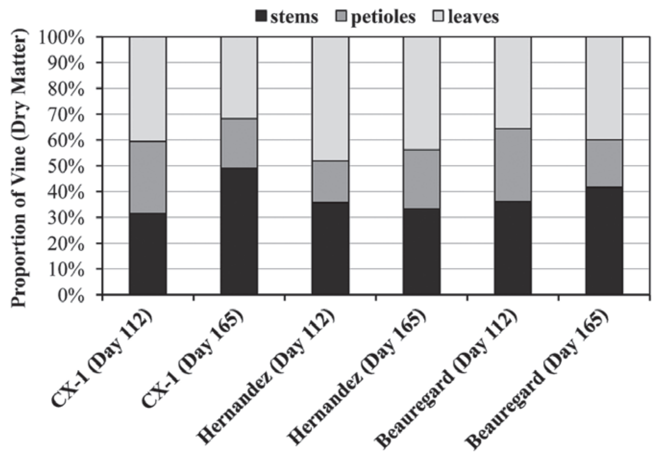

Figure 1. Physical composition of sweetpotato vines from all three cultivars at 112 and 165 days after planting.

applications from washing away. At the final stage of maturity (165 DAP), the lateral extent of the vines evaluated in this study ranged from 2.0 to 4.0 m, with no observable differences in vine length among the different cultivars. The distal end of the vine is considered the tip and it is generally defined as the last 10–15 cm of the vine.[3] The tip is the newest growth on the vine and supports a concentrated presence of leaves. Representative samples of the vines collected at 112 and 165 DAP consisted of the last 60 cm of the vines.

Typically, as plants mature, the stem growth dominates and fibrous depositions such as lignin begin to accumulate in the plant cell wall.[39] Stems provide the structural support for the plant, and the stems in sweetpotato vines have higher lignin concentrations than the other portions of the vine, namely leaves and petioles.[5] As growth advances, the plants naturally develop a more rigid structure with increased lignin deposits. Lignin inhibits the degradation of a feedstock and prevents the microbes from accessing the cellulose and hemicellulose within the plant cell wall and is therefore negatively correlated with digestibility.

When compared with the other cultivars, the CX-1 vines had significantly higher ($P < 0.05$) IVOMD concentrations at 165 DAP (Table 6). This is likely related to the fact that the CX-1 vines had the lowest ADL concentrations, as shown in Table 2. The IVOMD of all the vine cultivars decreased significantly ($P < 0.05$) with maturity, as shown in Table 6. The most notable difference was observed in the Beauregard vine, with an 18% decrease in digestibility, while the CX-1 only diminished by 5%. In both of these cultivars, the proportion of stems increased with maturity (see Fig. 1). The proportion of stems increased from 32% to 49% DM in the CX-1 vine and from 36% to 42% DM in the Beauregard vine as the vines matured from 112 to 165 DAP. Although the CX-1 vines had a much higher proportion of stems at harvest than at 112 DAP, the digestibility of the overall vine was nominally changed over time. This nominal difference is likely related to the lack of vine deterioration over time and the observed freshness during harvest, as previously noted.

Another notable difference was the decrease in CP in the vines as they matured. Although there is variation among cultivars, the expected trend is for CP in sweetpotato vines to be highest when nitrogen is readily available for both the vines and roots. Once the roots initiate (40 DAP) and begin to enlarge (80 DAP), there is competition for the available nitrogen, and the CP content in the vines typically decreases.[3] CP in the vine samples decreased significantly ($P < 0.05$) in all three cultivars at 165 DAP when compared to 112 DAP (see Table 6). The average CP concentration decreased by 25% in the CX-1, 21% in the Hernandez and 18% in the Beauregard vines. Other studies have demonstrated similar trends. Three of four cultivars compared in Swaziland decreased from an average CP of 190 g kg^{-1} DM at 70 DAP to 140 g kg^{-1} DM at 110 DAP.[4] The CP of the C-15 vines decreased from 175 g kg^{-1} DM at 60 DAP to 122 g kg^{-1} DM at 165 DAP.[35] In a comparison of 18 different cultivars of sweetpotato vines (whole plant fodder), the average CP content in the vines decreased from 110 g kg^{-1} DM at 84 DAP to 90 g kg^{-1} DM at 140 DAP.[36]

Sweetpotato vines offer the most potential in terms of digestibility and CP around the midpoint of the crop season. However, early defoliation (even partially) has been shown to diminish the overall vine and root yield.[35] Thus the vines that maintain their quality over the life of the crop are advantageous over the other cultivars. Oftentimes, mature tropical forages, mature stovers and crop residues do not maintain adequate CP for the host animal and rumen microbes.[48] The CX-1 vines remained green through the full harvest period (165 DAP), maintained adequate CP concentrations and maintained their superior digestibility over time. The high IVOMD of the CX-1 vines compared to the other cultivars and nominal decrease over time demonstrates their high potential for utilization as either animal forage or feedstock for biogas production.[49] Thus the longer growing season necessary for optimal root yields still provides an opportunity to harvest the vines as a valuable co-product for the CX-1 crop.

Starch content and bioethanol potential of sweetpotato roots

There is no global consensus on the most efficient feedstock for bioethanol production. The countries that currently generate the majority of the world's ethanol production are the USA (14.3 billion gallons), Brazil (6.2 billion gallons) and China (0.6 billion gallons).[50] The USA produces ethanol from corn, whereas Brazil uses sugar cane. As a result of recent regulations, China is shifting from corn and wheat to non-grain-based feedstocks including sweet sorghum, cassava and sweetpotato.[11] Industrial sweetpotatoes are a competitive feedstock for bioethanol production.[15,51,52] A recent energy analysis that incorporated all aspects of cultivating, harvesting, transporting and converting sweetpotatoes into ethanol demonstrated a positive net energy ratio (1.48), resulting in a net energy gain of 6.55 MJ L^{-1} ethanol.[53]

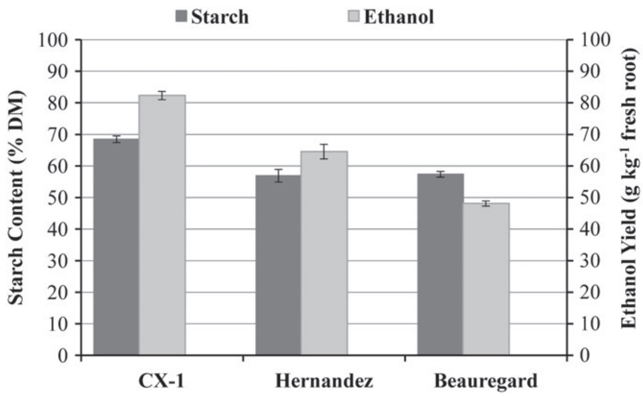

Figure 2. Starch concentration and theoretical ethanol yield of sweetpotato roots (error bars represent standard deviation, $n = 3$).

Industrial sweetpotatoes promote a higher production of starch than normal table varieties due to higher DM content, which has been directly correlated with starch content.[51,54] As predicted, the roots of CX-1 had a higher DM content and starch concentration (on a DM basis) than the table varieties, resulting in a higher theoretical ethanol yield per kilogram of fresh root, as shown in Fig. 2. The theoretical ethanol yield from the CX-1 root was 28% higher than from Hernandez and 71% higher than from Beauregard. The CX-1 crop also exhibited larger roots when compared with the table varieties. Jumbo roots, which are defined as roots weighing more than 1 kg, were highest for CX-1 (16.2% of the total root yield) compared to Hernandez (2.9%) and Beauregard (12.7%). Larger roots with higher DM promote more efficient harvest and transport. Therefore, in addition to the superior nutritional value of the vines, the CX-1 root offers more energy potential and CX-1 is thus a more efficient utilization of the land than normal table sweetpotatoes when the crop is grown for biofuel production.

CONCLUSION

Dual-purpose crops that can provide both feed and fuel can optimize energetic outputs, avoid the debate on food *versus* fuel and provide a sustainable approach to agricultural land use. The sweetpotato is an ideal candidate since it can be grown on marginal lands with minimal input requirements, while still producing a viable energy crop with high aerial biomass yield. The CX-1 sweetpotato root is a competitive feedstock for bioethanol production based on its high starch content, and the CX-1 vines offer superior nutritional value when compared with two common table varieties. The CX-1 vines had the highest RFV, fermentable nutrients and WSC, and the lowest concentrations of lignin, which all contributed to superior digestibility as measured by IVOMD. Macro- and micronutrients including potassium and iron, which are important dietary requirements for cattle, were also highest in the CX-1 vines. The CX-1 vines maintained their digestibility over time, even as the proportion of stem growth within the vine increased. The evaluation of the products and co-products in this field trial warrant further research on the agronomic yield potential of the CX-1 cultivar in various locations across the USA, particularly the southeast, to support emerging feedstocks for bioethanol production and to promote a nutritional supplement for animal feed.

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