Journal of Elementology ISSN 1644-2296

Sowiński J., Liszka-Brandau A. 2019.
Changes in the chemical compositions of sweet sorghum (Sorghum bicolor L. Moench*) stem fractions.*
J. Elem., 24(1): 71-80. DOI: 10.5601/jelem.2018.23.2.1598

RECEIVED: 22 January 2018
ACCEPTED: 15 August 2018

ORIGINAL PAPER

CHANGES IN THE CHEMICAL COMPOSITIONS OF SWEET SORGHUM (*SORGHUM BICOLOR* L. MOENCH) STEM FRACTIONS*

Józef Sowiński[1], Agata Liszka-Brandau[2]

[1]Institute of Agroecology and Crop Science, Wroclaw University of Environmental and Life Sciences, Poland
[2] Control Union Poland Sp. z o.o., Poland

Abstract

An investigation was carried out in the years 2006-2008 in order to compare the chemical composition of sweet sorghum stems. Two varieties of sweet sorghum: Sucrosorgo G-1990 (photoperiodically sensitive – *headless*) and Sucrosorgo 506 (photoperiodically insensitive – *headed*) were tested. Samples of large and small diameter stems were collected from both types of sorghum, from different parts of stem (lower, medium and top internodes). Each internode was fractionated into three stem part: leaves, the outer (rind) and the inner part (pith). The effect of the part of a stem and the place from which internodes were collected on the chemical composition was determined. The content of crude fibre and its fractions: neutral detergent fibre (NDF), acid detergent fibre (ADF), hemicellulose, crude proteins, carbohydrates: total carbohydrates, sucrose, reducing sugars and macroelements was determined in the plant material. The largest diversity in proportions of the chemical compounds was observed in the pith. Amounts of the NDF fraction in the rind depended on a stem's diameter. The site from where an internode sample was collected had the greatest effect on the chemical composition, mostly the concentrations of macroelements (N, P – in all three stem parts, K and Mg – in the pith, Ca – in leaves and the rind, Na – in leaves). The diameter of a stem had a negative effect on the chemical composition and deteriorated the technological value of sorghum, since the content of crude fibre and its fraction increased.

Keywords: nutrient content, headed sweet sorghum, headless sweet sorghum, internodes, leaves, rind, pith.

prof. dr hab. Józef Sowiński, Institute of Agroecology and Crop Science, Wroclaw University of Environmental and Life Sciences, Grunwaldzki square 24a, 50-363 Wroclaw, Poland, e-mail: jozef.sowinski@upwr.edu.pl
* Found by Wroclaw University of Environmental and Life Sciences.

INTRODUCTION

Sweet sorghum, owing to its ability to accumulate due large amounts of sugars in stems, is used worldwide for the energy, industry purposes and as a fodder for livestock (Yu et al. 2012). In the production of ethanol, the stem of sweet sorghum is the most important fermentation biomass (Tsuchihashi, Goto, 2005). In one of the sorghum processing technologies leaves and the rind of sorghum, which contain large amount of fibre, are separated and juice (for ethanol production) is obtained only from the inner parts of stems (Worley et al. 1991, Domínguez et al. 2001, Kundiyana et al. 2010). The stem juice of sweet sorghum may be used directly for fermentation to ethanol or it can be first concentrated and then submitted to fermentation (Ritter et al. 2007, Wang, Liu 2009). Billa et al. (1997) claim that the inner part, rich in water and soluble sugars, makes up 65% of the stem's fresh matter. The rind of the stem contains fibre and cellulose, hence it is difficult to obtain juice from this part of the plant (Zhao et al. 2009). Reduction in the content of fibre, i.e. by breeding other types of varieties (BMR – *brown mid-rib*) is used, as it increases the efficiency of obtaining plant juice (Worley et al. 1991, Murray et al. 2008).

The fibre content and its fractions are significant for plant morphology as well as for animal feeding. NDF determines feed intake and ADF decides about its digestibility. The contribution of the NDF fraction in biomass depends on sorghum varieties and water availability, but not on the seeding density (Jeon et al. 1992, Carmi et al. 2006). The higher ratio of leaves to steams shows a negative correlation with digestibility and a positive one with the content of NDF (Redy et al. 2003). Sorghum is a high yielding crop, and the uptake of minerals (macro- and microelements) as well as their partitioning are essential for the biomass quantity, quality and ethanol production effectiveness (Han et al. 2011, Chmielewska et al. 2014). The mineral uptake by sorghum and dynamics of minerals (mostly nitrogen) in soil influence the environmental pollution and nitrogen transformation processes (Kabała et al. 2017).

MATERIAL AND METHODS

The experiment was conducted in the years 2006-2008, on the experimental fields in Pawłowice (51°09′ N; 17°06′ E), a research station owned by the Institute of Agroecology and Crop Science, Wroclaw University of Environmental and Life Sciences, Poland. The investigations were carried out on loamy sand classified as Brunic Gleic Arenosols.

Nitrogen (130 kg ha^{-1}), phosphorus (39.5 kg P ha^{-1}) and potassium fertilisers (100 kg K ha^{-1}) were applied before sowing and then incorporated into the soil using an aggregate (a Howard harrow with a toothed packer roller). The sowing (20 germinated seeds $\cdot m^{-2}$) was performed in between 10 and 20 May, using a Wintersteiger seed drill.

The experiment was carried out in a split-plot design with five replication. Every year, before harvest, 10 stems were collected from each hybrid, divided according to the stem's diameter, and sampled from the internodes. In both varieties of sorghum, the lower internode was the first fully developed one above soil surface and the middle internode was separated at a halfway of the stem's length and the upper internode (the first fully developed one below the head). The upper internode was isolated only from the headed sweet sorghum. Every internode was fractionated into leaves, outer part (rind) and the inner part (pith) of the stem.

The results are presented according to the following design of the factors:

- Parts of a plant:
- leaves,
- outer part of the stem – rind,
- inner part of the stem – pith.

Sweet sorghum variety:

- headed sorghum – Sucrosorgo 506 (Ss506),
- headless sorghum – Sucrosorgo G-1990 (G1990).

Stem thickness:

- small diameter ∅ < 2 cm,
- large diameter ∅ > 2 cm.

The place from which the internode was collected (part of the stem):

- upper,
- middle,
- lower (only for Sucrosorgo 506).

The samples were taken when the variety of Sucrosorgo 506 was in the phase of grain filling and the variety of Sucrosorgo G-1990 was in the vegetative stage of the growth. Fresh biomass material was cut to an average particle size of 5-6 mm. The samples for chemical analyses was oven dried at 70°C for 24 h. The dried sorghum plant material was ground and sieved through a 1 mm screen.

The dry matter content was analysed to determine the following:

- protein, using the Kjeldahl method, after mineralization with sulphuric acid and perchlorate;
- the crude fibre content using the Hennenberg-Stohmann method;
- neutral detergent fibre NDF and acid detergent fibre ADF with the van Soest method;
- hemicellulose content calculated as a difference between the NDF and ADF fibre fraction content (Anioł et al. 2015);
- crude ash – by burning in an oven in 600°C for 4 h;

– phosphorus content – by colorimetry using the vanadium-molybdenum method;
– magnesium content – by colorimetry with titanium yellow;
– potassium, calcium and sodium content using the flame method;
– carbohydrates (total, sucrose and reducing sugars) were marked in the dry matter by the Lane-Eynon method (ADAMCZEWSKA-SOWIŃSKA, TURCZUK 2016).

The results were statistically analysed using Statistica 9.0 software, and ANOVA/MANOWA variance analysis was performed. Significant intervals were tested according the Duncan's test at a significance level $\alpha = 0.05$. Only the results of the measurements from the lower and middle internode were used in the statistical analysis of the data aimed to demonstrate differences between the varieties. Analysis of the correlation and regression was done between the dry matter content and the crude protein content.

RESULTS

The content of crude fibre and the fraction of fibre in headed and headless sorghum show significant differences in the inner part (Table 1).

Table 1

The effect of varieties and internode parts on chemical composition (g kg^{-1} DM). Average for years 2006-2008

Parameters	Leaves (*a*)		Rind (*a*)		Pith (*a*)		Significant	
	Ss506 (*b*1)	G1990 (*b*2)	Ss506 (*b*1)	G1990 (*b*2)	Ss506 (*b*1)	G1990 (*b*2)	for *b*	for *a* · *b*
Crude protein	73.7*a*	83.7*a*	42.6*a*	49.5*a*	43.7*a*	59.2*b*	n.s.	*
Crude fibre	299.4*a*	304.0*a*	358.3*a*	348.5*a*	141.6*a*	183.1*b*	n.s.	n.s.
NDF	658.5*a*	705.7*a*	697.2*a*	727.4*a*	331.6*a*	433.3*b*	n.s.	n.s.
ADF	403.0*a*	339.2*a*	424.9*a*	458.2*a*	160.7*a*	228.2*b*	n.s.	n.s.
Hemicellulose	255.5*a*	366.5*a*	272.3*a*	269.2*a*	170.9*a*	205.1*b*	n.s.	n.s.
Sugars total	102.5*a*	110.7*a*	184.7*a*	171.1*a*	413.5*a*	344.9*a*	n.s.	n.s.
Saccharose	82.1*a*	75.9*a*	142.0*a*	116.7*a*	296.5*a*	210.0*a*	n.s.	n.s.
Reducing sugar	22.5*a*	30.8*a*	35.2*a*	48.2*a*	101.4*a*	123.9*a*	n.s.	n.s.
N	13.1*a*	11.8*a*	6.8*a*	7.9*a*	7.0*a*	9.5*b*	n.s.	*
P	2.1*b*	1.5*a*	1.6*a*	1.6*a*	1.5*a*	1.2*a*	*	n.s.
K	7.3*a*	7.6*a*	4.6*a*	8.0*b*	13.5*a*	12.1*a*	n.s.	n.s.
Mg	3.5*b*	2.7*a*	2.0*a*	2.4*a*	1.9*a*	2.9*b*	n.s.	*
Ca	5.7*a*	5.3*a*	1.0*a*	1.3*a*	1.7*a*	2.5*b*	*	n.s.
Na	0.3*a*	0.3*a*	0.3*a*	0.3*a*	0.3*a*	0.3*a*	***	n.s.

Values with the same letter within treatment are not significantly different;
* significant at probability $p \leq 0.05$, ** significant at probability $p \leq 0.01$, *** significant at probability $p \leq 0.001$, n.s. – no significant

The content of macroelements in leaves and in the rind was also less diverse than in the pith of the stem. The inner part of Sucrosorgo G1990 was observed to contain more total protein (by 15.5 g), crude fibre (by 41.5 g), NDF fraction (by 101.7 g), ADF fraction (by 67.5 g), hemicellulose (by 34.2 g), nitrogen (by 2.5 g), magnesium (by 1.0 g) and calcium (by 0.8 g kg^{-1} DM) than that of the variety Sucrosorgo 506. Significantly more phosphorus (by 0.6 g kg^{-1} DM) and magnesium (by 0.8 g kg^{-1} DM) was observed in leaves of the variety Sucrosorgo 506. In the rind, there was significantly more potassium (by 3.4 g kg^{-1} DM) in Sucrosorgo G-1990. Differences between the varieties were significant in the content of macronutrients P, Ca and Na, which was higher in Sucrosorgo 506. Interaction between parts of the plant among the varieties was only observed in the content of total protein and Mg.

The content of crude fibre was significantly higher of the stem with low diameter in leaves (by 31.7 g kg^{-1} DM) and the pith (by 35.4 g kg^{-1} DM). The concentration of NDF was extensively higher in the rind part of the stem with small diameter (by 63.7 g kg^{-1} DM) than in stems with larger diameter (Table 2). Moreover, these stems were showing significantly lower content of protein (by 14.0 g kg^{-1} DM in the rind and by 20.2 g kg^{-1} DM in the pith). Small diameter stems had extensively higher content of fibre and its fraction. In the other organic and minerals compounds no significant differences between plant parts and diameter.

Table 2

The effect of stem thickness and internode parts on chemical composition (g kg^{-1} DM). Average for years 2006-2008

Parameters	Leaves (*a*)		Rind (*a*)		Pith (*a*)		Significant	
	large diameter (*c*1)	small diameter (*c*2)	large diameter (*c*1)	small diameter (*c*2)	large diameter (*c*1)	small diameter (*c*2)	for *c*	for *a* · *c*
Crude protein	90.1*a*	79.4*a*	52.4*b*	38.4*a*	65.6*b*	45.4*a*	n.s.	n.s.
Crude fibre	281.5*a*	313.2*b*	338.3*a*	370.4*a*	144.4*a*	179.8*b*	**	n.s.
NDF	674.4*a*	692.9*a*	677.4*a*	741.1*b*	380.2*a*	444.5*a*	*	n.s.
ADF	370.6*a*	352.2*a*	398.6*a*	477.9*a*	187.3*a*	259.4*a*	***	n.s.
Hemicellulose	303.8*a*	340.7*a*	278.8*a*	263.2*a*	192.9*a*	185.1*a*	**	n.s.
Sugars total	134.2*a*	77.4*a*	179.5*a*	178.9*a*	431.1*a*	341.0*a*	n.s.	n.s.
Saccharose	100.5*a*	58.8*a*	132.5*a*	131.2*a*	317.9*a*	205.8*a*	n.s.	n.s.
Reducing sugar	28.5*a*	28.5*a*	40.0*a*	40.8*a*	96.4*a*	124.4*a*	n.s.	n.s.
N	14.4*a*	12.7*a*	8.4*b*	6.1*a*	10.5*b*	7.3*a*	n.s.	n.s.
P	1.8*a*	2.1*a*	1.6*a*	1.6*a*	1.5*a*	1.4*a*	n.s.	n.s.
K	8.2*a*	6.8*a*	6.1*a*	5.8*a*	13.0*a*	11.3*a*	n.s.	n.s.
Mg	2.9*a*	3.1*a*	2.4*a*	1.9*a*	2.7*a*	2.5*a*	n.s.	n.s.
Ca	5.2*a*	4.8*a*	1.2*a*	1.0*a*	2.1*a*	2.0*a*	n.s.	n.s.
Na	0.3*a*	0.3*a*	0.3*a*	0.3*a*	0.3*a*	0.3*a*	n.s.	n.s.

Explamations under Table 1

Table 3

The effect of internode place collection and internode parts on chemical composition (g kg^{-1} DM). Average for years 2006-2008

Parameters	Leaves (a)			Rind (a)			Pith (a)			Significant	
	lower ($d1$)	middle ($d2$)	upper ($d3$)	lower ($d1$)	middle ($d2$)	upper ($d3$)	lower ($d1$)	middle ($d2$)	upper ($d2$)	for d	for $a \cdot d$
Crude protein	56.6a	98.8b	113.1b	40.1a	40.8a	65.2b	54.2a	48.7a	71.8b	***	***
Crude fibre	325.6b	277.7a	280.0a	352.8a	364.8a	336.6a	148.9a	175.8a	161.3a	n.s.	*
NDF	719.6a	644.6a	689.1a	697.4a	724.8a	701.9a	364.9a	399.9a	531.9b	**	*
ADF	428.3a	313.9a	322.5a	425.3a	473.7a	393.4a	189.7a	199.3a	338.9a	n.s.	*
Hemicellulose	291.3a	330.7a	366.6a	272.1a	251.1a	308.5a	291.3a	330.7a	366.6a	n.s.	*
Sugars total	100.5a	129.8a	68.5a	186.7a	183.3a	156.0a	335.5a	448.7a	362.0a	n.s.	n.s.
Saccharose	83.1a	92.7a	46.8a	132.6a	134.9a	124.3a	329.1a	329.1a	250.2a	n.s.	n.s.
Reducing sugar	22.6a	32.3a	19.3a	47.1a	41.4a	25.2a	102.2a	108.6a	98.6a	n.s.	n.s.
N	9.0a	15.8b	18.1b	6.4a	6.5a	10.4b	8.7a	7.8a	11.5b	***	***
P	1.5a	2.1b	2.3b	1.5a	1.3a	2.1b	1.5a	1.2b	2.0c	***	**
K	6.6a	8.3a	7.8a	5.9a	6.2a	5.6a	14.7b	10.8a	9.8a	n.s.	*
Mg	3.2a	3.0a	2.6a	2.0a	2.1a	2.8a	2.2a	2.6a	3.5b	n.s.	**
Ca	6.3b	4.7ab	3.1a	1.0a	1.0a	1.5b	2.3a	1.8a	1.9a	n.s.	**
Na	0.4b	0.3a	0.3a	0.3a	0.3a	0.3a	0.3a	0.3a	0.3a	n.s.	*

Explamations under Table 1

The greatest variation in the chemical compound was observed in the place of internodes collection from the stem (Table 3). Significantly more protein was noted in the upper internode in leaves (113.1 g kg^{-1} DM), rind (65.2 g kg^{-1} DM) and pith (71.8 g kg^{-1} DM) and in the middle internode in leaves (98.8 g kg^{-1} DM) relative to lower internode. The disparity in the content of NFD fraction of fibre was observed only in the inner part. In the upper internode found significantly more NDF content than in the other stems part. Macronutrients concentration in some of stems was diverse. Leaves in the upper and middle part displayed higher concentration of nitrogen and phosphorus. The rind and pith of the upper internode showed more concentration of nitrogen and phosphorus. The place from where the internode was collected displayed significant difference in the content of total protein, crude fibre, NDF fraction and phosphorus, potassium, magnesium, calcium and sodium. The statistical analysis showed interaction between the place where the internode was collected and the part of the stem regarding the content of total protein, crude fibre, NDF and ADF fraction and all macroelements.

All compounds showed significant differences between the parts of the plant (Table 4). Leaves displayed the highest concentrations of protein, hemicellulose, P, Mg, Ca, and Na. Higher concentrations of fibre and its fraction

Table 4

The effects of internode parts on chemical composition (g kg^{-1} DM) (analysis of means). Average for years 2006-2008

Parameters	Leaves	Rind	Pith	Significant
Crude protein	84.8	45.4	55.5	***
Crude fibre	297.3	354.3	162.1	***
NDF	683.5	709.3	412.3	***
ADF	361.4	438.2	223.3	***
Hemicellulose	322.1	271.1	189.0	***
Sugars total	105.8	179.2	386.1	***
Saccharose	79.6	131.9	261.9	***
Reducing sugar	25.8	40.4	110.4	***
N	13.6	7.3	8.9	***
P	1.9	1.6	1.5	**
K	7.5	6.0	12.2	***
Mg	3.0	2.2	2.6	***
Ca	5.0	1.1	2.0	***
Na	0.33	0.28	0.31	*

were found in the rind part of stems. The pith of stems was characterised by a higher content of carbohydrates and potassium.

An analysis of the correlation and regression chart showed the dependence of total protein on the content of dry matter in particular parts of the plant (Figure 1). In leaves, rind and pith of stems, the content of protein decreased with an increase in the content of dry mass. The largest decline was observed in leaves, which was the result of their earlier desiccation in the lower part of the stem.

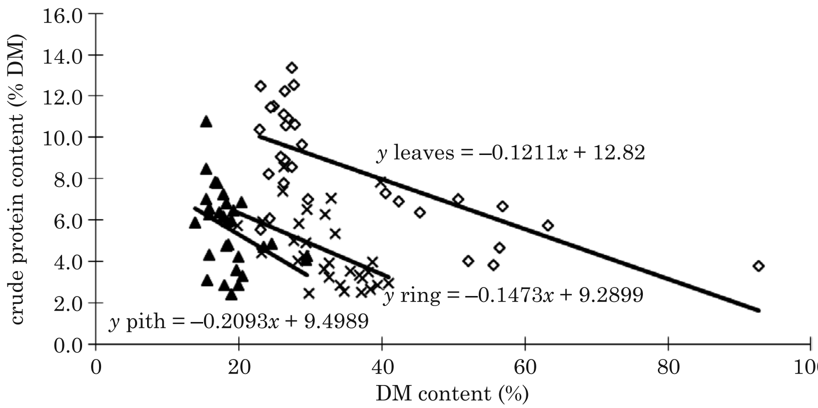

Fig. 1. The effect of dry matter content on crude protein concentration in internodes parts

DISCUSSION

Sorghum is a plant which contains fibres most densely accumulated in the rind, which surrounds the main part of the cross-section of the plant, consisting of core cells with vascular bundles and inner canals (Jones et al. 1979, Zhao et al. 2009). Our results significantly confirmed a higher content of crude fibre and its fraction in rind parts of the stem. Billa et al. (1997) achieved similar results, thus verifying that the rind part of sorghum is richer in cellulose, hemicellulose and lignin (which equalled 19.2, 17.5 and 8.8% DM, respectively).

Billa et al. (1997) indicated that the pith contained on average 80.4% of carbohydrates in dry mass, whereas the outer parts had 76% of these compounds. The highest share consisted of glucose (59.2% in the rind and 49.7% in the inner part) and xylose (15.1 and 23.3%, respectively). Krishnavani et al. (1984) stated that most carbohydrates were generally observed in the middle part of the stem (from 52.8% to 54.4% DM). In our research, the tested varieties of sorghum contained far less of carbohydrates, which reached up to 448.7 g kg^{-1} D.M. in the pith of the middle internode. Reddy at al. (2003) concluded that the content of carbohydrates was positively correlated with high digestibility and a low concentration of the NDF fraction in the stem. A similar relationship can be found in our research, particularly with respect to the pith, which is rich in carbohydrates in general, and contains significantly less NDF than the other parts of the plant. Vietor at al. (2010) showed that the NDF content ranged from 576 to 640 g kg^{-1} DM in leaves and from 419 to 542 g kg^{-1} DM in stems, depending on a variety. In our research, leaves contained far more NDF (683.5 g kg^{-1} DM on average) and the content of this fraction in the rind was significantly higher (709.3 g kg^{-1} DM) than in the pith (412.3 g kg^{-1} DM). Zielewicz, Kozłowski, (2008) showed that the variety Sucrosorgo 506, in the dough stage, had more total protein, phosphorus, potassium, calcium and sodium in leaves (156.20, 2.52, 19.62, 11.62, 0.69 g kg^{-1} DM, respectively). Zhao et al. 2009 confirm the previous findings by other authors, as they notede that the content of cellulose and hemicellulose in stems of sweet sorghum decreased at the generative growth stage, when sugar accumulation was usually the highest. The stem fibre content was negatively correlated with sugar concentration (Murray et al. 2008).

Han et al. (2011) indicated less nitrogen and phosphorus in stems than in leaves in all early sorghum varieties. In our research, such a relathionship was only observed in the content of nitrogen, which was higher in leaves of the early maturing variety. The potassium concentration was lower in the late maturing varieties (Han et al. 2011). Our results showed that the rind of the stem contained more potassium in the late maturing Sucrosorgo G1990 variety.

CONCLUSION

The diversity of chemical compounds in the tested varieties of sorghum should be taken into account while making a decision about the use of the crop. The headed variety of sorghum contained more carbohydrates, especially in the inner part of the stem, and therefore can be recommend for bioethanol production. The variety Sucrosorgo G-1990, characterized by a high contribution of leaves to total biomass and a high content of total proteins, should be grown for feeding purposes. Sorghum cultivated for forage or as a biotechnological feedstock should be seeded at a lower plant density. A smaller stem's diameter lowers the technological value of sorghum, since the content of crude fibre and its fraction are higher. Sorghum leaves are the main source of protein. The rind of the stem contains a high amount of fibre and its fraction. The pith is the most useful part of sorghum for a technological purpose when making syrup or ethanol because its soluble sugar content is the highest, higher by 115% than in the rind and by 265% than in leaves.

REFERENCES

Adamczewska-Sowińska K., Turczuk J. 2016. *Yielding and biological value of garlic chives (Allium tuberosum Rottl. ex Spreng.) depending to the type of mulch*. J. Elem., 21(1): 7-19. DOI: 10.5601/jelem.2015.20.2.910

Anioł, M., Sowiński J., Aniołowska M. 2015. *The content of soluble sugars and lignocellulose in sorghum hybrids*. Przem. Chem., 94/10 s. 1832-1834. (in Polish) DOI: 10.15199/62.2015.10.37

Billa, E., Koullas, D.P., Monties, B., Koukios, E.G. 1997. *Structure and composition of sweet sorghum stalk components*. Ind. Crop. Prod., 6: 297-302. doi.org/10.1016/S0926-6690(97)000-9

Carmi A., Aharoni, Y., Edelsrein, M., Umiel, N., Hagiladi, A., Yosef, E., Nikbachat, M., Zennou, A., Miron, J. 2006. *Effect of irrigation and plant density on yield, composition and in vitro digestibility of a new forage sorghum variety, Tal, at two maturity stages*. Anim. Feed Sci. Techn., 131: 120-132. DOI: doi.org/10.1016/j.anifeedsci.2006.02.005

Chmielewska J., Sowiński J., Foszczyńska B., Szydełko-Rabska E., Kawa-Rygielska J., Dziuba E. 2014. *Production of bioethanol from sweet sorghum juices with varying content of mineral compounds*. Przem. Chem., 93(4): 999-1001. (in Polish) DOI: dx.medra.org/10.12916/przemchem.2014.XX

Domínguez A., Rivela I., Couto S.R., Sanromán M. 2001. *Design of a new rotating drum bioreactor for ligninolytic enzyme production by Phanerochaete chrysosporium grown on an inert support*. Proc. Biochem., 37: 549-554. DOI: 10.1016/S0032-9592(01)00233-3

Han, L., Steinberger, Y., Zhao, Y., Xie, G. 2011. *Accumulation and partitioning of nitrogen, phosphorus and potassium in different varieties of sweet sorghum*. Field Crop Res., 120: 230-240. DOI: doi.org/10.1016/j.fcr.2010.10.007

Jeon, B., Lee, S., Shin, D., Moon, S., Kim, U. 1992. *Effect of plant density and planting on the growth characteristics, dry matter yield and feeding value of sorghum-sudangrass hybrid*. J. Korean Grassl. Sci., 12(1): 49-58

Jones, R.W., Krull, L.H., Blessin, C.W., Inglett, G.E. 1979. *Neutral sugars of hemicellulose fraction of pith from stalks of selected plants*. Cereal Chem., 56(5): 441-442.

Kabała C., Karczewska A., Gałka B., Cuske M., Sowiński J. 2017. *Seasonal dynamics of nitrate and ammonium ion concentrations in soil solutions collected using MacroRhizon suction cups*. Environ Monit Assess., 189: 304: 1-12. DOI: 10.1007/s10661-017-6022-3

KRISHNAVENI S., BALAUSUBRAMANIAN T., SADASIVAM S. 1984. *Sugar distribution in sweet stalk sorghum*. Food Chem., 15: 229-232. DOI: org/10.1016/0308-8146(84)90007-4

KUNDIYANA D.K., BELLMER D.D., HUHNKE R.L., WILKINS M.R., CLAYPOOL P.L. 2010. *Influence of temperature, pH and yeast on in-field production of ethanol from unsterilized sweet sorghum juice.* Biomass Bioenerg., 34(10): 1481-1486. DOI: org/10.1016/j.biombioe.2010.04.022

MURRAY S.C., ROONEY W.L., MITCHELL S.E., SHARMA A., KLEIN P.E., MULLET J.E., KRESOVICH S. 2008. *Genetic improvement of sorghum as a biofuel feedstock*. II. *QTL for stem and leaf structural carbohydrates*. Crop Sci., 48: 2180-2193. DOI: 10.2135/cropsci2008.01.0068

PING Z., WENSHENG S., ZHIAN L., BIN L., JINTIAN L., JINGSONG S. 2009. *Removal of metals by sorghum plants from contaminated land*. J. Environ. Sci., 21: 1432-1437. DOI: org/10.1016/S1001-0742(08)62436-5

REDDY, B., REDDY, P., BIDINGER, F. BLUMMEL M. 2003. *Crop management factors influencing yield and quality of crop residues*. Field Crop Res. 84: 57-77. DOI: 10.1016/S0378-4290(03)00141-2

RITTER K.B., MCINTYRE C.L., GODWIN I.D., JORDAN D.R., CHAPMAN S.C. 2007. *An assessment of the genetic relationship between sweet and grain sorghums, within Sorghum bicolor ssp. bicolor (*L.*)* Moench*, using AFLP markers*. Euphytica, 157: 161-176. DOI: 10.1007/s10681-007-9408-4

TSUCHIHASHI N., GOTO Y. 2005. *Internode characteristics of sweet sorghum (Sorghum bicolor (L.) Moench) during dry and rainy season in Indonesia*. Plant Prod. Sci.*,* 8(5): 601-607. DOI: org/10.1626/pps.8.601

WORLEY J., VOUGHAN D., CUNDIFF J. 1992. *Energy analysis of ethanol production from sweet sorghum.* Biores. Technol., 40: 263-273. DOI: org/10.1016/0960-8524(92)90153-O

WORLEY J., VOUGHAN D., CUNDIFF J., PARRISH D. 1991. *Influence of sweet sorghum spacing on stalk pith yield.* Biores. Technol., 36: 133-139. DOI: org/10.1016/0960-8524(91)90170-O

YU J , ZHANG T , ZHONG J , ZHANG X , TAN T. 2012. *Biorefinery of sweet sorghum stem.* Biotechnol. Adv., 30(4): 811-816. DOI: 10.1016/j.biotechadv.2012.01.014

WANG F, LIU C.Z. 2009. *Development of an economic refining strategy of sweet sorghum in the inner Mongolia region of China*. Energy Fuels, 23:4137-4142. DOI: 10.1021/ef900317s

VIETOR D., RHODES G., ROONEY W. 2010. *Relationship of phenotypic variation in sorghum to nutritive value of crop residues.* Field Crop Res., 118: 243-250. DOI: 10.1016/j.fcr.2010.06.001

ZHAO Y.L., DOLAT A., STEINBERGER Y., WANG X., OSMAN A., XIE G.H. 2009. *Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel*. Field Crop Res., 111: 55-64. DOI: org/I10.1016/j.fcr.2008.10.006

ZIELEWICZ, W., KOZŁOWSKI, S. 2008. *Fertilization limiting and chemical composition of sweet sorghum*. Grassland Science in Poland, 11: 223-235. (in Polish)