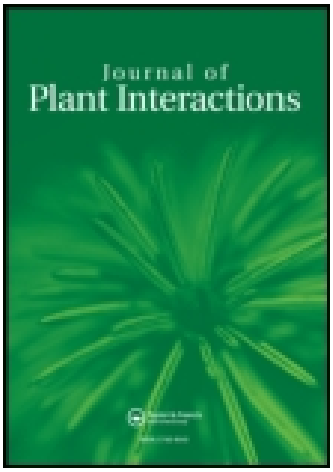

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RESEARCH ARTICLE

Yield and morpho-agronomical evaluation of food-grade white sorghum hybrids grown in Southern Italy

Paola Pontieri[a,b]*, Pasquale De Vita[c], Antonio Boffa[a], Mitchell R. Tuinstra[d], Scott R. Bean[e], Gabriel Krishnamoorthy[f], Charles Miller[f], Earl Roemer[g], Pietro Alifano[h], Domenico Pignone[i], Domenica Rita Massardo[a,b] and Luigi Del Giudice[a,b]

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Grain sorghum [*Sorghum bicolor* (L.) Moench] is a gluten-free grain that is gaining attention as a food crop that can be used in the management of celiac disease. At present, sorghum is widely grown in many semiarid regions of the world. New food-grade sorghum cultivars are of particular interest in Mediterranean countries due to improved quality characteristics and gluten-free status of the grains. Until now very few studies have examined the grain yield (GYLD) and agronomic performance characteristics of food-grade sorghum hybrids in Italy. A 2 year study was conducted to evaluate the agronomic performance of eight food-grade sorghum hybrids representing different maturity classes in trials conducted in Southern Italy. The results showed wide variation in adaptation of these hybrids as measured by differences in GYLD (2.35–8.50 t ha^{-1}) and other pheno-morphological characteristics. Of particular interest was the fact that many of the early-flowering hybrids (e.g. SP-X303) performed better than the later-flowering hybrids (e.g. ArchX-02). These results demonstrated that flowering time of hybrid and crop cycle length are important factors to consider in selecting cultivars for production in the Mediterranean region.

Keywords: food-grade sorghum; sorghum hybrid; yield; celiac disease

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop worldwide after wheat, rice, maize, and barley (FAO 2011) and is strongly adapted to water-limited environments performing better than other cereal crops under various environmental stresses such as drought, water logging and salinity (ICRISAT 1996). An estimated 39% of global sorghum production was used as food and 54% for feed in the 1980s (Awika & Rooney 2004). The proportion of sorghum utilized as food has gradually increased as a result of a greater food use in Africa and the substitution of other grains (mainly maize) for sorghum as feed elsewhere. By the 1990s, approximately 42% of total sorghum utilization was for food and 48% for animal feed (ICRISAT 1999; Awika & Rooney 2004).

The USA is the largest producer and exporter of sorghum, accounting for 20% of world production and almost 80% of world sorghum exports in 2001–2003 (USDA-FAS 2003; Awika & Rooney 2004). Public and private sector sorghum breeding programs have released many improved sorghum varieties that are adapted to semi-arid and tropic environments including cultivars that meet specific food and industrial requirements (Tuinstra 2008). The demand for sorghum also is increasing in many developing countries, particularly in West Africa. This is due to growing population as well as government policies that promote processing and industrial utilization (Akintayo & Sedgo 2001; Dicko et al. 2006).

Many thousands of sorghum accessions have been developed and are represented in seed collections around the world, particularly collections in Ethiopia, China, USA, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Rosenow & Dahlberg 2000). There is a need for further characterization of the sorghum collections with respect to food and other quality attributes. The acquisition of good quality grain is fundamental to production of acceptable food products from sorghum. In addition, sorghum is often recommended as

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a safe food for celiac patients, whose digestive systems do not tolerate protein sequences contained in both the gliadins (Kagnoff et al. 1982) and glutenins (Van de Wal et al. 1999) of wheat (Kasarda 2001; Taylor et al. 2006). Recently, in vitro and in vivo tests of the toxicity of sorghum proteins and peptides showed no toxicity for these patients (Ciacci et al. 2007). Sorghum, therefore, provides a good basis for gluten-free foods. Recently, our research group began cultivating white grain, tan-plant, 'food-grade' sorghum cultivars in Southern Italy (Del Giudice et al. 2008; Pontieri et al. 2010, 2011). The present study was conducted to compare the agronomical performances of these hybrids representing a range of different maturities with the perspective of their introduction in temperate Italian climate areas as competitive crop.

Materials and methods

Experimental site

Field trials were conducted at San Bartolomeo in Galdo (BN, Italy) on a clay-loam soil during 2010 and 2011. San Bartolomeo in Galdo is an inland area at the east of the Campania Region, about 530 m above the sea level. Eight hybrids of sorghum (Table 1) were sown on 6 May 2010 and 8 May 2011 in 2-row plots (2 m $\times$ 5 m) replicated 3 times in a randomized block design. The average plant density was of 3,00,000 plants ha at harvest. Before sowing, 200 kg ha^{-1} of complex fertilizer (NPK = 12-12-17 and -2-14 unit of MgO–SO_3) was applied, while 100 kg ha^{-1} of Urea (N46%) was distributed at stem elongation stage. An herbicide treatment of glyphosate (4 l ha^{-1}) was applied to the field to eliminate weeds before planting. After planting, weeds were controlled by hand hoeing as necessary. Plants were grown without supplemental irrigation. Each year the hybrids were harvested starting from the end of August to mid-September. One of the hybrids in the study (Fontanelle 1000) flowered very late and did not reach physiological maturity. Therefore, only results from seven hybrids were discussed later.

Table 1. List of sorghum hybrids.

No.	Hybrid name (Hy)	Source	Supplied by
1	Hy X10341	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
2	Hy X10315	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
3	Hy X87341	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
4	Hy Fontanelle 1000	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
5	Hy F-X525	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
6	Hy ArchX-02	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
7	Hy SP-X303	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer
8	Hy F-X715 Ch	Richardson Seeds, Ltd (Vega, TX)	Earl Roemer

Traits evaluated

Seedling emergence (EME) was scored as days required for 50% of the seeds to germinate. Flowering time (FLO) was recorded as the number of days from sowing to when 50% of plants had started flowering in a plot. Days to maturity was recorded as the number of days from planting to when seeds on 50% of the plants in a plot exhibited black layer on the lower third of the panicle. Grain filling period (GFP) was measured as the number of days between flowering date and physiological maturity.

At physiological maturity, data were collected for panicle yield (PYLD), grain yield (GYLD); randomly selected 10 plants were used for plant height (PH), length of panicle exertion (LPE), and panicle length (PL). PH (cm) was measured during the milk waxy maturation when maximum height was achieved from the ground to the tip of the main panicle. PL (cm) was recorded as length of the panicle from its base to tip; LPE (cm) was measured as length between the base of the flag leaf and the base of the panicle; and the PYLD (average of 10 plants or panicles in the plot) was used to estimate the grain yield per panicle (GYP). In addition, the number of fertile (FP) and infertile panicles (FI) was also estimated. No bird damage was observed during the study period.

The site was dominated by a Mediterranean climate where rainfall occurs from the end of autumn to the beginning of spring and the average rainfall during the crop cycle of sorghum (April–September) ranges from 350 to 400 mm. During the field experiment, climate data were measured using a standard meteorological station located on a grassy area near the experimental field. Maximum and minimum temperatures and precipitation were collected on a monthly basis (Table 2). Soil characteristics of the site are reported in Table 3.

Although a more accurate indication of the efficiency of conversion of water to yield is called (WUE) is obtained when fallow water is measured (by probing or coring), WUE based on an estimate of fallow efficiency will provide a useful rule of thumb for assessing future yield potential. In the present study the crop WUE was estimated according to the following the equation proposed by Passioura and Angus (2010):

$$\text{Crop WUE (kg/ha/mm)} = \text{GYLD (kg/ha)}/\text{R (mm)} - 100\,\text{(mm)}$$

where R is the amount of rainfall during the growing-season and 100 represents a threshold value to account for (1) the water needed to grow crop

Table 2. Monthly rainfall, maximum and minimum temperature of growing season 2010 and 2011 recorded at San Bartolomeo in Galdo, Italy.

	2010				2011			
Month	T. max (°C)	T. min (°C)	T. mean (°C)	Rainfall (mm)	T. max (°C)	T. min (°C)	T. mean (°C)	Rainfall (mm)
April	13.9	6.7	10.3	68.0	14.6	7.2	10.9	149.0
May	17.6	9.7	13.7	57.8	17.9	10.3	14.1	145.7
June	22.8	13.7	18.3	48.8	23.8	14.5	19.2	27.8
July	27.5	17.6	22.6	81.8	26.0	15.9	21.0	65.6
August	26.9	17.1	22.0	6.2	29.1	18.4	23.8	0.0
September	20.5	13.0	16.8	116.2	28.1	17.9	23.0	26.8
	21.5	13.0	17.3	378.8	23.3	14.0	18.7	414.9

biomass before it can start to produce grain; (2) in crop run-off and evaporation; and (3) water not used and left over at harvest.

Statistical analyses were conducted for each parameter by analysis of variance (ANOVA) in a factorial design with 2 years and 7 hybrids. Least significant difference (LSD) values were calculated at the 5% probability level using Statistica Software (StatSoft, Inc. 2005).

Results

ANOVA

Considering the main factors year (Y) and hybrids (Hy) and their interaction, all traits showed statistically significant variations with the exception of LPE for the year factor. Although it is true that the $Y \times Hy$ interaction was statistically significant, it is also true that it was of relatively little biological importance. For instance, regarding yield as the main attribute (but this is true for most of the traits considered) the mean square (MS) of genotypes was far greater than the MS for the interaction (data not shown). This may be interpreted as primary evidence that the interaction, although statistically significant, may not represent major changes in hybrid rankings for most attributes.

Table 3. Soil characteristics of the experimental site (San Bartolomeo in Galdo, Italy).

Soil characteristic	0–60 cm depth
Clay (%)	40.5
Silt (%)	19.3
Sand (%)	40.2
pH	8.3
Exchangeable Ca (g/kg)	122
Available P (mg/kg)	12
Exchangeable K (meq/100 g)	1.2
Exchangeable Mg (meq/100 g)	1.2
Total Ca Carbonate (g/kg)	70
Total N (g kg^{-1})	1.0
CSC (meq/100 g)	30
Organic C (g kg^{-1})	3.0

The year by hybrid interaction, although significant, did not display major crossover effects for the traits studied and thus was of minor importance.

Weather conditions and year effect

The patterns of climate parameters registered during the sorghum growing seasons were generally average for the area. In fact, the amount of rainfall during the growing-season (April–September) was only slightly different between the 2 years ranging from 378.8 to 414.9 mm (Table 2). However, as is typical of the Mediterranean climate, the distribution of rainfall was highly variable between the 2 years. The study in 2010 was characterized by a lower amount of rainfall during the early crop growth stages while the distribution of rainfall in 2011 was concentrated around the sowing period and during the early vegetative stages of growth. In both years, a short period of drought was detected in August, when both the environmental evapotranspiration and mean temperature reached the maximum values (data not shown).

The mean values of morpho-agronomical parameters recorded at San Bartolomeo in Galdo (Italy) during the growing season 2010 and 2011 are reported in Table 4. The favorable climatic conditions, in terms of distribution and mean temperatures, recorded in 2011 promoted good emergence and better hybrid performance (GYLD) than in 2010 (5.91 t ha^{-1} vs. 4.71 t ha^{-1} for 2011 and 2010, respectively). Furthermore, the field data also showed that the climatic conditions of the second growing season positively affected all other traits evaluated (Table 4).

Hybrid performance

The mean PH was 84.3 cm and the hybrids varied significantly ranging from 72.5 (F-X525) to 92.9 cm (Hy 10341). Significant variation also was observed for LPE (2.9 vs. 9.7 cm for ArchX-02 and Hy10341, respectively). The hybrid Hy 10315 suffered more than the others from drought stress during the month of August. This fact probably also influenced

Table 4. Morpho-agronomical parameters recorded at San Bartolomeo in Galdo, BN (Italy) during 2010 and 2011.

		PH	PL	LPE	PYLD	FP	FI	GYP	GYLD	EME	FLO	GFP
YEAR (Y)												
	2010	77.2	52.6	6.2	5.03	148	15	64.3	4.71	9.7	57.0	39.9
	2011	91.3	61.2	7.6	6.39	190	3	74.5	5.91	11.8	61.1	49.5
	Mean	84.3	56.9	6.9	5.7	169.0	8.6	69.4	5.3	10.8	59.0	44.7
	LSD0.05	2.2	0.8	ns	0.32	20	8	10.1	0.30	0.5	0.7	0.6
HYBRID (Hy)												
	SP-X303	80.5	51.2	8.7	7.96	194	0	101.3	7.44	9.8	51.5	36.8
	F-X715 Ch	83.5	55.0	8.3	7.40	132	2	94.1	6.68	10.0	54.5	44.9
	X87341	91.2	60.8	7.9	7.01	191	0	62.9	6.68	11.8	59.8	48.5
	X10341	92.9	60.1	9.7	6.53	196	0	65.8	6.05	12.0	60.5	53.0
	X10315	90.1	63.4	5.1	3.88	103	45	76.8	3.55	12.8	64.5	41.8
	F-X525	72.5	50.0	5.8	3.79	177	14	54.3	3.53	9.3	57.8	49.3
	ArchX-02	79.4	58.1	2.9	3.38	190	0	30.9	3.25	9.8	64.7	38.8
	Mean	84.3	56.9	6.9	5.7	169.0	8.6	69.4	5.3	10.8	59.0	44.7
	LSD0.05	4.2	1.5	3.4	0.59	37	15	19.2	0.60	1.0	1.3	1.2
Y × Hy												
2010	X87341	86.4	59.4	6.8	6.62	180	0	60.3	6.60	12.0	60.5	47.5
	SP-X303	69.3	43.7	8.0	6.83	176	0	84.5	6.38	8.5	44.0	31.5
	X10341	95.6	60.8	11.1	6.60	205	0	63.0	6.00	10.5	63.0	53.5
	F-X715 Ch	70.9	46.9	7.0	6.30	110	2	78.8	5.70	8.5	46.5	38.8
	F-X525	62.1	42.9	5.0	3.25	152	12	46.5	3.03	8.0	49.5	42.3
	ArchX-02	68.0	49.9	2.6	2.99	163	0	26.2	2.90	8.5	66.7	33.3
	X10315	88.4	65.1	3.0	2.60	50	90	91.0	2.35	12.0	68.5	32.5
	Mean	77.2	52.6	6.2	5.00	148	14.8	64.3	4.7	9.7	57.0	39.9
2011	SP-X303	91.8	58.6	9.4	9.10	213	0	118.0	8.50	11.0	59.0	42.0
	F-X715 Ch	96.1	63.1	9.5	8.50	155	2	109.5	7.65	11.5	62.5	51.0
	X87341	96.0	62.3	9.0	7.40	202	0	65.5	6.75	11.5	59.0	49.5
	X10341	90.3	59.4	8.3	6.45	188	0	68.5	6.10	13.5	58.0	52.5
	X10315	91.8	61.6	7.3	5.15	156	0	62.5	4.75	13.5	60.5	51.0
	F-X525	82.8	57.2	6.7	4.33	202	16	62.0	4.03	10.7	66.0	56.3
	ArchX-02	90.7	66.4	3.1	3.77	217	0	35.7	3.60	11.0	62.7	44.3
	Mean	91.3	61.2	7.6	6.39	190	2.5	74.5	5.9	11.8	61.1	49.5
	LSD0.05	6	2.1	4.6	0.84	52.4	20.5	26.9	0.87	1.4	1.9	1.7

PH, plant height; PL, panicle length; LPE, length of peduncle exertion; PYLD, panicle yield; PF, number of fertile panicle; PI, number of infertile panicle; GYP, grain yield per panicle; GYLD, grain yield; EME, number of days from sowing to seedling emergence; FLO, number of days from sowing to 50% of flowering plant; GFP, grain filling period.
Note: Least significant difference (LSD) test was used for comparing the means at 0.05% probability level.

the level of fertility of panicle so that hybrid Hy 10315 recorded both the lowest number of fertile panicles (103) and the largest number of infertile panicles (45), confirming that severe moisture stress limits head exertion from the flag-leaf sheath, preventing pollination.

The mean PYLD value was 5.71 t ha^{-1} with individual hybrids varying from 3.38 t ha^{-1} (ArchX-02) to 7.96 t ha^{-1} (SP-X303). Similarly, the GYLD recorded for the hybrid SP-X303 (7.4 t ha^{-1}) was 2.2 times higher than ArchX-02 (3.25 t ha^{-1}). A similar trend was observed for GYP, with the ArchX-02 hybrid performing poorest (30.9 g), and SP-X303 showing the highest value (101.3 g) for this trait.

The large variations in hybrid performance generally reflected the differences in FLO. Among the hybrids evaluated, the hybrids with the highest GYLD, SP-X303 and F-X715 Ch, flowered earlier (51.5 and 54.5 days, respectively) than the hybrids with the lowest GYLD (ArchX-02) (64.7 days) indicating that the long cropping cycle of late hybrids was unsuitable for the study-area. Contextually, the ArchX-02 hybrid exhibited the shortest GFP (38.8 days) together with SP-X303 (36.8 days).

Discussion

Almost all studies in Italy that have investigated the agronomic or quality traits of sorghum refer to forage (Dolciotti et al. 1998; Colombo et al. 2007), biomass (Belletti et al. 1991; Habyarimana et al. 2004) or sweet sorghum (Monti & Venturi 2003; Barbanti et al. 2006). White grain sorghum is an interesting crop for the southern regions of the EU. High quality human food products can be made from sorghum flour – products such as breads (Satin 1988; Cauvain 1998; Schober et al. 2005), parboiled sorghum (Young et al. 1990), sorghum tortillas (Choto et al. 1985), snack foods (Serna-Saldivar et al. 1988), cookies (Badi & Hoseney 1976; Morad et al. 1984) and flatbreads

(Lindell & Walker 1984; Morad et al. 1984). In addition, white grain sorghum may provide a good basis for gluten-free breads and other baked products such as pasta, cookies, and snacks since direct testing has been conducted on its safety for celiac patients (Ciacci et al. 2007).

The present study represents one of the first attempts to evaluate the possibility of introducing food-grade white grain sorghum in Italy. For this reason eight hybrids, characterized by different morpho-phenological traits, were compared in order to identify those capable of fully expressing their maximum yield potential in the environmental conditions of South Italy.

Sorghum grown under rain-fed conditions is usually affected by drought stress at different stages resulting in a negative effect on yield. Moisture stress at the boot stage may prevent the head from exerting completely from the flag leaf sheath, which may cause harvest difficulty. The crop will respond favorably to irrigation at this stage. Following the boot stage, the peduncle grows rapidly extending the head through the flag leaf sheath. Prasad et al. (2008) documented that sorghum was most sensitive to heat stress about 10 days before and during pollination, causing maximum reductions in seed set and yield. Our findings seem to confirm these previous data since late-flowering hybrids ArchX-02, X10315 and F-X525 were exposed to a short period of high-temperature stress (10–14 and 20–25 July with maximum temperature $> 30°C$ during 2010 and 2011, respectively) during reproductive development. Nevertheless, a few highly productive hybrids were identified. In particular, the high yield levels recorded from early-flowering hybrids underline the possibility of cultivating this species in the areas of Center and South of Italy environment, providing a valid crop alternative to durum wheat monoculture for farmers.

As previously reported (Saeed et al. 1987; Rajewski et al. 1991; Larson & Vanderlip 1994; Lesoing & Francis 1999; Maman et al. 2004), shorter hybrids (PH) showed a significant positive correlation with panicle (PYLD) and GYLD performance (0.67 $p \leq 0.001$ and 0.65 $p \leq 0.05$, respectively) and an LPE longer than taller hybrids (0.86 $p \leq 0.001$) (Table 5). As expected in the study area, hybrids that flowered late were positively correlated with PI (0.98 $p \leq 0.001$) and negatively with PF (-0.85 $p \leq 0.01$) compromising the yielding ability of hybrids.

Results showed yield advantages of four early improved sorghum hybrids (SP-X303, F-X715 Ch, X87341 and X10341) with yields over 5.5 t ha^{-1} in both years of study. SP-X303, in particular, ranked number one for GYLD, GYP and PYLD. Based on yield performance, SP-X303 could be recommended to be grown in Southern Italy and to promote white grain sorghum cultivation and production of high quality human food products.

The climatic conditions of the experimental site were characterized by a limited amount of rainfall during June and a complete lack of rainfall and high temperatures during August for both years. For this reason, the substantial differences in GYLD were linked to differences in precocity of hybrids. Only the early hybrids (SP-X303, F-X715 Ch, X87341, and X10341) were able to complete the crop growing cycle while the later hybrids (ArchX-02) had difficulty in reaching physiological maturity before harvest. Therefore, the most important criterion in selecting hybrids is based on synchronizing the phenology of the cultivar with the climate characteristic of the growing area. Moreover, the early improved sorghum hybrids increase also the WUE (data not shown) in fact the greater WUE was recorded during the first study-year with X87341 (23.7 kg/ha/mm) and SP-X303 (22.9 kg/ha/mm) and during the 2011 with SP-X303 (27.0 kg/ha/mm) and F-X715 Ch (24.3 kg/ha/mm).

In conclusion, our data indicated that careful hybrid selection, food-grade sorghum producers could identify hybrids that produce high yield equal to those of non-food-grade hybrids. To fully exploit

Table 5. Correlation coefficients of sorghum hybrids traits recorded at San Bartolomeo in Galdo, BN (Italy) during 2010 and 2011.

	PH	LPE	PYLD	PF	PI	GYP	GYLD	EME	FLO	GFP
PH	1.00									
LPE	0.62	1.00								
PYLD	0.67***	0.86***	1.00							
PF	0.12	0.43	0.44	1.00						
PI	−0.32	−0.54	−0.55	−0.87	1.00					
GYP	0.33	0.43	0.62	−0.30	0.24	1.00				
GYLD	0.65*	0.86**	0.99***	0.46	−0.57	0.61	1.00			
EME	−0.04	−0.14	−0.13	−0.36	0.03	−0.08	−0.12	1.00		
FLO	−0.30	−0.55	−0.59	−0.85**	0.98***	0.19	−0.61	−0.07	1.00	
GFP	0.07	0.57	0.31	0.62	−0.72*	−0.29	0.31	−0.01	−0.69*	1.00

PH, plant height; LPE, length of peduncle exertion; PYLD, panicle yield; PF, number of fertile panicle; PI, number of infertile panicle; GYP, grain yield per panicle; GYLD, grain yield; EME, number of days from sowing to seedling emergence; FLO, number of days from sowing to 50% of flowering plant; GFP, grain filling period.
Significant correlation at $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$.

the potential of these hybrids, future work should be directed in solving some physiological bottlenecks, for example, late flowering.

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