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BIOMASS AND BIOGAS YIELDING POTENTIAL OF SORGHUM AS AFFECTED BY PLANTING DENSITY, SOWING TIME AND CULTIVAR

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Abstract

Biogas from biomass is a promising renewable energy source whose importance is increasing in European as well as in other countries. A field experiment at one location (Experimental Station Giessen, Justus Liebig University of Giessen, Germany) over two years was designed to study the effect of altering sowing time (ST), planting density and cultivar on the biomass yield and chemical composition of biomass sorghum, and its potential for methane production. Of the two cultivars tested, cv. Goliath (intraspecific hybrid) was more productive with respect to biomass yield than cv. Bovital (*S. bicolor* x *S. sudanense* hybrid). ST also influenced biomass yield and most of the quality parameters measured. Delayed sowing was in general advantageous. The choice of cultivar had a marked effect on biogas and methane yield. The highest biogas and methane yields were produced by late sown cv. Bovital. Sub-optimal planting densities limited biomass accumulation of the crop, however neither the chemical composition nor the methane yield was affected by planting density.

Key words: Sowing date; Planting density; Biomass yield; Protein content; Fibre content; Methane production.

Introduction

Following a policy decision to reduce the level of CO_2 emission and increase energy efficiency, the European Union has set a goal of raising the proportion of total energy contributed by renewables to 20% by 2020 (Richter *et al*., 2009). Different countries of the world are invested in different sort of biogas systems depending on environment and energy programs. The South Korea and UK for example are getting most of biogas from landfill sites, whilst Sweden and Switzerland have made systems for decomposition at sewage plants. Denmark uses manure to a large extent as this has been a means of dealing with the overproduction of manure there. Germany, Denmark, UK and Sweden are main examples of countries where biogas production is being produced from energy crops and food waste (Anon., 2015).

As a result, the exploitation of agricultural crops for the generation of biogas is gaining importance (Karpenstein-Machan, 2001, Schittenhelm, 2008, Mahmood & Honermeier, 2012a). Different crops are being studied for biogas production through anaerobic digestion. These include sunflower (*Helianthus anus* L.), sorghum (*Sorghum bicolor* L.), cup plant, switch grass, poor oat grass meadows (*Arrhenaterion*), small-sedge poor-fen meadow (Caricion fuscae), tall herb meadow (*Filipendulion ulmariae*), montane hay meadow (Polygono-Trisetion), hemp, sorghum and sudan grass (Beck *et al*., 2007; Rishter *et al*., 2009, Schittenhelm 2010, Mahmood & Honermeier, 2012b, Mahmood *et al*., 2013). In Germany, maize silage is presently the most important source of biogas production (Schittenhelm, 2008), but further intensification of maize cropping would put pressure on crop species diversity and increase the risk of pest damage and nutrient losses (Schittenhelm, 2010). An attractive alternative to maize is sorghum, which produces a biomass compositionally similar to that of maize, and is known to be highly productive for biomass (Fribourg, 1995, Mahmood & Honermeier, 2012b, Mahmood *et al*., 2013). Sorghum is a warm climate crop, which has yet to be adapted to the temperate climate prevailing in northern Europe. In particular, its husbandry needs to be modified from that practised in its more traditional cropping environment. The chemical composition and biodegradability of biomass are major factors in methane yield. Compounds like crude protein (XP), crude fat, crude fibre, cellulose, hemi-cellulose, starch, and sugars clearly influence methane production (Amon *et al*., 2007). Two readily manipulatable agronomic variables which require optimization are sowing time and planting density, both of which are known to affect biomass yield (Berenguer & Faci, 2001, Blum & Naveh, 1976, Cusicanqui & Lauer, 1999, Defoor *et al*., 2001, Hipp *et al*., 1970, Kucharik, 2008), while the latter variable can also influence the chemical composition of the biomass (Caravetta *et al*., 1990, Lafrage & Hammer, 2002, Rosenthal *et al*., 1993). The present study describes the outcome of experiments designed to explore the effect of varying sowing time and planting density on the biomass yield and composition of forage sorghum in the context of its use for biogas production.

Materials and Methods

Site description and crop management: The experiments were conducted over two seasons (2008 and 2009) at Gross-Gerau Experimental Station (49°55’N 8°28’E, 83-145m over sea level), Germany. The local soil varies from a slightly loamy to loamy sand. The crop was given supplemental irrigation of 40mm in 2008 and 36mm in 2009. The mean air temperature during the growing season was 14.9°C in 2008 and 16.2°C in 2009, and total rainfall from April to October amounted to, 448mm and 405mm respectively (Table 1). The experiments were set out as randomized complete blocks, with a factorial arrangement and four replications. The treatments consisted of three sowing times (ST) (2008: May 13 and 27, June 10; 2009: May 14, June 10 and 23), three planting densities (PD) (16, 24 and 32 plants m^{-2}) and two cultivars bred by Agroczemek KFT, Hungary (cv. Goliath, a late-maturing intraspecific hybrid and cv. Bovital, an early maturing *S. bicolor* x *S. sudanense* hybrid). Each $10m^2$ plot was dressed directly after sowing with 120kg N ha^{-1} in the form of ammonium nitrate and weeds were controlled by the application of 3.5L ha^{-1} Gardo Gold (chloroacetinelide) supplemented by hand weeding. The crop was harvested (at 25 to 28% DM) with a silage plot harvester.

Table 1. Climatic variables measured during the 2008 and 2009 growing seasons at Gross-Gerau Experimental Station.

Months	2008				2009			
	AT °C	LAT °C	PS mm	LPS mm	AT °C	LAT °C	PS mm	LPS mm
April	8.8	9.4	76	41	15.1	9.5	36	41
May	17.0	14.0	39	57	15.7	14.0	55	57
June	18.3	17.2	115	64	17.1	17.2	109	65
July	19.4	19.0	30	67	19.7	19.0	72	67
August	18.4	18.2	72	64	20.2	18.2	46	64
September	12.6	14.4	56	47	15.6	14.4	40	47
October	9.6	9.5	60	50	9.4	9.5	47	50
Sum	-	-	448	390	-	-	405	391
Mean	14.9	14.5	-	-	16.2	14.5	-	-

AT: Air temperature (°C), LAT: Long term air temperature (°C), PS: Precipitation sum (mm), LPS: Long term precipitation average (mm)

Biomass characterization and chemical composition: Plant height at the time of harvest was measured by using bricklayer ruler. Prior to bulk harvesting, a $1m^2$ sample was removed from each plot and separated into leaves, stems and panicles, and the dry weight of each component was determined after baking at 105°C for 48h. Numbers of tillers were calculated from the $1m^2$ harvested area. Immediately post bulk harvesting, the biomass moisture content was determined by reweighing a 100g sample held at 105°C for 48h. Material used for the assessment of chemical composition was dried and finely ground. The concentrations of protein, sugar, neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) were determined using near infrared reflectance spectroscopy. Scanning of the samples was done with a Foss NIR system scanning monochromator (Model 6500, Silver, Spring, MD) at the range of 780 to 2500 nm. The prediction equation based on a calibration established in our lab with sorghum in 2008. Results from the calibrated samples were used to develop a prediction equation by modified partial least squares regression (Shenk & Westerhaus, 1991). The volatile solids (VS) content was calibrated as weight loss during incineration at 550°C by muffle furnace for the estimation of organic matter in the samples. The ash content was measured as the incineration residues.

Specific biogas and methane yield measurement: The determination of biogas yield was obtained using a laboratory digester operated at 38°C, based on the method described by Richter *et al*. (2009). Liquid manure provided the source of microbes for the 21 day anaerobic digestion process in a digester composed of 300g of chopped whole plant material and 16kg of liquid manure. The volume of biogas produced was measured by using a Wet Ritter device. It works upon the principle of positive displacement. As biogas travelled from one chamber of the drum to the other, the drum rotated. This rotated the needle-dials around the scales so that the positions of the needles on the scales were read directly as the volume of gas that has flown through the meter. The information about full volume and the fractions of the volumes was provided by large needles and smaller needle respectively. On the basis of calculated volatile solids the specific biogas (nL/kg VS) of the corresponding sorghum samples was measured.

A non-dispersive infrared sensor (model GS IRM-100) was used to quantify the methane content of the biogas. The main components are an infrared source (lamp), a sample chamber, a wavelength filter, and an infrared detector. The gas is diffused into the sample chamber, and gas concentration is estimated electro-optically by its absorption of a specific wavelength in the infrared (IR). The IR light is pumped through the sample chamber towards the detector which has an optical filter that prevents all types of light except the wavelength that the selected gas molecules can absorb. The intensity of IR light that reaches the detector is inversely related to the concentration of target gas in the sample chamber. As the concentration of specific gas increases, the intensity of IR light striking the detector decreases.

Statistical analysis: The experimental data were statistically analysed using the software package PIAF (Planning information analysis program for field trials). A general linear model was assumed, and multiple comparisons were performed using a *t* test, with a chosen significance level of $p \leq 0.05$. Mean values were compared using a least significant difference test.

Results

In both seasons, the cv. Goliath plants grew taller than those of cv. Bovital, but there were significant interaction between cultivar and ST, cultivar and PD. At the two later sowings in 2008, cv. Goliath plants grew taller than those grown from the earliest sowing, while in 2009, cv. Bovital plants sown at both the earliest and latest dates were taller than those sown at the intermediate one (Table 2). DM content was largely unaffected by cultivar, although that of cv. Bovital was somewhat higher than that of cv. Goliath. Significant interactions for this trait were observed between both cultivar and ST, and cultivar and PD in 2008 (Table 2). In both seasons, cv. Bovital plants developed a higher tiller density than did cv. Goliath plants. In 2008, ST had no significant effect on tiller density, but in 2009, late sown plants tillered more profusely. The higher PDs (24 and 32 plants m^{-2}) increased tiller density per m^2 over the lowest PD (data not shown). Significant cultivar by ST and cultivar by PD interactions were noted for tiller density in 2009. The most densely sown crop of cv. Bovital produced the highest tiller density, particularly following its latest sowing, while the least densely sown crop of cv. Goliath produced the lowest tiller density per m^2 (Table 2). With respect to biomass production, there was a major cultivar effect, with cv. Goliath out-yielding cv. Bovital in both seasons. ST also had significant influence on biomass yield, with the later sowings in 2008 producing significantly higher biomass yields (Table 3). There was a significant interaction between cultivar and in 2009. Goliath produced maximum biomass at early sowing time while, cv. Bovital exhibited lowest yield at latest sowing time (Table 2). Increasing the PD enhanced biomass yield in 2008, and there was a large interaction with cultivar in 2009. At each level of PD, cv. Goliath was more productive than cv. Bovital (Table 2). There was no significant impact of PD on the proportion of biomass occupied by leaf material in 2008, but in 2009 the two cultivars performed significantly differently for this trait, when the later maturing cv. Goliath produced a rather larger proportion of leaf material than cv. Bovital. On the other hand, the cv. Bovital biomass comprised a higher proportion panicle material than that of cv. Goliath. There was no effect of ST on the distribution of dry matter among the three fractions in 2009, but a significant effect was clear in 2008, when the proportion of the biomass represented by stem material was significantly higher in the later-sown materials, and the contribution of panicle material was lower (Table 3).

Table 2. Effect of sowing time (ST), planting density (PD) and cultivar (CV) on plant height (Ph), tillers density, dry matter content (DM %) and dry matter yield (DM) of sorghum (2008 and 2009 seasons).

Treatment		2008		2009		
		Ph (cm)	DM %	Ph (cm)	DM (t/ha)	Tillers/m^2
Plant density	**Cultivar**					
16 plants m^{-2}	Goliath	382 a	25.2 c	366 a	17.76 a	17 d
	Bovital	271 d	26.8 a	265 c	11.73 c	31 b
24 plants m^{-2}	Goliath	364 b	26.0 abc	328 b	17.65 a	23 c
	Bovital	280 cd	25.2 c	279 c	13.47 b	34 a
32 plants m^{-2}	Goliath	358 b	25.7 bc	309 b	16.57 a	29 b
	Bovital	292 c	26.4 ab	276 c	13.03 b	35 a
Sowing date						
1st sowing	Goliath	335 b	27.1 a	342 a	19.38 a	25 c
	Bovital	251 e	27.7 a	251 c	12.12 e	31 b
2nd sowing	Goliath	389 a	24.2 c	326 a	17.33 b	21 c
	Bovital	283 d	25.1 bc	295 b	13.83 d	29 b
3rd sowing	Goliath	379 a	25.6 b	336 a	15.27 c	23 c
	Bovital	307 c	25.6 b	274 c	12.29 e	40 a

Values sharing a letter in common within a column do not differ significantly at $p \leq 0.05$

Table 3. Effect of sowing time (ST), planting density (PD) and cultivar (CV) on biomass dry matter yield (DM) and partitioning of sorghum (2008 and 2009 seasons).

Treatment	DM ($t\ ha^{-1}$)	2008			DM ($t\ ha^{-1}$)	2009		
		Leaves	Panicles	Stems		Leaves	Panicles	Stems
		(%DM)	(%DM)	(%DM)		(%DM)	(%DM)	(%DM)
Cultivar								
Goliath	17.5 a	16.8	4.0 b	79.1 a	17.32 a	23.3 a	4.6 b	72.1 a
Bovital	11.6 b	16.9	14.7 a	68.4 b	12.75 b	17.2 b	25.6 a	57.2 b
Plant density								
16 plants m^{-2}	13.6 b	17.3 a	9.5 ab	73.2	14.75	18.9	15.2	65.8
24 plants m^{-2}	15.3 a	16.8 a	10.0 a	73.3	15.56	20.5	15.8	63.7
32 plants m^{-2}	14.8 a	16.5 a	8.7 b	74.8	14.80	21.3	14.3	64.5
Sowing time								
1st sowing	13.8 b	17.0	11.1 a	71.9 b	15.78 a	19.9	15.0	65.1
2nd sowing	14.7 a	16.2	9.0 b	74.9 a	15.58 a	19.9	14.8	65.2
3rd sowing	15.2 a	17.3	8.1 b	74.6 a	13.80 b	20.9	15.4	63.7
$LSD_{0.05}$								
Cultivar	0.59	ns	0.8	1.9	0.74	2.3	3.3	3.3
Plant densiy	0.73	ns	1.0	ns	ns	ns	ns	ns
Sowing date	0.73	ns	1.0	2.3	0.91	ns	ns	ns
CV x PD	ns	ns	ns	ns	1.29	ns	ns	ns
CV x ST	ns	ns	ns	ns	1.29	ns	ns	ns
PD x ST	ns	ns	ns	ns	ns	ns	ns	ns

Values sharing a letter in common within a column do not differ significantly at $p \leq 0.05$

PD did not affect protein, sugar, NDF, ADF or ADL contents significantly in either of the two years (Table 4). There was a cultivar effect on protein concentration, which ranged from 6 to 9% on a dry biomass weight basis. In both years, the protein content of cv. Bovital biomass was higher than that of cv. Goliath (Table 4). In 2008, earlier sowing was associated with a higher protein concentration, but in 2009, the highest protein concentrations were recorded from the later sowings. A delayed ST also increased the biomass sugar concentration, with cv. Goliath tissue accumulating more sugar than cv. Bovital (Table 4). A significant interaction was observed between cultivar and ST interaction occurred in 2008, with the early sown cv. Bovital plants accumulating the least sugar (Fig. 1a). NDF accumulation differed between the two cultivars, ranging from 50-63%. During both years, the NDF content of cv. Goliath biomass was considerably higher than that of cv. Bovital (Table 4). A significant cultivar by ST interaction occurred in 2008, when cv. Goliath responded markedly to the intermediate ST (Fig. 1b). There was also a notable cultivar effect on lignin accumulation, which ranged from 4-6%, with cv. Bovital out-performing cv. Goliath (Table 4). Lignin accumulation was unaffected by ST in 2008, but decreased as ST was delayed in 2009. A significant interaction cultivar by ST interaction occurred in 2009, with the poorest accumulation of lignin recorded by cv. Bovital sown at the intermediate date (Fig. 2a). .

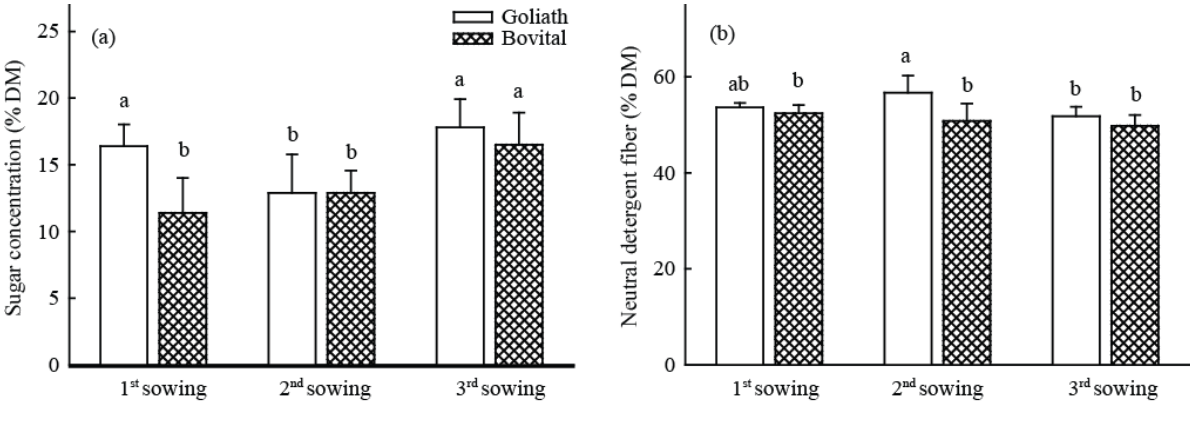

Fig. 1. Effect of varying sowing time and cultivar on (a) sugar concentration and (b) neutral detergent fiber of sorghum (2008 season). Values represent means ± S.D. significant differences were measured by the least significant differences (LSD) at $p \leq 0.05$ and indicated by different letters.

Table 4. Effect of sowing time (ST), planting density (PD) and cultivar (CV) on the concentrations of protein (XP), sugar (XZ), acid detergent fiber (ADF), acid detergent lignin (ADL) and neutral detergent fiber (NDF) of sorghum (2008 and 2009 seasons).

Treatment	XP (%DM)	2008			XP (%DM)	2009		
		ADL (%DM)	XZ (%DM)	NDF (%DM)		ADL (%DM)	XZ (%DM)	NDF (%DM)
Cultivar								
Goliath	7.3 b	4.9 a	15.7 a	54.0 a	6.8 b	6.0 a	11.3 a	59.9 a
Bovital	8.4 a	4.3 b	13.6 b	50.9 b	8.1 a	5.1 b	8.1 b	58.3 b
Plant density								
16 plants m^{-2}	7.8	4.6	15.0	52.6	7.5	5.5	10.1	58.8
24 plants m^{-2}	7.7	4.5	15.1	52.3	7.4	5.6	9.9	58.8
32 plants m^{-2}	8.1	4.6	13.8	52.6	7.5	5.6	9.2	59.7
Sowing time								
1st sowing	7.2 b	4.6	13.9 b	53.0 ab	7.5 ab	5.8 a	7.2 c	62.5 a
2nd sowing	8.0 ab	4.6	12.9 b	53.8 a	7.2 b	5.4 b	9.6 b	58.3 b
3rd sowing	8.4 a	4.5	17.2 a	50.8 b	7.7 a	5.5 b	12.3 a	56.5 c
LSD $_{0.05}$								
Cultivar	0.8	0.4	2.0	1.8	0.6	0.2	1.1	1.1
Plant densiy	ns	ns	ns	ns	ns	ns	ns	ns
Sowing date	1.1	ns	2.1	2.9	0.6	0.1	1.4	1.07
CV x PD	ns	ns	ns	ns	ns	ns	ns	ns
CV x ST	ns	ns	2.9	3.2	ns	0.3	ns	ns
PD x ST	ns	ns	ns	ns	ns	ns	ns	ns

Values sharing a letter in common within a column do not differ significantly at p≤0.05

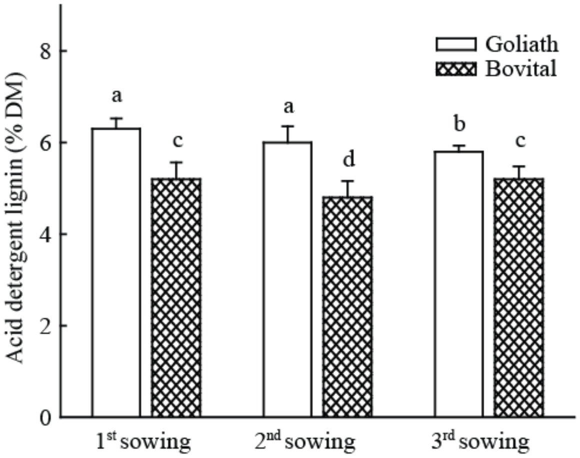

Fig. 2. Effect of varying sowing time and cultivar on acid detergent lignin of sorghum (2009 season). Values represent means ± S.D. significant differences were measured by the least significant differences (LSD) at p≤0.05 and indicated by different letters.

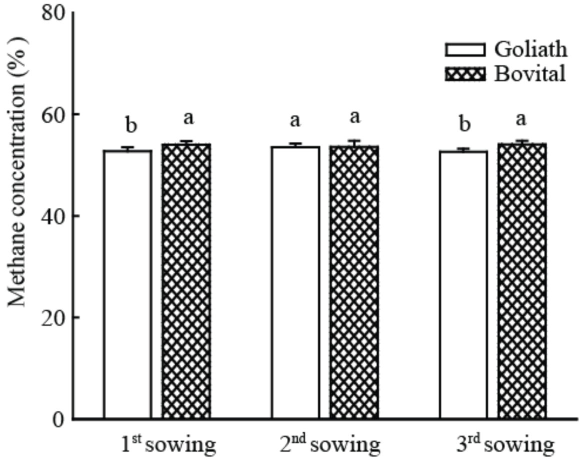

Fig. 3. Effect of varying sowing times and cultivars on methane concentration of sorghum (2008 season). Values represent means ± S.D. significant differences were measured by the least significant differences (LSD) at p≤0.05 and indicated by different letters.

The methane content of the biogas varied from 52-54%. In the 2008 material, both cultivar and PD, but not ST, had significant influence on this trait. Material harvested from cv. Bovital tissue produced somewhat higher proportions of methane than cv. Goliath tissue, but in 2009, there was little effect of either cultivar or PD (Table 5). In 2008, however, there was a significant cultivar by ST interaction. For all three STs, cv. Bovital produced a similar mean methane concentration in its biogas, whereas cv. Goliath performed poorly from its earliest and latest ST (Fig. 3). With respect to specific biogas and methane yield, there was a strong cultivar effect, ranging from, respectively, 406-601 and 213-317 Nl per kg volatile solid. In 2008, cv. Goliath tissue produced a markedly higher specific biogas and methane yield than cv. Bovital tissue (Table 5), and there was a strong cultivar by ST interaction in 2009. The highest biogas and methane yields were produced by late-sown cv. Bovital plants, while the lowest were obtained from cv. Bovital plants sown at the intermediate date (Fig. 4a,b). PD had no effect on either biogas or methane yield

Table 5. Effect of different sowing time (ST), planting density (PD) and cultivar (CV) on biogas (BG), methane yield (MY) and methane concentration (XM) of sorghum (2008 and 2009 seasons).

Treatment		2008			2009	
	BG	MY	XM	BG	MY	XM
	(Nl/kg VS)	(Nl/kg VS)	(%)	(Nl/kg VS)	(Nl/kg VS)	(%)
Cultivar						
Goliath	601 a	317 a	53 b	467 b	248 b	53
Bovital	523 b	282 b	54 a	548 a	292 a	53
Plant density						
16 plants m^{-2}	562	297	53 b	540	288	53
24 plants m^{-2}	550	295	54 a	503	268	53
32 plants m^{-2}	573	306	53 b	480	253	52
Sowing time						
1st sowing	578	307	53	551	294	53
2nd sowing	547	292	54	406	213	52
3rd sowing	560	298	53	566	302	53
LSD $_{0.05}$						
Cultivar	73	32	0.5	65	34	ns
Plant densiy	ns	ns	0.7	ns	ns	ns
Sowing date	ns	ns	ns	ns	ns	ns
CV x PD	ns	ns	ns	ns	ns	ns
CV x ST	ns	ns	1	221	125	ns
PD x ST	ns	ns	ns	ns	ns	ns

Values sharing a letter in common within a column do not differ significantly at $p \leq 0.05$

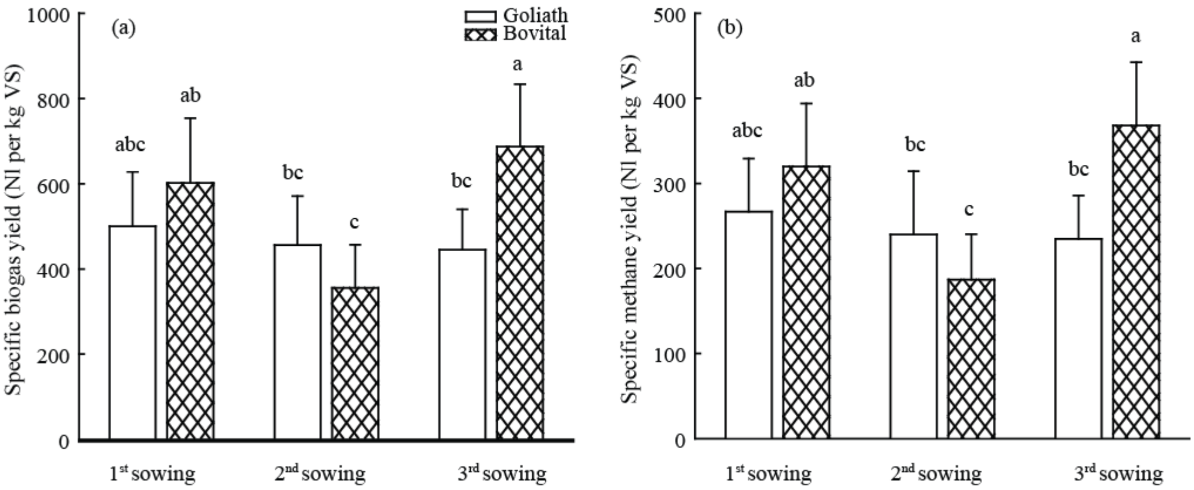

Fig. 4. Effect of varying sowing time and cultivar on (a) specific biogas yield and (b) specific methane yield of sorghum (2009 season). Values represent means ± S.D. significant differences were measured by the least significant differences (LSD) at $p \leq 0.05$ and indicated by different letters

Discussion

Biomass yield: Of the two cultivars, cv. Goliath was the more productive, largely because its later maturity allowed for a longer duration of vegetative growth. Genetic variation for biomass yield of forage sorghum has been shown repeatedly (Amaducci *et al*., 2000, Habyarimana *et al*., 2004, Zhao *et al*., 2009). In general, the higher the PD the more productive the crop, presumably because sub-optimal PD (16 plants m^{-2}) led to inefficient utilization of applied inputs for growth, i.e., water, nutrients and sunlight. Biomass yield responded poorly to sowing prior to the beginning of June, which probably reflects its preference for somewhat higher temperatures than are normal in the early summer in Northern Europe.

Chemical composition: There was a pronounced cultivar effect on the protein concentration of the biomass. The better performance of cv. Bovital may derive from its superior tillering capacity, since the younger physiological age of secondary tillers implies a greater representation of metabolically more active tissue at the time of harvest. By the time of harvest, the main tiller has become heavily committed to the assimilation of carbohydrate in form of sugars and fibre. Inter-cultivar variation with respect to the protein content of forage sorghum has been recorded repeatedly (Beck, 2007, Miron *et al*., 2005). PD did not significantly affect biomass protein concentration, consistent with other observations recorded in the literature for either sorghum or maize (Marsalis *et al*., 2010, Miron *et al*., 2006). The enhancement of protein concentration achieved by a delay in ST may be associated with the vegetative phase of the crop coinciding with a period of longer daylengths. Under these conditions, the production of leaves is favoured over that of stems and panicles, and it is known that the leaf is the major organ contributing to the protein content of sorghum biomass (Hanna *et al*., 1981). There was also a major cultivar effect on the sugar content of the biomass. The higher sugar content of cv. Goliath biomass probably reflected its higher proportion of stem tissue than obtained for cv. Bovital biomass. The stem has been identified as a sink for soluble sugar (Zhao *et al*., 2009), at least during the vegetative phase. ST had clear influence on the sugar concentration, presumably associated with the improved rate of photosynthesis made possible by the longer and warmer days experienced by the later sown material. NDF and ADF accumulation also differed between the two cultivars. The better performance of cv. Goliath may reflect the higher proportion of stems in its biomass, since stems are more fibre rich than other organs (Carmi *et al*., 2005). The higher concentration of lignin accumulated by cv. Goliath seems likely to have reflected the different proportions of leaf and stem (as opposed to panicle) in the biomass of the two cultivars. Since both of the former biomass components contain more lignin than panicles (Miron *et al*., 2005).

Biogas and methane yield: The specific methane yield (213-317 Nl kg^{-1}) achieved here compares favourably with the levels achieved from other plant biomass materials (Baserga, 1998, Lemmer & Oechsner, 2001, Richter *et al*., 2009). Despite achieving a higher lignin concentration, the later maturing cv. Goliath produced more biogas as well as more methane than cultivar Bovital in 2008, consistent with the idea that the complexity of cell wall carbohydrate aggregates increases with physiological maturity (Schittenhelm, 2008). The earlier maturity of cv. Bovital therefore produced biomass which was less digestible, and thus less productive of biogas and methane. However in the 2009 harvest, cv. Bovital was more productive than cv. Goliath, which implied that the same difference in maturity at harvest was more than compensated for by the lower representation of leaf matter in the cv. Bovital biomass, since the highly lignified leaf is associated with a reduced level of NDF digestibility (Miron *et al*., 2005). However, the role of certain secondary metabolites cannot be ignored. Sorghum leaves contain the cyanogenetic glucoside dhurrin, which upon hydrolysis releases hydrocyanic acid (Sleper & Poehlman, 1997) a substance which is highly toxic for acetate consuming methanogenic organisms (Gijzen *et al*., 2000). The smaller proportion of leaf matter present in the 2009 cv. Bovital biomass therefore may have led to a reduced inhibition to digestion by secondary metabolites, thereby promoting its biogas and methane yields.

Conclusion

The experiments demonstrated a major difference between cv. Goliath and cv. Bovital with respect to both their biomass and biogas potential. The later maturing cv. Goliath produced taller plants with thicker stems and a higher biomass yield. Biomass yield was improved by delaying sowing until the days had become warmer and longer, conditions to which sorghum is more suitably adapted. This late sowing would allow sufficient time for the prior cropping for silage purposes of short-season temperate species such as wheat, barley, rye or oilseed rape. The yield of methane was comparable to what can be achieved using other feedstocks. ST was a more influential than PD in determining biomass yield and quality; a sub-optimal PD was associated with reduced yield potential, but PD had little effect on either the chemical composition of the biomass or the derived methane yield. Further experiments are clearly required to clarify the role of secondary metabolites on the inhibition of biogas and methane yields.

References

Amaducci, S., M.T. Amaducci, R. Enati and G. Venture. 2000. Crop yield and parameters of four annual fibre crops (hemp, kenaf, maize and sorghum) in north of Italy. *Ind. Crops Prod*., 11: 179-186.

Amon, T., B. Amon, V. Kryvoruchko, W. Zollitsch, K. Mayer and L. Gruber. 2007. Biogas production from maize and dairy cattle manure-influence of biomass composition on the methane yield. *Agric Ecosyst Environ*., 118: 173-182.

Anonymous. 2015. Biogas report. http://www.igu.org/sites/default/files/node-page field_file/IGU% 20Biogas%20Report %202015..

Baserga, U. 1998. FAT-Berichte, 512: Landwirtschaftliche Co-Vergarungs-Biogasanlagen. Biogas aus organischen Reststoffen und Energiegras (FAT reports, 512: Agricultural co-fermentation biogas plants. Biogas from organic wastes and energy grass). Ta¨nikon, Switzerland: Eidgeno¨ ssische Forschungsanstalt für Agrarwirtschaft und Landtechnik (FAT).

Beck, P.A., S. Hutchison, A.S. Gunter, C.T. Losi, B.C. Stewart, K.P. Capps and M. Phillips. 2007. Chemical composition and in situ dry matter and fiber disappearance of Sorghum x Sudangrass hybrids. *J. Animal Sci*., 85: 545-555.

Berenguer, M.J. and J.M. Faci. 2001. Sorghum (*Sorghum bicolor* L. Moench) yield compensation processes under different plant densities and variable water supply. *Eur. J. Agron*., 15: 43-55.

Blum, A. and M. Naveh. 1976. Improved water-use efficiency in dryland grain sorghum by promoted plant competition. *Agron. J*., 68: 111-116.

Caravetta, G.J., J.H. Cherney and K.D. Johnson. 1990. Influence of within row spacing on diverse sorghum genotype: I. Morphology. *Agron. J*., 82: 206-210.

Carmi, A., N. Umiel, A. Hagiladi, E. Yosef, D. Ben-Ghedalia and J. Miron. 2005. Field performance and nutritive value of a new forage sorghum variety Pnina recently developed in Israel. *J. Sci. Food Agric*., 85: 2567-2573.

Cusicanqui, J.A. and J.G. Lauer. 1999. Plant density and hybrid influence on corn forage yield and quality. *Agron. J*., 91: 911-915.

Defoor, P.J., N.A. Cole, M.L. Galyean and O.R. Jones. 2001. Effect of grain sorghum planting density and processing methods on nutrient digestibility and retention by ruminants. *J. Anim. Sci*., 79: 19-25.

Fribourg, H.A. 1995. Summer annual grasses. In: Forages, Vol. I, *An Introduction to Grassland Agriculture* (Eds.): Barnes R.F., D.A. Miller & C.J. Nelson. Iowa State University Press Ames Iowa. 463-472.

Gijzen H.J., M.E. Bernal and H. Ferrer 2000. Cyanide toxicity and cyanide degradation in anaerobic wastewater treatment. WAT. RES. VOL. 34, NO. 9, PP. 2447-2454.

Habyarimana, E., D. Laureti, M. De Ninno and C. Lorenzoni. 2004. Performance of biomass sorghum [*Sorghum bicolor* (L.) Moench] under different water regimes. *Ind. Crop Prod*., 20: 23-28.

Hanna, W.W., W.G. Monson and T.P. Gaines. 1981. IVDMD, total sugars, and lignin measurements of normal and brown midrib (bmr) sorghums at various stages of development. *Agron. J*., 73: 1050-1052.

Hipp, B.W., W.R. Cowley, C.J. Gerard and B.A. Smith. 1970. Influence of solar radiation and date of planting on yield of sweet sorghum. *Crop Sci*., 10: 91-92.

Karpenstein-Machan, M. 2001. Sustainable cultivation concepts for domestic energy production from biomass. *Crit. Rev. Plant Sci*., 20: 1-14.

Kausar, A., M. Y. Ashraf AND M. Niaz 2014. Some physiological and genetic determinants of salt tolerance in sorghum (Sorghum bicolor (L.) MOENCH): Biomass production and nitrogen metabolism. Pak. J. Bot., 46(2): 515-519.

Kucharik, C.J. 2008. Contribution of planting date trends to increase maize yields in the central United States. *Agron J*., 100: 328-336.

Lafrage, T.A. and G.L. Hammer. 2002. Shoot assimilates partitioning and leaf area ratio, are stable for a wide range of sorghum population densities. *Field Crops Res*., 77: 137-151.

Lemmer, A. and H. Oechsner. 2001. Co-fermentation of grass and forage maize. *Landtechnik*., 56: 412-413.

Mahmood, A. and B. Honermeier. 2012a. Effect of row spacing and cultivars on biomass yield and quality of *Sorghum bicolor* L. Moench. *Journal für Kulturpflanzen*, 64: 250-257.

Mahmood, A. and B. Honermeier. 2012b. Chemical composition and methane yield of sorghum cultivars with contrasting row spacing. *Field Crops Res*., 128: 27-33.

Mahmood, A., H. Ullah, M. Ijaz, A.S. Naeem and B. Honermeier. 2013. Evaluation of sorghum cultivar for biomass and biogas production. *Aust. J. Crop Sci*., 7(10): 1456-1462.

Marsalis, M.A., S.V. Angadi and S.V. Contreras. 2010. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. *Field Crops Res*., 116: 52-57.

Miron, J., E. Zuckerman, D. Sadeh, G. Adin, M. Nikbakhat, E. Yosaf, B.D. Ghedalia, A. Carmi, T. Kipnas and R. Solomon. 2005. Yield, composition and in vitro digestibility of new forage sorghum varieties and their ensilage characteristics. *Anim. Feed Sci. Technol*., 120: 17-32.

Miron, J., R. Solmon, G. Adin, U. Nir, M. Nikbachat, E. Yosef, A. Carmi, G.Z. Weinberg, T. Kipnis, E. Zuckerman and D. Ben-Ghedalia. 2006. Effects of harvest stage and re-growth on yield, ensilage and *In vitro* digestibility of new forage sorghum varieties. *J. Sci. food Aric*., 86: 140-147.

Richter, F., R. Graß, T. Fricke, W. Zerr and M. Wachendorf. 2009. Utilization of semi-natural grassland through integrated generation of solid fuel and biogas from biomass. II. Effects of hydrothermal conditioning and mechanical dehydration on anaerobic digestion of press fluids. *Grass Forage Sci*., 64: 354-363.

Rosenthal, D.W., J.T. Gerik and J.L. Wade. 1993. Radiation use efficiency among grain sorghum cultivars and plant densities. *Agron. J*., 85: 703-705.

Schittenhelm S. 2008. Chemical composition and methane yield of maize hybrids with contrasting maturity. *Eur. J. Agron*., 29: 72-79.

Schittenhelm, S. 2010. Effect of drought stress on yield and quality of maize/sunflower and maize/sorghum intercrops for biogas production. *J. Agron. & Crop Sci*., 196: 253-261.

Shenk, J.S. and M.O. Westerhau 1991. Population structuring of near infrared spectra and modified partial least square regression. Crop Sci. 31, 1548–1555.

Sleper, A.D. and M.J. Poehlman. 1997. Breeding of field crops. 5th ed. Ames Lowa: Blackwell.

Zhao, L.Y., A. Dolat, Y. Steinberger, X. Wang, A. Osman and H.G. Xie. 2009. Biomass yield and changes in chemical composition of sweet sorghum grown for biofuel. *Field Crops Res*., 111: 55-64.

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