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Effect of nitrogen fertilization on sorghum for biomass production

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Abstract. Two field experiments were carried out in 2005 and 2006 in central Italy in order to evaluate the effects of different nitrogen (N) application rates (0, 50 100 and 150 kg ha^{-1}) on flowering date, plant height, biomass production and partitioning (leaves, panicles and stems) and biomass quality of a sorghum hybrid (H133). Sorghum showed a high potential in terms of biomass production without N fertilization (18.5 t ha^{-1} of d.m. in 2005 and 26.6 t ha^{-1} of d.m. in 2006). The rate that maximized the biomass production was 100 kg ha^{-1} of N, increasing the biomass dry weight by 23.8% in 2005 and 18.8% in 2006, with respect to unfertilized sorghum; higher N rates are not advisable in order to avoid increasing fertilization costs and environmental impact without benefit of greater biomass production. The two highest N rates when combined with low water availability appeared to increase the rate of plant development, causing earlier flowering and increasing the percentage of panicles in total biomass. Higher heating value (HHV), lower heating value (LHV) and ash concentration of biomass varied among N rates, with values of HHV and LHV lower for unfertilized sorghum (17.6 and 16.7 MJ kg^{-1} d.m., respectively) than when N was applied (from 19.0 to 19.7 and from 18.1 to 18.8 MJ kg^{-1} d.m., respectively); on the contrary, ash concentration was greater for unfertilized sorghum (7.5% d.m.) than for fertilized sorghum (from 5.8 to 6.7% d.m.). This research showed the high potential of sorghum in terms of biomass production also when cultivated with limited irrigation and fertilization inputs. The biomass dry yield obtained by one hectare of sorghum crop without N nitrogen fertilization (i.e. 22.6 t ha^{-1} of d.m., average of 2005 and 2006 values) produces the same energy, by thermal utilisation, of 9.3 toe, that is equivalent to energy produced by 10,385 L of diesel fuel or 11,097 m^3 of methane fuel. This aspect increases the certainty of the energetic and environmental sustainability of sorghum crop.

Key words: ash content, biomass quality, biomass yield, heating values, energy crop, N rate.

INTRODUCTION

Sorghum [*Sorghum bicolor* L. (Moench)] can be classified as grain, sweet, forage and biomass types (Dogget, 1998; Almodares et al., 2009). It is a widely adapted crop with potential for bioenergy production thanks to its relatively low input requirements, drought and salinity tolerance, ability to use water efficiently and to maintain high yields under a wide range of soil and environmental conditions (Regassa & Wortmann, 2014; Shakeri et al., 2017). Sorghum is used to obtain the most disparate products: food, forage, paper pulping, plastics, sugar for bioethanol and biomass for energy use

(Zegada-Lizarazu & Monti, 2012; Pannacci & Bartolini, 2016). In general, sweet sorghum types are richer than forage or biomass ones in the content of non-structural carbohydrates (sucrose, glucose, fructose and starch) (Almodares et al., 2011); while the biomass and forage types are predominantly composed by structural carbohydrates (hemicellulose, cellulose, and lignin) and their biomass can be used for combustion and 2nd generation biofuels (Zegada-Lizarazu & Monti, 2012). Sorghum is a C4 crop with a high biomass yield and good N use efficiency (Gardner et al., 1994). N is essential for plant growth and it is one of major factors limiting crop yield (Zhao et al., 2005). However, in this context, the evaluation of N requirement is crucial in order to quantify the rate of application needed to ensure high biomass production without waste. In fact, N fertilizer production is associated with significant CO_2 emissions and energy consumption, decreasing the net energy obtained by the crop (Lewandowski et al., 1995). Furthermore, the high mobility of N in the soil can increase the potential risk of aquifer pollution (Jaynes et al., 2001; Celik et al., 2017). Biomass sorghum potentially is a good feedstock candidate for the biofuel energy industry, but management information for the crop is still limited (Shahandeh et al., 2015). Currently, most management practices for energy sorghum production are based on interpolations from forage, grain and sweet sorghum production guidelines (Buxton et al., 1999; Han et al., 2012; Kering et al., 2017). The biomass yields of sweet sorghum have been reported to vary across a range of N fertilizer rates, cultivars, and plant populations (Uchino et al., 2013; Olugbemi & Ababyomi, 2016). Instead, information on the response of biomass sorghum to N fertilizer in conjunction with other management factors is still scarce, although is slowly accumulating. Maughan et al. (2012) observed responses up to 150 kg N ha^{-1} in 2009 and 224 kg N ha^{-1} in 2010 for biomass sorghum in southern Illinois, while recently, Hao et al. (2014) determined that optimal N fertilizer rates for yield and efficiency for photoperiod-sensitive sorghums in the Texas High Plains were 183 and 78 kg N ha^{-1}, respectively, in 2010, and 148 and 90 kg N ha^{-1} in 2011. The objectives of this study, carried out under environmental conditions of central Italy, were to evaluate the effects of different N application rates on flowering date, plant height, biomass production and partitioning (leaves, panicles and stems) and biomass quality of a biomass sorghum hybrid.

MATERIALS AND METHODS

Two field experiments were carried out in 2005 and 2006 in central Italy (42°57'N, 12°22'E, 165 m a.s.l.) on two adjacent fields (one for each year), with similar characteristics in terms of agronomic practices and soil composition (clay-loam soil, 22% sand, 35% clay and 43% silt, 1.5% organic matter). The sorghum hybrid H133 was used (Table 1).

Experimental design was a randomized complete block with four replicates and plot size of 32 m^2 (4 m width). The experimental treatments were represented by different N rates: 0, 50, 100 and 150 kg ha^{-1} of N. Each plot was established from eight rows, six central rows for measurements and two border rows on the perimeter of each plot to reduce potential border effects. The main agronomic practices are shown in Table 1. The trials were carried out in accordance with good ordinary practices, as concerns soil tillage, seedbed preparation and weed control (Bonciarelli & Bonciarelli, 2001), adopting low input in terms of irrigation. In both years, wheat, as preceding crop, was not fertilized with N in order to reduce greatly the soil nitrogen content and then available for the subsequent sorghum crop, with the aim to obtain the zero nitrogen level in the field experiment. A pre-plant fertilization based on phosphorus and potassium was applied on sorghum (Table 1).

Table 1. Agronomic practices in the field experiments

Year	2005	2006
Preceding crop	Wheat	Wheat
Pre-plant fertilization (kg ha^{-1})	75 P_2O_5; 75 K_2O	75 P_2O_5; 75 K_2O
Sowing date	17 May	15 May
Sorghum hybrid	H133	H133
Density (plants m^{-2})	31	31
Spacing between rows (m)	0.5	0.5
N fertilizer at sowing	23 May	17 May
Emergence date	25 May	19 May
Irrigation: m^3 ha^{-1} (n.)	600 (3)	1,150 (4)
Pre-emergence weed control	Terbuthylazine (750 g ha^{-1})	Terbuthylazine (750 g ha^{-1})
Harvest	13 October	25 September

Measurements and statistical analysis

The plant height of sorghum was measured at the height of the last leaf on 30 plants per plot at 92 and 95 days after emergence (DAE), in 2005 and 2006, respectively. Flowering time was the date (reported as DAE) at which 50% of plants in each plot were flowered and was used to evaluate the effect of N on the length of the growth cycle. The fresh and dry weight of biomass of sorghum and the moisture concentration were determined at harvest (141 DAE in 2005 and 129 DAE in 2006). At harvest, identified around 3 weeks after the soft dough stage of grain filling, the plants from the six rows in the central part of each plot (21 m^{-2}) were cut, subdivided in stems, leaves and panicles and their weight was evaluated. A sample from each plant part (20% of total fresh biomass) was taken, weighed fresh and oven dried at 105 °C to a constant weight in order to assess moisture concentration, dry weight of biomass and then an equivalent yield (t ha^{-1}) for each plot. Furthermore, in 2006, a sample of total dry biomass was obtained collecting a sub-sample of biomass (taking stems, leaves and panicles at the quantity of 10% of their respective weight) from each pot and then compositing the samples across replicates within a nitrogen treatment so that there were a total of four composite samples, i.e., one for each nitrogen treatment. These samples were analysed to determine lower and higher heating values (LHV and HHV) and ash concentration of biomass, using, respectively, a calorimeter (AC-350 Leco) and a thermo-gravimetrical analyzer (TGA-701 Leco).

All data (except HHV, LHV and ash concentration, because without replications) were subjected to ANOVA using the EXCEL® Add-in macro DSAASTAT (Onofri & Pannacci, 2014). The year and treatment (N rate) were treated as fixed factors, with replication being a random factor. The differences between treatment means were separated using Fisher's protected LSD at $P = 0.05$ level when ANOVA was significant. A combined analysis of data showed that the interactions '*years x N rate*' were significant ($P < 0.05$); therefore, the results were shown and discussed separately for each year.

Meteorological data (daily maximum and minimum temperature and rainfall) were collected from a nearby station. The average decade of daily values was calculated and compared with multi-annual average values (from 1921) (Fig. 1).

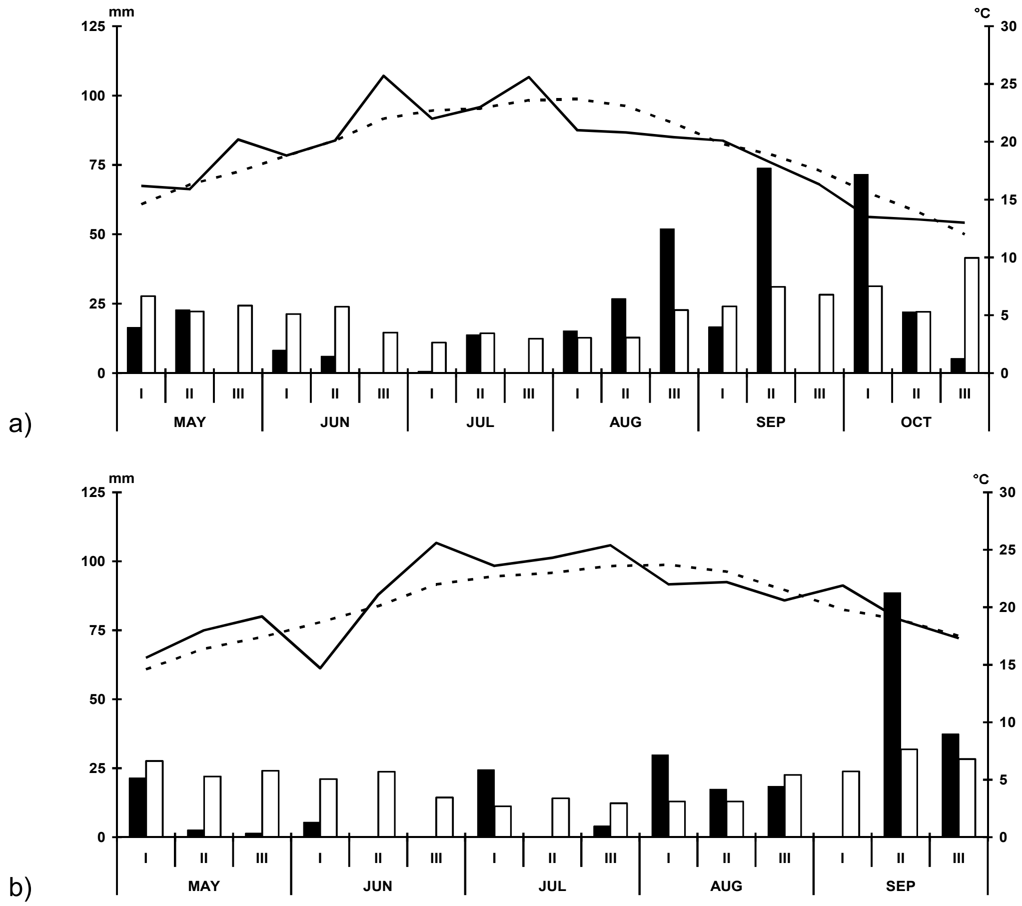

Figure 1. Average ten days values of rainfall (mm; bold bar) and temperature (°C; solid line) recorded during the experimental trial in 2005 (a), 2006 (b), compared to multi-annual (from 1921) averages (rainfall: mm, empty bar; temperature: °C, sketched line).

RESULTS AND DISCUSSION

In 2005, all response variables were significantly affected by N rates (Table 2).

In particular, N rates of 100 kg ha^{-1} and 150 kg ha^{-1} increased rate of plant development, shortening time to flower by 6 and 7 days, respectively, relative to the unfertilized crop (Table 2). N rates affected plant height, with unfertilized plants being taller than those in 100N and 150N plots (Table 2). Biomass production of sorghum fertilized with 100 and 150 kg N ha^{-1} was greater than unfertilized sorghum (0N), but there was no difference between the two highest N rates (Table 2). The rate with maximum numeric biomass production was 100 kg ha^{-1} of N, and biomass dry weight was 23.8% greater for this treatment than unfertilized sorghum (Table 2). The moisture concentration of biomass ranged from 67% for 100N and 150N, to 71% for 0N (Table 2). Total dry biomass yield partitioning showed that only data of stems and panicles were significantly different among N rates (Table 3).

Table 2. Differences among the N nitrogen rates in terms of flowering time, plant height, dry weight and moisture content of biomass in 2005

N rate (kg ha^{-1})	Flowering time (DAE)	Plant height (m) (92 DAE)	Dry weight of biomass, t ha^{-1} (141 DAE)	Moisture concentration of biomass, % (141 DAE)
0	93.4 a	3.01 a	18.5 b	71.2 a
50	90.1 ab	2.85 ab	19.7 ab	68.5 ab
100	87.0 b	2.79 b	22.9 a	66.9 b
150	86.6 b	2.69 b	22.7 a	67.1 b
Average	***89.3***	***2.84***	***21.0***	***68.4***
LSD (p=0.05)	*3.9*	*0.19*	*3.4*	*2.8*

DAE: days after emergence. In each column, values followed by the same letter are not significantly different according to the Fisher's protected LSD test (P = 0.05).

In particular, N increased significantly the percentage of panicles on behalf of stems in the partitioning of total biomass with respect to the unfertilized sorghum (Table 3).

In 2006, only biomass production was affected by N rates (Table 4). This can be explained by the greater irrigation volume in 2006 than in 2005 that reduced the effects of N rates in terms of flowering time and plant height, maintaining the effects on dry weight of biomass, as already observed by Moghaddam et al. (2007). In particular, flowering time was 102 DAE (average value) with the plant height of 3.34 m (average value at 95 DAE).

Table 3. Total dry biomass yield partitioning as determined by the weight of stems, leaves and panicles at the different N rates in 2005

N rate, kg ha^{-1}	Total dry biomass partitioning, %		
	Stems	Leaves	Panicles
0	70.7 a	18.8	10.5 b
50	62.8 b	16.6	20.6 a
100	61.5 b	18.7	19.8 a
150	61.9 b	20.3	17.7 a
Average	***64.2***	***18.6***	***17.2***
LSD (p=0.05)	*5.3*	*n.s.*	*6.6*

n.s. = no significant differences. In each column, values followed by the same letter are not significantly different according to the Fisher's protected LSD test (P = 0.05).

Table 4. Differences among the N rate in terms of flowering time, plant height, dry weight and moisture content of biomass in 2006

N rate, kg ha^{-1}	Flowering time (DAE)	Plant height, m (95 DAE)	Dry weight of biomass, t ha^{-1} (129 DAE)	Moisture content of biomass, % (129 DAE)
0	102	3.33	26.6 a	68.2
50	102	3.31	29.1 ab	68.7
100	102	3.40	31.6 b	68.7
150	101	3.30	29.4 ab	69.3
Average	***102***	***3.34***	***29.2***	***68.7***
LSD (p=0.05)	*n.s.*	*n.s.*	*3.16*	*n.s.*

DAE: days after emergence; n.s. = no significant differences. In each column, values followed by the same letter are not significantly different according to the Fisher's protected LSD test (P = 0.05).

The dry weight of biomass showed significant differences among N rates, confirming as 100 kg ha^{-1} of N seems to be near the optimal rate in order to maximize biomass production. In fact, in both years (see Tables 2 and 4), dry weight of biomass (dependent variable y) showed a quadratic response to N rate (independent variable x), according to the follow equations:

$$y = -0.0001x^2 + 0.0525x + 18.226\ (R^2 = 0.899) \text{ in 2005,} \quad (1)$$

$$y = -0.0005x^2 + 0.0928x + 26.353\ (R^2 = 0.914) \text{ in 2006,} \quad (2)$$

whose relationships are showed in Fig. 2.

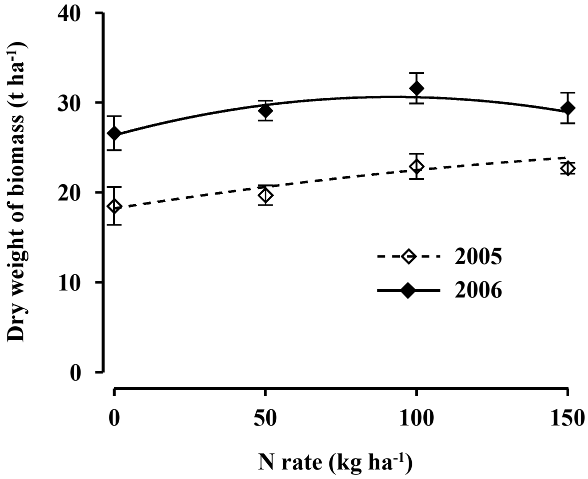

Figure 2. Relationships between N rate and dry weight of sorghum biomass observed in 2005 and 2006. Error bars represent ± standard errors of the means (n = 4).

In 2006, the total dry biomass yield partitioning was not affected by N rates (Table 5). In particular, there was a reduction in proportion of panicles and an increase in stem proportion in 2006 relative to 2005.

Table 5. Total dry biomass yield partitioning as determined by the weight of stems, leaves and panicles at the different N rates in 2006

N rate,	Total dry biomass partitioning (%)		
kg ha^{-1}	Stems	Leaves	Panicles
0	76.6	16.6	6.8
50	75.5	17.7	6.8
100	76.7	17.1	6.2
150	75.6	18.7	5.7
Average	***76.1***	***17.6***	***6.4***
LSD (p = 0.05)	*n.s.*	*n.s.*	*n.s.*

n.s. = no significant differences.

HHV, LHV and ash concentration of biomass showed different values among N rates, with values of HHV and LHV lower for unfertilized sorghum (17.6 and 16.7 MJ kg^{-1} d.m., respectively, see Table 6) than in the cases of N applications (from 19.0 to 19.7 and from 18.1 to 18.8 MJ kg^{-1} d.m., respectively); while, on the contrary, ash concentration was greater for unfertilized sorghum (7.5% d.m.) than for fertilized sorghum (from 5.8 to 6.7% d.m.) (Table 6).

Table 6. Heating values (HHV and LHV) and ash concentration of total dry biomass for the different N rates in 2006

N rate, kg ha^{-1}	HHV, MJ kg^{-1} d.m.	LHV, MJ kg^{-1} d.m.	Ash concentration, % d.m.
0	17.6	16.7	7.5
50	19.0	18.1	6.1
100	19.7	18.8	5.8
150	19.0	18.1	6.7
Average	***18.8***	***18.0***	***6.5***
S.E.	*0.43*	*0.44*	*0.37*

The faster rate of sorghum development when subjected to higher N rates supports the report of Uchino et al. (2013) who evaluated sweet sorghum in the semi-arid tropical zone of India. The extended duration of the growth cycle for the unfertilized plants (0N), means that these plants grow faster than fertilized plants (100N and 150N), as shown by plant height at 92 DAE (Table 2). The delay of flowering time in the 0N implies an extension of the growth cycle and an increase in time available for plant growth, resulting in taller plants. On the other hand, this study confirms the positive effects of N on biomass production, identifying 100 kg N ha^{-1} as an optimum rate in terms of biomass production while minimizing fertilizer costs and environmental impact. Furthermore, considering the average values 2005–2006 of sorghum biomass production, 100 kg N ha^{-1} is resulted to be the most economic N rate, thanks to the highest difference between profit to biomass sale and cost of N rate (Table 7). Similar results, in term of biomass production, were obtained by Cozzolino et al. (2007) with the same sorghum hybrid (H133) at the same N rate (100 kg ha^{-1}), in the Mediterranean area with similar weather conditions. However, the previous authors tested sorghum under different N rate, in the southern Italy and only for one year. For these reasons, this research, thanks to two years of experimentation, allowed to confirm definitely the potentiality of sorghum as biomass crop, in response to different N rates, in central Italy. Furthermore, the quadratic response between dry weight of biomass and N rate found in this study was reported also by Kering et al. (2017) investigating the effect of N fertilizer on five sweet sorghum varieties in mid-central Virginia.

Table 7. Evaluation of the most economic N rate (average 2005–2006)

N rate, kg ha^{-1}	Dry weight of biomass t ha^{-1} (Average 2005–2006)	Profit of biomass sale*, € ha^{-1} (A)	Cost of N rate** € ha^{-1} (B)	Difference, € ha^{-1} (A–B)
0	22.6	523.2	0	523.2
50	24.4	566.1	37.5	528.6
100	27.3	632.2	75	557.2
150	26.1	604.4	112.5	491.9

* calculated considering the actual price of sorghum biomass equal to 23.2 € t^{-1}; ** calculated considering the actual cost of urea nitrogen equal to 0.75 € kg^{-1}.

The biomass yield results for sorghum showed its high potential for biomass production in central Italy, confirming the data obtained by the same authors in the same area (Pannacci & Bartolini, 2016) and by other authors in the same country (Habyarimana et al., 2004; Quaranta et al., 2010; Marsalis & Bean, 2010). On average, the values of biomass production, plant height and flowering time of sorghum were greater in 2006 than in 2005. This was likely due to greater irrigation volume in 2006 than 2005 (Table 1), since the weather conditions during the sorghum growth cycle (from May to September) were similar in 2005 and 2006 with rainfall of 252 mm and 251 mm, respectively (Fig. 1). This is in accordance with Montemurro et al. (2002) who found increasing N Use Efficiency (NUE) increase when irrigation increased up to 100% of crop evapotranspiration (ETc). Similarly, Marsalis & Bean (2010) indicated that in irrigated environments with high yield potentials, N application as high as 269 kg N ha^{-1} may be needed, while little to no N fertilizer may be required under dry land conditions.

The moisture concentration of biomass was greater at 0N than at 100N and 150N, and this is in accordance with the extending of the growth cycle at low N rates, resulting in a greater moisture concentration of sorghum biomass at harvest (141 DAE). Similarly, concerning total dry biomass yield partitioning, the percentage of panicles was greater in fertilized than unfertilized sorghum due to the earlier flowering induced by N that allowed the proportion of panicle to increase until harvest, as already reported for sweet sorghum (FAO, 2017). Furthermore, the reduction of panicle proportion in favor of increased proportion of stems in 2006 relative to 2005, is likely due to greater irrigation volume in 2006 that prolonged the growth cycle, delaying the flowering time and as a consequence reducing panicle growth before harvest (occurred at 129 DAE in 2006 and 141 DAE in 2005).

The results of quality of biomass (HHV, LHV and ash concentration) were comparable to those of Pannacci & Bartolini (2016) and Monti et al. (2008). However, the quality of biomass can be influenced by management practices and environmental conditions as reported by Pannacci et al. (2009) and Singh et al. (2012). Furthermore, Monti et al. (2008) observed that leaves and panicles have greater ash concentration than stems, while Obernberger et al. (2006) reported that low ash concentration is preferred for solid biofuels in order to avoid high deposit formation, corrosion and fly ash emissions during thermal utilization. In order to reduce the leaf component in the total biomass yield, Pannacci & Bartolini (2016) suggested to separate the leaves at harvest time, using only the stems as biofuel. Leaves could then be incorporate into the soil with the aim of reducing loss of nutrients and potentially increasing organic matter in the soil.

Overall, this research showed the high potential of sorghum in terms of biomass production when cultivated with limited irrigation and fertilization inputs, as demonstrated by dry weight of biomass without N fertilization of 18.5 t ha^{-1} of d.m. in 2005 and 26.6 t ha^{-1} of d.m. in 2006. Furthermore, considering the LHV value at 0N (16.7 MJ kg^{-1} of d.m.) (Table 6), one tonne of dry biomass of sorghum corresponds to 16,700 MJ. Since 1 tonne of oil equivalent (toe) = 41,868 MJ, one tonne of dry biomass of sorghum may be expressed as 0.41 toe. As a consequence, the biomass dry yield obtained by one hectare of sorghum crop without N fertilization (i.e. 22.6 t ha^{-1} of d.m., average of 2005 and 2006 values) produces the same energy, by thermal utilisation, of 9.3 toe, that is equivalent to energy produced by 10,385 L of diesel fuel or 11,097 m^3 of methane fuel. The above mentioned aspect increases the certainty of the energetic and environmental sustainability of sorghum crop, as already reported by Venturi & Venturi (2003). In fact, in the sorghum crop for biomass production, the mineral fertilization is the highest input (60.3% of the total energy consuming) to consider in the energy balance (Bartolini, 2008). This research was able to point out as sorghum for biomass production needs to N in order to maximize yield. However, this crop seems to be sustainable both from an energetic and environmental point of view, thanks to its highly documented drought tolerance and low input requirements that allows it to maintain high yields also with low N input and low water supply.

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REFERENCES

Almodares, A, Jafarinia, M. & Hadi, M.R., 2009. The Effects of Nitrogen Fertilizer on Chemical Compositions in Corn and Sweet Sorghum. *American-Eurasian J. Agric. & Environ. Sci.* **6**(4), 441–446.

Almodares, A., Taheri, R. & Eraghizadeh, F., 2011. The effects of ethephon on biomass and carbohydrate content in two sweet sorghum cultivars. *Int. J. Plant Prod*. **5**(3), 221–226.

Bartolini, S. 2008. Pioppo e sorgo da biomassa per scopi energetici: sperimentazione agronomica e analisi LCA (Life Cycle Assessment). Department of Environmental and Agricultural Science, University of Perugia, Italy. (PhD Dissertation) pp. 161. Available on line at: https://www.tesionline.it/default/tesi.asp?idt=25522

Bonciarelli, F. & Bonciarelli, U. 2001. *Crop Science* (*Coltivazioni Erbacee*). Calderini Edagricole, Bologna, 492 pp. (in Italy).

Buxton, D.R., Anderson, I.C., Hallam, A. 1999. Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. *Agron. J.* **91**, 93−101.

Celik, I., Günal, H., Acar, M., Gök, M., Bereket Barut, Z. & Pamiralan, H. 2017. Long-term tillage and residue management effect on soil compaction and nitrate leaching in a Typic Haploxerert soil. *Int. J. Plant Prod.* **11**(1), 131–149.

Cozzolino, E., Leone, V., Zeno, G. & Raimo, F. 2007. Influenza di differenti input agrotecnici sulla produttività di due ibridi di sorgo da biomassa energetica in ambiente meridionale. In: *Proceedings of XXXVII Conference of Italian Society for Agronomy*, Catania, Italy, 13–14 September 2007, pp. 49–50.

Dogget, H. 1998. Sorghum. In: Tropical agriculture Series. 2nd ed. Wiley, New York, 512 pp.

FAO, 2017. *Breeding and cultivation of sweet sorghum*. Available on line at: http://www.fao.org/docrep/T4470E/t4470e05.htm

Gardner, J.C., Maranville, J.W. & Paparozzi, E.T. 1994. Nitrogen use efficiency among diverse sorghum cultivars. *Crop Sci.* **34**, 728–733.

Habyarimana, E., Bonari, P., Laureti, D., Di Bari, V., Casentino, S. & Lorenzoni, C. 2004. Multilocational evaluation of biomass sorghum hybrids under two stand densities and variable water supply in Italy. *Ind. Crops Prod.* **20**, 3–9.

Han, K.J., Putnam, W.D., Alison, M.W., Harrell, D.L., Viator, H.P., McCormick, M.E., Gravois, K.A., Kim, M. & Dayet, D.F. 2012. Agronomic considerations for sweet sorghum biofuel production in the south-central USA. *Bioenergy Res.* **5**, 748–758.

Hao, B., Xue, Q., Bean, B.W., William, L.R. & Becker, J.D. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas high plains. *Biomass Bioenergy* **62**, 108−116.

Jaynes, D.B., Colvin, T.S., Karlen, D.L., Cambardell, C.A. & Meek, D.W. 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. *J. Environ. Qual.* **30**, 1305–1314.

Kering, M.K., Temu, V.W. & Rutto, L.K. 2017. Nitrogen Fertilizer and Panicle Removal in Sweet Sorghum Production: Effect on Biomass, Juice Yield and Soluble Sugar Content. *J. Sustain. Bioen. Syst.* **7**, 14–26.

Lewandowski, I., Kicherer, A. & Vonier, P. 1995. CO_2-balance for the cultivation and combustion of miscanthus. *Biomass Bioenergy* **2**, 81–90.

Marsalis, M.A. & Bean, B. 2010. Western forage production guide. United Sorghum Checkoff Program Lubbock, TX 79403. Available on line: file:///C:/Users/Utente/Downloads/westernforageguide_final.pdf

Maughan, M., Voigt, T., Parrish, A., Bollero, G., Rooney, W. & Lee, D. 2012. Forage and energy sorghum responses to nitrogen fertilization in central and southern Illinois. *Agron. J.* **104**, 1032–1040.

Moghaddam, H., Chaichi, M.R., Mashhadi, H.R., Firozabady, G.S. & Zadeh, A.H. 2007. Effect of Method and Time of Nitrogen Fertilizer Application on Growth,Development and Yield of Grain Sorghum. *Asian Journal of Plant Sciences* **6**, 93–97.

Montemurro, F., Colucci, R. & Martinelli, N., 2002. Fertilization and N use efficiency in sweet sorghum growing under mediterranean conditions (Nutrizione azotata ed efficienza della fertilizzazione del sorgo in ambiente mediterraneo). *Italian Journal of Agronomy* (*Rivista di Agronomia*) **36**, 313–318 (in Italy).

Monti, A., Di Virgilio, N. & Venturi, G., 2008. Mineral composition and ash content of six major energy crops. *Biomass Bioenergy* **32**, 216–23.

Obernberger, I., Brunner, T. & Bärnthaler, G., 2006. Chemical properties of solid biofuels–significance and impact. *Biomass Bioenergy* **30**, 973–82.

Olugbemi, O. & Ababyomi, Y.A. 2016. Effects of Nitrogen Application on Growth and Ethanol Yield of Sweet Sorghum [Sorghum bicolor (L.) Moench] Varieties. Advances in Agriculture, ID 8329754, 7 pages, http://dx.doi.org/10.1155/2016/8329754.

Onofri, A. & Pannacci, E. 2014. Spreadsheet tools for biometry classes in crop science programmes. *Commun. Biom. Crop Sci.* **9**(2), 3–13.

Pannacci, E. & Bartolini, S. 2016. Evaluation of sorghum hybrids for biomass production in central Italy. *Biomass Bioenergy* **88**, 135–141.

Pannacci, E., Bartolini, S. & Covarelli, G. 2009. Evaluation of Four Poplar Clones in a Short Rotation Forestry in Central Italy. *Ital. J. Agron.* **4**, 191–8.

Quaranta, F., Belocchi, A., Bentivenga, G., Mazzon, V. & Melloni, S. 2010. Fibre sorghum: influence of harvesting period and biological cycle on yield and dry matter in some hybrids. *Maydica* **55**, 173–177.

Regassa, T.H. & Wortmann, C.S. 2014. Sweet sorghum as a bioenergy crop: literature review. *Biomass and Bioenergy* **64**, 348–355.

Shahandeh, H., Hons, F.M., Wight, J.P. & Storlien, J.O. 2015. Harvest strategy and N fertilizer effects on bioenergy sorghum production. *AIMS Energy* **3**(3), 377–400.

Shakeri, E.,Yahya Emam, Tabatabaei, S.A. & Sepaskhah, A.R. 2017. Evaluation of grain sorghum (Sorghum bicolor L.) lines/cultivars under salinity stress using tolerance indices. *Int. J. Plant Prod.* **11**(1), 101–115.

Singh, M.P., Erickson, J.E., Sollenberger, L.E., Woodard, K.R., Vendramini, J.M.B. & Fedenko, J.R. 2012. Mineral composition and biomass partitioning of sweet sorghum grown for bioenergy in the southeastern USA. *Biomass Bioenergy* **47**, 1–8.

Uchino, H., Watanabe, T., Ramu, K., Sahrawat, K.L., Marimuthu, S., Wani, S.P. & Ito, O. 2013. Effects of Nitrogen Application on Sweet Sorghum (Sorghum bicolor (L.) Moench) in the Semi-Arid Tropical Zone of India. *JARQ* **47**, 65–73.

Venturi, P. & Venturi, G. 2003. Analysis of energy comparison for crops in European agricultural system. *Biomass Bioenergy* **25**, 235–255.

Zegada-Lizarazu, W. & Monti, A. 2012. Are we ready to cultivate sweet sorghum as a bioenergy feedstock? A review on field management practices. *Biomass Bioenergy* **40**, 1–12.

Zhao, D., Reddy, K.R., Kakani, V.G. & Reddy, V.R. 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis and hyperspectral reflectance properties of sorghum. *Eur. J. Agron.* **22**, 391–403.