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Bioenergy from Coastal bermudagrass receiving subsurface drip irrigation with advance-treated swine wastewater

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ABSTRACT

Coastal bermudagrass (*Cynodon dactylon L.*) may be a potentially important source of bio-based energy in the southern US due to its vast acreage. It is often produced as part of a waste management plan with varying nutrient composition and energy characteristics on fields irrigated with livestock wastewater. The objective of this study was to determine the effect of subsurface drip irrigation with treated swine wastewater on both the quantity and quality of bermudagrass bioenergy. The treated wastewater was recycled from an advanced treatment system and used for irrigation of bermudagrass in two crop seasons. The experiment had nine water and drip line spacing treatments arrayed in a randomized complete block-design with four replicates. The bermudagrass was analyzed for calorific and mineral contents. Bermudagrass energy yields for 2004 and 2005 ranged from 127.4 to 251.4 MJ ha^{-1}. Compared to irrigation with commercial nitrogen fertilizer, the least biomass energy density was associated with bermudagrass receiving treated swine wastewater. Yet, in 2004 the wastewater irrigated bermudagrass had greater hay yields leading to greater energy yield per ha. This decrease in energy density of wastewater irrigated bermudagrass was associated with increased concentrations of K, Ca, and Na. After thermal conversion, these compounds are known to remain in the ash portion thereby decreasing the energy density. Nonetheless, the loss of energy density using treated effluent via SDI may be offset by the positive influence of these three elements for their catalytic properties in downstream thermal conversion processes such as promoting a lesser char yield and greater combustible gas formation.

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1. Introduction

Sustainability and long-term success of agriculture relies on reducing the dependence on fossil fuels as a primary energy source. Nested within the solution for this reduction is the opportunity to increase bio-based energy; this renewable, bio-based energy, in turn, becomes a part of the agricultural infrastructure and economy. Numerous agricultural crops and cropping systems, which includes woody, starch, sugar, oilseed, and perennial lignocellulosic crops, are being examined for their potential as bioenergy feedstocks. These renewable energy sources should have the following: high dry matter and energy yields; reduced agricultural input requirements (e.g., water, fertilizers, and fossil fuels); positive environmental impacts (e.g., enhanced wildlife and increased water quality); and low-contaminant compositions (Adler et al., 2006; McKendry, 2002; Schmer et al., 2008). As interest in bioenergy crop production grows, demands on water for agricultural use will eventually exceed the rates of fresh water replacement. Utilization of nonreplenishable fresh ground water, to possibly ease the "food versus fuel" global concerns, will lead to a depletion of geological water reserves. This depletion is likely to occur in a similar manner to – if not as worse than – current crude oil reserve depletion (Postel et al., 1996). With increasing agricultural water demands to satisfy a growing population requiring more food, fuel, and water, it will be critically important for farming to shift its view of animal manure, like swine manure wastewater, as a valuable nutrient resource to that of a water resource.

Coastal bermudagrass is grown in the Southeastern US and is the primary warm-season perennial grass planted for forage production. Despite its moderate nitrogen requirement for optimum production (Silveira et al., 2007), bermudagrass has numerous attributes that include persistence, drought tolerance, response to increased fertility, and greater yield potential (Burns and Fisher, 2007). These same positive attributes make bermudagrass a good bioenergy feedstock candidate. Coastal bermudagrass, among other cropping systems, has routinely been incorporated as part of a waste management plan for uptake of nutrients and water in the liquid fraction of swine lagoons through land application. Application of swine lagoon effluent as fertilizer for bermudagrass hay production has been extensively studied as it related to environmental impact (Burns et al., 1985; King et al., 1985; Liu et al.,

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1998). An increased load of swine lagoon effluent increased soil phosphorous and nitrates (King et al., 1985; Liu et al., 1998). Swine lagoon effluent was applied to Coastal bermudagrass with sprinkler irrigation with nitrogen loading rates of 335–1340 kg ha^{-1}. With increasing nitrogen application rates, there was also a documented increase in both production and bermudagrass nutrient and mineral content (Burns et al., 1985). At the greater nitrogen application rates, it was concluded that large quantities of applied nutrients were not recovered in the forage – thus, lost to the environment. Even though this traditional practice has many aspects that make it environmentally unsound (Stone et al., 1998), bermudagrass receiving traditional spray field irrigation or overhead wastewater irrigation will likely remain as an important and positive crop in future waste management plans.

By offering an alternative to traditional sprinkler application, subsurface drip irrigation (SDI) systems for land application of treated animal manure effluent can help address associated environmental concerns (Stone et al., 2008). The SDI systems apply effluent below the soil surface and can eliminate spray and drift. Consequently, a reduction is realized in both odors and ammonia volatilization. The SDI systems may also be used during periods of high wind or low temperatures. Under these conditions, sprinkler application implementation is not acceptable since the irrigation medium is susceptible to spray drift and freezing.

While the recycling of swine manure effluent via SDI mitigates potential environmental impacts of bioenergy crop production, its influence as both a fertilizer and irrigation source has not been addressed on fuel characteristics for bermudagrass, including energy density, energy yield, and plant mineral concentrations. As noted by Burns et al. (1985), irrigation and fertilization with swine lagoon effluent increased plant minerals. This increase in minerals, and ultimately ash, decreases crop energy density. The inorganic minerals commonly found in plants (Si, K, Ca, Mg, and S) exert both adverse and beneficial influences on bioenergy thermal conversion unit operations. Silicates, K, and Ca are primary components of particles involved in agglomeration (Ohman et al., 2000). This phenomenon leads to slagging and fouling of biomass-fired boilers and combustion units, which, consequently, decreases their efficiency. In addition to compromising efficiencies, the silica and other metals contents can also affect the biomass decomposition behavior. The silica component can tie-up carbon making it unavailable for conversion (Raveendran et al., 1995). In contrast, some inorganic components can act as a catalyst that can affect the rate of degradation leading to both char yield reductions and greater combustible gas formation (Priyadarsan et al., 2004; Sheth and Turner, 2002). For instance, inorganic compounds such as dolomites ($CaMg(CO_3)_2$) reduce tar formation in the gasification process (Gil et al., 1999). Thus, it will become important to match bioenergy crops with appropriate energy conversion technologies.

The objective of this investigation was to assess the influence of SDI irrigation with advance-treated swine wastewater on both the Coastal bermudagrass fuel characteristics and potential effect on downstream bioenergy thermal conversion processes. Specifically, this was accomplished by evaluating: (1) energy density; (2) energy yield; and (3) measured plant nutrient concentrations.

2. Methods

2.1. 1 Site description

Coastal bermudagrass SDI experiment was conducted from 2003 to 2005 on a 0.53-ha field site next to a swine finishing facility in Duplin County, North Carolina that had 4400 animals contained in six barns. This site was adjacent to a full-scale swine wastewater treatment facility constructed and operated by Super Soil Systems USA of Clinton, North Carolina (Fig. 1). The facility treated swine manure by both removing solids and reducing nutrient concentrations (Table 1; Vanotti and Szogi, 2008). The new wastewater treatment facility replaced an anaerobic lagoon and treated all the manure (39 m^3 d^{-1}). The facility provided between 2% and 8% of its total treated effluent to the pilot scale SDI experiment.

Coastal bermudagrass was grown over an Autryville loamy sand on 36 plots (9.6 × 9.6 m) containing eight irrigation treatments and a control each with four replicates (Stone et al., 2008). Treatments consisted of treated effluent plus well water and commercial fertilizer plus well water, all applied via SDI at either 75% or 100% of calculated evapotranspiration (ET). These four treatments were repeated using lateral spacing in the SDI system of 0.6 m and 1.2 m. This resulted in eight treatments with a ninth treatment consisting of a commercially fertilized non-irrigated control (Table 2). The target total nitrogen application rate per plot was 270 kg ha^{-1}. The bermudagrass plots were fertilized annually in three equal applications: the commercial fertilizer SDI treatments received 30% urea-ammonium nitrate (UAN); the treated effluent fertilizer SDI treatments received irrigation containing wastewater with 94–465 mg L^{-1} total nitrogen; the non-irrigated plots only received surface applications of commercial fertilizer containing 34% ammonium nitrate (Stone et al., 2008).

2.2. Biomass and energy production

Bermudagrass hay was harvested three times on four to eight week intervals based on logistics and weather conditions in both 2004 (June 23, 2004; August 10, 2004; and September 21, 2004) and 2005 (July 12, 2005; August 11, 2005; and October 13, 2005). Within each plot, hay yields were determined by weighing biomass harvested from an area across the plot center with a measurement of 15.4 m^2 (1.6 × 9.6 m). A hay sample was collected from each harvested plot, weighed in the laboratory, dried at 43 °C for 72 h, and weighed after drying to determine both the moisture concentration and subsequent dry hay yields. Dried grass samples were ball milled and analyzed for energy density or higher heating values (HHV) using a LECO AC500 Isoperibol Calorimeter (Leco Corp., St. Joseph, MI) following ASTM Standard D5865 (ASTM, 2006). Subsequent bermudagrass energy yields (E_{ha}) were calculated as the product of the energy density and hay yield.

2.3. Plant tissue characterization

Dried and milled grass samples were analyzed using a Leco C/N 2000 Analyzer (Leco Corp., St. Joseph, MI) for total combustible carbon and nitrogen. These same ground samples were analyzed for the following nutrients: phosphorous (P); potassium (K); calcium (Ca); magnesium (Mg); sulfur (S); zinc (Zn); copper (Cu); manganese (Mn); iron (Fe); and sodium (Na). Plant nutrient analyses by inductive coupled plasma (ICP) were provided by the Agricultural Service Laboratory at Clemson University and conducted following general procedures outlined elsewhere (Peters et al., 2003).

2.4. Statistical analysis

The experimental design was a randomized complete block with four replicates. Bermudagrass was the main treatment with plots consisting of combinations for irrigation (lateral spacing and irrigation applications) and irrigated nitrogen application (commercial and treated wastewater). Data were analyzed by Proc GLM (General Linear Model) and LSD (least significant difference) with Version 9.1 of Statistical Analysis System (SAS Institute Inc., Cary, NC). Significant differences for main plot and sub-plots and interactions were based on F-test ($P > 0.05$). Any correlations be-

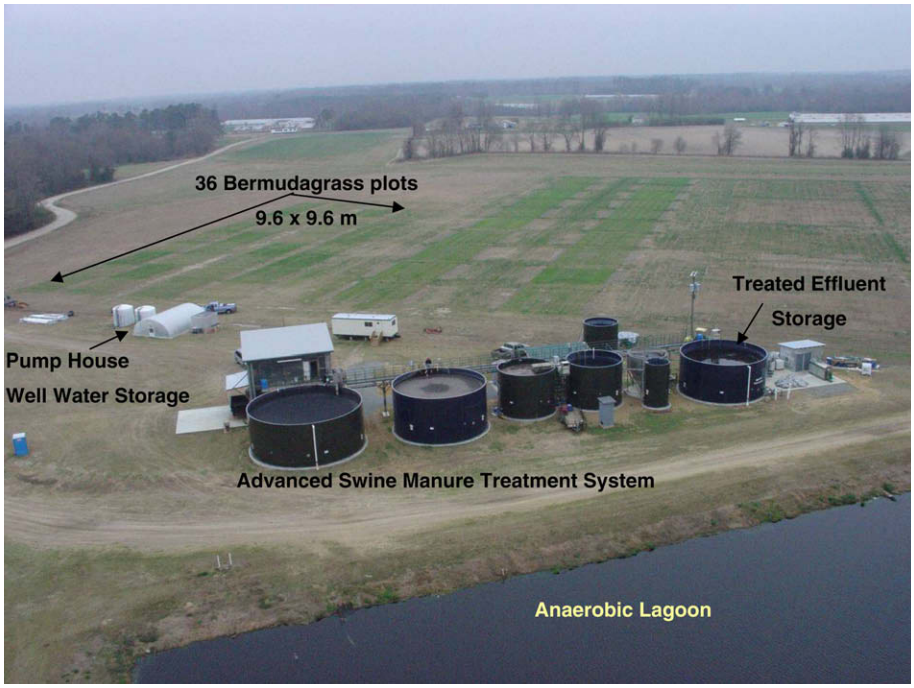

Fig. 1. Arial view of SDI experiment including bermudagrass plots, advanced swine manure treatment system, pump house, and water storages.

Table 1
Typical characteristics of treated raw swine manure, lagoon liquid, and treated effluent[a] (Vanotti and Szogi, 2008).

Water quality parameter	Raw flushed swine manure (mg L^{-1})[b]	Swine lagoon liquid (mg L^{-1})[b]	Treated effluent (mg L^{-1})[b]
TSS	11612 ± 6746	273 ± 58	232 ± 152
TDS	1800 ± 13083	3489 ± 344	3050 ± 792
COD	16758 ± 9910	1692 ± 449	413 ± 185
BOD_5	3046 ± 2341	207 ± 137	10 ± 16
TKN	1501 ± 567	506 ± 110	26 ± 25
NH_4–N	838 ± 311	464 ± 100	14 ± 19
Oxidized–N	1.5 ± 4.5	0.1 ± 0.2	235 ± 116
TP	566 ± 237	130 ± 10	26 ± 16
Soluble P	131 ± 39	118 ± 6	7 ± 7
K	1162 ± 328	1145 ± 77	997 ± 244
Ca	314 ± 171	33.6 ± 17	142 ± 97
Mg	229 ± 112	7.4 ± 4.1	9 ± 5
Cu	32.0 ± 16.8	0.2 ± 0.1	0.3 ± 0.3
Zn	31.2 ± 16.4	0.4 ± 0.3	0.2 ± 0.3
S	167 ± 86	33 ± 15	15 ± 6
Na	250 ± 71	237 ± 15	215 ± 48
pH	7.6 ± 0.2	8.0 ± 0.1	10.5 ± 0.6

[a] TSS = total suspended solids; TDS = total dissolved solids; BOD = biological oxygen demand; COD = chemical oxygen demand; TKN = total Kjeldhal nitrogen; Oxidized–N = NO_3–N + NO_2–N (nitrate plus nitrite); TP = total phosphorous.
[b] Except for pH.

Table 2
Coastal bermudagrass experimental irrigation treatments and non-irrigated control (*rep* = 4).

Treatment	SDI spacing	Fertilizer	Irrigation rate (%)
1	0.6	Commercial[a]	100
2	0.6	Commercial	75
3	0.6	Effluent	100
4	0.6	Effluent	75
5	1.2	Commercial	100
6	1.2	Commercial	75
7	1.2	Effluent	100
8	1.2	Effluent	75
9	Non-irrigated	Commercial[b]	

[a] Commercial fertilizer for SDI spacing treatments was urea-ammonium nitrate.
[b] Commercial fertilizer for non-irrigated control was ammonium nitrate.

tween the energy density and plant nutrient concentrations were identified using Proc CORR and *P*-value less than 0.05 for the Pearson's correlation test.

3. Results and discussion

3.1. Energy yields

Bermudagrass energy densities (MJ kg^{-1}) and yields (MJ ha^{-1}) were analyzed for statistical differences by year due to differences in the total growing period and measureable rainfall between years. For both years, the type of fertilizer affected the energy density (E_{kg}); the commercial-fertilized treatments generated bermudagrass hay with a slightly greater E_{kg} (Table 3). In 2004, bermudagrass E_{kg}-values ranged from 18.62 to 18.91 MJ kg^{-1}; energy densities were slightly greater in 2005 with values between 18.88 and 19.18 MJ kg^{-1}. These energy densities were comparable to the HHV reported by Boateng et al. (2007a) as 18.67 MJ kg^{-1}.

For 2005, bermudagrass hay yields associated with commercial and effluent irrigation averaged 11.9 and 13.3 Mg ha^{-1}, respectively (Table 3). In 2004, commercial fertilizer hay yields were 77.6% of hay yields associated with the effluent treatments (6.76 compared with 8.71 Mg ha^{-1}). The differences in 2004 hay yields, as explained by Stone et al. (2008), were attributed to multiple factors including shorter growing period, rainfall patterns, and potential leaching of nutrients below the root zone.

In 2004, bermudagrass energy yields ranged from 106.9 to 193.1 MJ ha^{-1}; yet, in 2005 yields were much greater ranging from 210.1 to 265.9 MJ ha^{-1} (Table 3). For both years, E_{ha}-values had no significant interaction between fertilizer, irrigation rate, or SDI lateral spacing. Although, the bermudagrass receiving commercial fertilizer had greater energy density each year, the energy yields

Table 3
Coastal bermudagrass annual energy density and yields and summary statistics at the subsurface drip irrigation study site (based on plot harvest).

SDI spacing	Fertilizer	Irrigation rate	Hay yield (Mg ha^{-1})		Energy density (MJ kg^{-1})		Energy yield (MJ ha^{-1})	
			2004	2005	2004	2005	2004	2005
0.6	Commercial	100%	6.70 ± 0.43	12.68 ± 1.57	18.80 ± 0.078	19.01 ± 0.0448	125.96 ± 8.53	241.27 ± 29.49
0.6	Commercial	75%	7.50 ± 0.61	12.93 ± 1.26	18.84 ± 0.202	19.11 ± 0.1871	141.14 ± 13.15	247.09 ± 25.17
0.6	Effluent	100%	7.99 ± 2.19	12.24 ± 3.69	18.64 ± 0.171	18.96 ± 0.0919	148.92 ± 40.66	232.16 ± 69.23
0.6	Effluent	75%	7.98 ± 0.18	14.08 ± 1.30	18.62 ± 0.256	18.88 ± 0.1264	148.61 ± 1.51	265.88 ± 23.07
1.2	Commercial	100%	5.65 ± 1.64	10.97 ± 2.90	18.91 ± 0.136	19.12 ± 0.1523	106.87 ± 31.12	210.06 ± 55.33
1.2	Commercial	75%	7.20 ± 1.84	11.04 ± 4.16	18.87 ± 0.185	19.18 ± 0.1395	135.80 ± 34.08	211.27 ± 78.20
1.2	Effluent	100%	8.58 ± 1.71	13.21 ± 3.34	18.72 ± 0.089	18.90 ± 0.1126	160.84 ± 32.27	249.53 ± 61.63
1.2	Effluent	75%	10.31 ± 1.05	13.64 ± 1.04	18.74 ± 0.120	18.91 ± 0.0919	193.13 ± 19.50	258.12 ± 19.24
Non-irrigated	Commercial		8.13 ± 0.69	12.26 ± 3.12	18.78 ± 0.213	19.08 ± 0.1891	152.82 ± 14.33	233.61 ± 57.74
$LSD_{0.05}$			1.76	3.92	0.147	0.151	32.3	73.5
Summary statistics for SDI irrigated plots								
Means[A]	Spacing	0.6	7.54a[B]	12.98a	18.73a	18.99a	141.2a	246.6a
		1.2	7.93a	12.22a	18.81a	19.03a	149.2a	232.3a
	Fertilizer	Commercial	6.76a[B]	11.91a	18.86a	19.11a	127.4a	227.4a
		Effluent	8.71b	13.29a	18.68b	18.91b	162.9b	251.4a
	Irrigation rate	100%	7.23a	12.28a	18.77a	19.00a	135.7a	233.3a
		75%	8.25a	12.92a	18.77a	19.02a	154.7a	245.6a

[A] No statistical differences (at the $P = 0.05$ level) were noted for spacing and irrigation rate treatments.
[B] Means followed by the same letter were not significantly difference at the $P = 0.05$ level.

were altered only by fertilizer in 2004. Fertilization with treated effluent would provide 21.8% more biomass energy available for a local combustion plant. With an increase in available energy per area, a larger power plant can be supported (Fig. 2). Assuming 40% electrical conversion efficiency (Demirbas, 2001), bermudagrass grown using commercial or treated effluent within a 48 km (~30 mi) radius (i.e., harvested from 7323 km^2 area) would provide 6–7 MW.

One of the benefits of using treated effluent in an SDI system with its reduced nutrient concentrations is that the treated effluent can be used to supplement existing irrigation water supplies. Previously reported in Stone et al. (2008), total irrigation among the commercial fertilization plots averaged 104.4 mm in 2004 and 323.6 mm in 2005. Total irrigation water for the treated effluent plots averaged 126.5 mm in 2004 and 323.6 mm in 2005. The treated effluent volume accounted for 48.4% and 76.5%, respectively, of the total irrigation volumes. Using treated effluent increased the water-energy yield potential for 2004 and 2005 from 1.23 and 0.71 MJ ha^{-1} mm^{-1}, respectively, to 1.39 and 0.79 MJ ha^{-1} mm^{-1}. Ultimately, the application of effluent reduced the bioenergy crop production dependency on fresh ground water at this site. Thus, more fresh ground water is available for other purposes within a farm such as agricultural food production.

3.2. Feedstock characterization

For this study, plant nitrogen was not affected by fertilizer, SDI lateral spacing, or irrigation rate (Table 3). However, plant carbon was statistically greater for commercial-fertilized bermudagrass hay – 44.63 compared with 44.24 wt% (Table 4).

For the consecutive years this study was performed, bermudagrass plant N concentrations averaged among treatments were not different while some individual bermudagrass plant N concentrations were found to be different and ranged between 2.04% and 2.25% and 1.93% and 2.04%, respectively. These N concentrations are generally lower than the 2.2% critical N concentration in Coast-

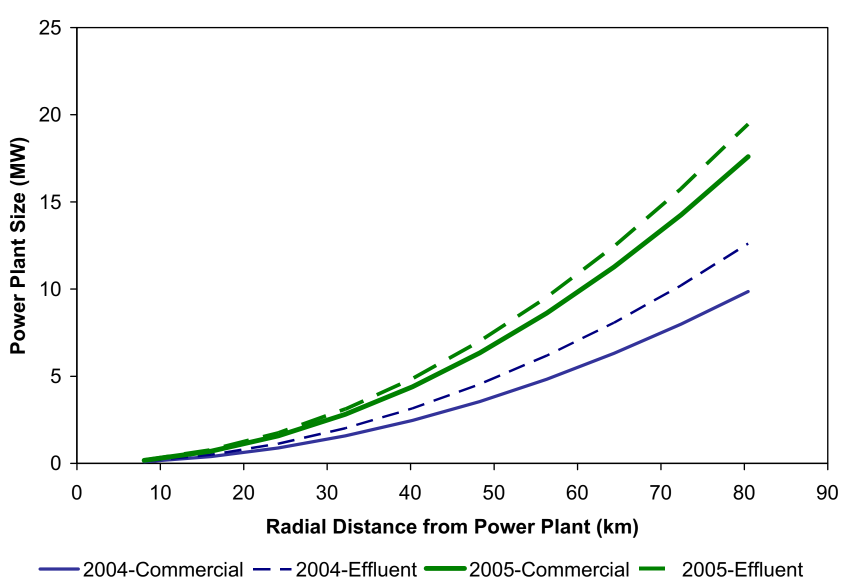

Fig. 2. Relative power plant size* supported by combustion of bermudagrass grown within defined radius. *Calculations assume 40% conversion efficiency.

Table 4
Coastal bermudagrass hay carbon and nitrogen concentrations and summary statistics at the subsurface drip irrigation study site (based on plot harvest).

SDI spacing	Fertilizer	Irrigation rate	Plant carbon (%)		Plant nitrogen (%)	
			2004	2005	2004	2005
0.6	Commercial	100%	44.60 ± 0.13	46.14 ± 0.38	2.05 ± 0.06	1.94 ± 0.10
0.6	Commercial	75%	44.52 ± 0.35	46.23 ± 0.22	2.12 ± 0.10	1.96 ± 0.06
0.6	Effluent	100%	44.14 ± 0.19	45.45 ± 0.23	2.25 ± 0.20	2.02 ± 0.19
0.6	Effluent	75%	44.25 ± 0.15	45.46 ± 0.30	2.17 ± 0.05	1.94 ± 0.11
1.2	Commercial	100%	44.68 ± 0.15	45.81 ± 0.36	2.14 ± 0.11	2.04 ± 0.13
1.2	Commercial	75%	44.70 ± 0.37	45.57 ± 0.33	2.04 ± 0.06	1.95 ± 0.08
1.2	Effluent	100%	44.23 ± 0.20	45.20 ± 0.69	2.21 ± 0.13	1.99 ± 0.11
1.2	Effluent	75%	44.32 ± 0.14	45.27 ± 0.68	2.10 ± 0.04	1.93 ± 0.04
Non-irrigated	Commercial		44.43 ± 0.26	46.30 ± 0.85	2.23 ± 0.06	2.06 ± 0.16
$LSD_{0.05}$			0.25	0.75	0.12	0.07
Summary statistics for SDI Irrigated plots						
Means[A]	Spacing	0.6	44.38a[B]	45.82a	2.16a	1.96a
		1.2	44.48a	45.46a	2.12a	1.98a
	Fertilizer	Commercial	44.63a[B]	45.94a	2.09a	1.97a
		Effluent	44.24b	45.35a	2.18a	1.97a
	Irrigation rate	100%	44.41a	45.65a	2.16a	2.00a
		75%	44.45a	45.63a	2.11a	1.95a

[A] No statistical differences (at the $P = 0.05$ level) were noted for spacing and irrigation rate treatments.
[B] Means followed by the same letter were not significantly difference at the $P = 0.05$ level.

al bermudagrass forage to achieve 90% of the maximum hay yield (Robinson, 1996). In fact, hay yields increased while plant N decreased. This was observed even for the non-irrigated plots. The nitrogen source, application method, and other environmental factors have contributed to the varying yield response (Silveira et al., 2007). Plant N concentrations were between those reported for Coastal hybrid bermudagrass receiving chicken litter (Sistani et al., 2008) and Coastal bermudagrass receiving swine lagoon effluent (Burns et al., 1985).

Among the measured plant nutrients (Tables 5 and 6), Mg and P were the only measured minerals affected by an interaction of year and treatment. Magnesium concentrations decreased while P concentrations increased in 2005. Thus, concentrations reported are averaged across years. Potassium was the most significant mineral present with concentrations upwards of 2.28%. Subsequently, this mineral had the greatest measured concentration in treated effluent (Table 1). Plant Mg, P, S, Ca, and Na were also present in relatively large quantities. Sulfur concentrations were not influenced by treatments. Concentrations of Mg and Mn in non-irrigated were higher than concentration of irrigated plots. While plant nutrients were not affected by spacing, differences in plant nutrients based on irrigation rate were noted primarily when there were statistical differences in the commercial and effluent treatments. Greater concentrations of P, K, Ca, and Mn were noted with the treatments receiving more irrigation to meet 100% of ET.

The use of treated swine wastewater effluent verses commercial fertilizer decreased plant concentrations of P while at the same time increased the plant concentrations of Ca. Greater Ca levels in the bermudagrass receiving effluent can be attributed to the waste treatment system that removed soluble P from the swine wastewater with the addition of a lime slurry (30% $Ca(OH)_2$) (Vanotti and Szogi, 2008). Although this lime addition removed up to 94% of soluble P, some Ca remained in the wastewater effluent and was readily available for bermudagrass uptake. Even with the lime addition, plant Ca concentrations in both the commercial and effluent treatments were comparable to other studies where Coastal bermudagrass received swine lagoon effluent with values reported between 0.31% and 0.42% (Burns et al., 1985).

Application of treated swine wastewater effluent also increased the uptake of water-soluble metal salts of K and Na (Tables 5 and 6).

Table 5
Measured phosphorous, potassium, calcium, magnesium, and sulfur bermudagrass nutrient concentrations and treatment summary statistics at the subsurface drip irrigation study site (based on plot harvest).

SDI spacing	Fertilizer	Irrigation rate	P (%)	K (%)	Ca (%)	Mg (%)	S (%)
0.6	Commercial	100%	0.250 ± 0.035	2.01 ± 0.115	0.303 ± 0.014	0.171 ± 0.018	0.242 ± 0.043
0.6	Commercial	75%	0.245 ± 0.022	2.00 ± 0.244	0.314 ± 0.026	0.176 ± 0.022	0.248 ± 0.028
0.6	Effluent	100%	0.252 ± 0.040	2.27 ± 0.130	0.345 ± 0.067	0.166 ± 0.021	0.254 ± 0.027
0.6	Effluent	75%	0.218 ± 0.013	2.19 ± 0.101	0.331 ± 0.040	0.176 ± 0.022	0.270 ± 0.046
1.2	Commercial	100%	0.250 ± 0.045	2.02 ± 0.185	0.325 ± 0.061	0.166 ± 0.018	0.258 ± 0.059
1.2	Commercial	75%	0.247 ± 0.031	1.93 ± 0.270	0.294 ± 0.024	0.177 ± 0.019	0.245 ± 0.051
1.2	Effluent	100%	0.244 ± 0.033	2.28 ± 0.174	0.334 ± 0.039	0.167 ± 0.022	0.267 ± 0.025
1.2	Effluent	75%	0.215 ± 0.016	2.15 ± 0.109	0.308 ± 0.022	0.164 ± 0.018	0.269 ± 0.033
Non-irrigated	Commercial		0.228 ± 0.019	2.00 ± 0.172	0.300 ± 0.017	0.198 ± 0.019	0.263 ± 0.038
$LSD_{0.05}$			0.017	0.151	0.026	0.019	0.023
Summary statistics for SDI irrigated plots							
Means[A]	Spacing	0.6	0.241a[B]	2.12a	0.323a	0.172a	0.254a
		1.2	0.239a	2.09a	0.315a	0.168a	0.260a
	Fertilizer	Commercial	0.248a[B]	1.99a	0.309a	0.173a	0.248a
		Effluent	0.232b	2.22b	0.329b	0.168a	0.265a
	Irrigation Rate	100%	0.249a	2.14a	0.327a	0.168a	0.255a
		75%	0.231b	2.07b	0.312b	0.173a	0.258a

[A] No statistical differences (at the $P = 0.05$ level) were noted among spacing treatments.
[B] Means followed by the same letter were not significantly difference at the $P = 0.05$ level.

Table 6
Measured zinc, copper, manganese, iron, and sodium bermudagrass nutrient concentrations and treatment summary statistics at the subsurface drip irrigation study site (based on plot harvest).

SDI spacing	Fertilizer	Irrigation rate	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	Na (ppm)
0.6	Commercial	100%	31.0 ± 4.69	18.0 ± 6.61	55.8 ± 18.2	101.1 ± 29.3	117.8 ± 14.0
0.6	Commercial	75%	30.2 ± 2.51	19.1 ± 12.0	50.7 ± 12.8	128.5 ± 78.4	113.4 ± 17.1
0.6	Effluent	100%	25.0 ± 3.80	16.5 ± 8.43	40.1 ± 11.1	125.7 ± 82.3	172.7 ± 15.9
0.6	Effluent	75%	24.9 ± 2.11	15.9 ± 6.46	41.8 ± 10.1	101.3 ± 23.9	174.4 ± 21.0
1.2	Commercial	100%	31.2 ± 4.04	20.7 ± 7.33	56.4 ± 13.2	89.4 ± 20.9	124.9 ± 22.2
1.2	Commercial	75%	31.1 ± 6.40	16.0 ± 5.69	51.5 ± 19.3	98.6 ± 37.8	118.5 ± 20.8
1.2	Effluent	100%	25.1 ± 3.56	18.5 ± 10.4	49.1 ± 17.8	87.4 ± 17.7	194.9 ± 24.1
1.2	Effluent	75%	22.6 ± 2.08	17.2 ± 6.09	40.4 ± 7.43	88.6 ± 40.4	170.8 ± 18.0
Non-irrigated	Commercial		31.6 ± 5.37	14.3 ± 3.59	68.1 ± 13.4	91.6 ± 31.0	124.9 ± 15.2
$LSD_{0.05}$			2.77	4.96	6.59	49.9	16.8
Summary statistics for SDI irrigated plots							
Means[A]	Spacing	0.6	27.8a[B]	17.4a	47.1a	114.1a	144.6a
		1.2	27.5a	18.1a	49.3a	91.0a	152.3a
	Fertilizer	Commercial	30.9a[B]	18.4a	53.6a	104.4a	118.6a
		Effluent	24.4b	17.0a	42.8b	100.7a	178.2b
	Irrigation rate	100%	28.1a	18.4a	50.3a	100.9a	152.5a
		75%	27.2a	17.0a	46.1b	104.2a	144.3a

[A] No statistical differences (at the $P = 0.05$ level) were noted among spacing treatments.
[B] Means followed by the same letter were not significantly difference at the $P = 0.05$ level.

For K and Na, many solid–liquid separation processes have shown nominal removal of soluble nutrients (Vanotti et al., 2002; Zhang and Westerman, 1997). In a previous study by Vanotti and Szogi (2008), K and Na concentrations in the original waste were only reduced through treatment by 14% (Table 1); thereby potentially allowing excessive nutrient application. Consequently, K and Na concentrations in the bermudagrass increased from non-irrigated to effluent irrigated plots by 10% and 30%, respectively. Even though greater concentrations of K and Na were in the effluent-treated bermudagrass, values did not exceed those previously reported (Burns et al., 1985). The increased concentration of these two components as well as the P and Ca, would directly contribute to an increased ash portion. This increase contributed to the effluent-treated bermudagrass exhibiting a reduction in energy density (Table 2). In fact, the concentrations of K, Ca, and Na had an inverse correlation with the energy density (Table 7, Fig. 3).

Other metals such as Zn, Cu, and Mn also contribute to a plant's ash portion. Even though Zn and Cu are common mineral supplements in swine rations, concentration differences between the commercial and effluent treatments were only noted for Zn. Effluent-treated bermudagrass yielded greater Zn concentrations of 30.9 versus 24.4 ppm. In addition, Mn concentrations were least among all treatments for effluent-treated bermudagrass. Whereas these metals were removed primarily using polymer flocculation with an upper removal efficiency of 99% (Vanotti and Szogi, 2008) from the original swine wastewater, potentially less of these constituents were available for plant uptake. The use of an advanced wastewater treatment system not only promotes nutrient removal from the manure but also removal of these nutrients from the ash portion in a plant thereby potentially increasing the bioenergy quality of irrigated crops.

3.3. Potential impacts on thermochemical conversion

Because of elevated alkali and silica concentrations, the nutrient composition of lignocellulosic feedstocks like bermudagrass places specific demands on thermal conversion (TC) technologies like combustion, pyrolysis, and gasification. During pyrolysis, which is an initial step in many thermochemical conversion operations, many inorganic components are retained in the char thereby influencing ash chemistry, slagging, and fouling characteristics (Fahmi et al., 2007). The slagging of ash and subsequent fouling of construction materials are attributed to the agglomeration consisting primarily of K, Ca, and Si (Ohman et al., 2000). At elevated temperatures, the ash enters a liquid state or slag and when combined with silica forms a sticky phase that deposits onto interior surfaces. This deposition onto boiler pipes, heat exchangers, and internal combustion parts are a function of not only physical design and operation but fuel properties (Miles et al., 1996). In one reported instance for gasification of Kentucky bluegrass in a dual-functioning gasifier (Boateng et al., 2007b), control of the 650 °C operating temperature generated a high silica, high alkaline unreacted char (SiO_2 – 34.8 wt%; K_2O – 23.4 wt%; P_2O_5 – 3.24; CaO – 4.09 wt%; MnO_2 – 0.20 wt%; Na_2O – 0.07 wt%) that had little to no slagging. In the case of the current study, the effluent fertilizer, however, promoted plant accumulation of K, Ca, and Na and may result in decreased efficiency of an existing TC unit.

Contrary to causing a decrease in mechanical efficiencies, these same inorganic components (K, Ca, and Na) are thought to act as catalysts improving the rate of both degradation and pyrolytic char yield. Inorganic salts have been shown to reduce the onset temperature for degradation (Williams and Horne, 1994). Sodium carbonate, limestone, and dolomite increased both the gasification conversion efficiency and calorific values of product gases (Gil et al., 1999; NSF, 2008; Zhou et al., 2007). Both K and Na have been identified to promote the secondary char gasification reactions with CO_2 and H_2O that generate the combustible gases of CO and H_2 (Abu El-Rub et al., 2004; Raveendran and Ganesh, 1996; Sheth and Turner, 2002). Using KCl and $ZnCl_2$ salts to amend agricultural residual biomass for pyrolysis reduced char yield and increased gaseous volatiles (Raveendran et al., 1995). However, a significant portion of K and Na were vaporized and would have required

Table 7
Pearson correlation coefficients (PCC) for relationship between bermudagrass energy density on mean plant nutrient concentrations of P, K, Ca, Mg, Zn, Cu, Mn, Fe, S, and Na.

	P	K	Ca	Mg	S	Zn	Cu	Mn	Fe	Na
PCC	0.814	−0.466	−0.253	−0.180	0.177	0.027	0.432	−0.064	−0.110	−0.364
P-Value	0.500	<0.001	0.032	0.129	0.137	0.820	0.0002	0.592	0.359	0.002

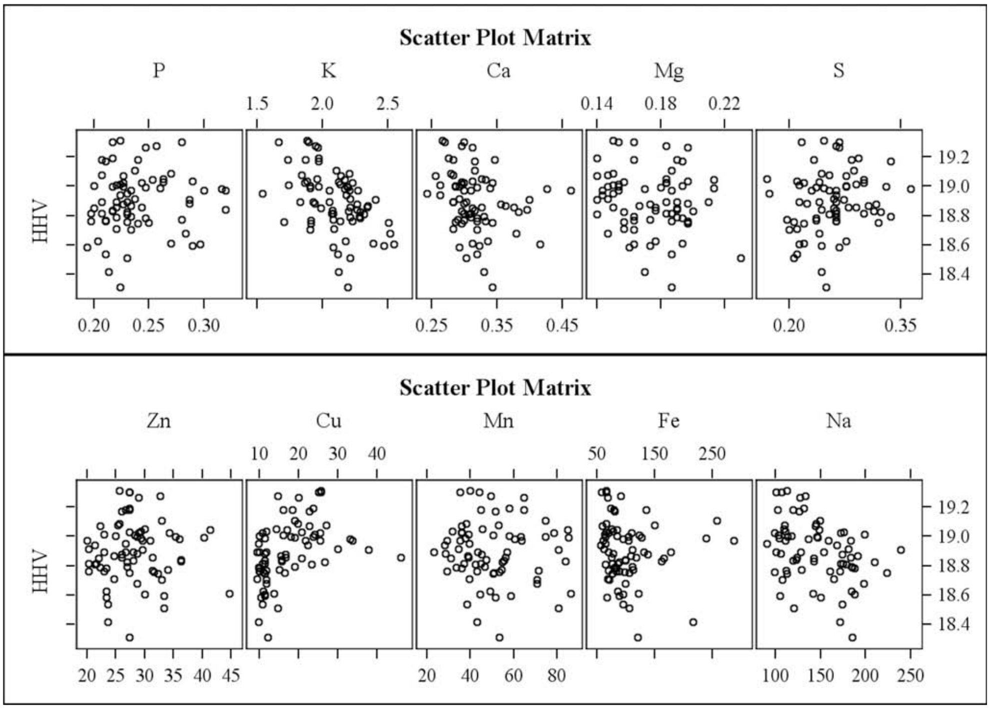

Fig. 3. Scatter plot between energy density (HHV) on plant nutrient concentrations of P, K**, Ca**, Mg, Zn, Cu**, Mn, Fe, S, and Na**. **Significant for $P < 0.05$ (Pearson's correlation test); df = 71. Units are: HHV MJ kg^{-1}; P, K, Ca, Mg, S%; Zn, Cu, Mn, Fe, and Na ppm.

downstream removal for a higher quality combustible gas. Referring back to the present study, treated effluent promoted plant accumulation of K, Ca, and Na; as such, the respective bermudagrass may lend itself to be a better feedstock for gasification purposes.

To increase the energy yield by reducing the ash, the grasses can be leached with water to remove large fractions of alkali metals, upwards of 80% of K and Na (Dayton et al., 1999). However, developing a quality feedstock for gasification or pyrolysis where a combustible gas or oil is desired will require a balance among minerals.

4. Conclusion

While the irrigation rate and SDI spacing did not affect bermudagrass hay or energy yields, irrigation with treated swine wastewater effluent via SDI compared to commercial fertilizer produced greater hay yields and subsequent greater energy yields (MJ ha^{-1}). Commercial fertilizer applied to bermudagrass resulted with hay having a greater energy density (MJ kg^{-1}). Effluent-irrigated treatment reduced plant concentrations of Zn, Mn, and P. This reduction, attributed to the use of polymer-assisted solid separation and lime additive P-removal during the waste treatment process, may improve the bermudagrass' bioenergy conversion characteristics. This is especially true since these components are found in ash and consequently decrease energy density and conversion operation efficiency. Subsurface drip irrigation with swine effluent also increased K, Ca, and Na in the bermudagrass hay, which may have positive implications on future thermochemical conversion processes by promoting combustible gas formation.

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