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Variability and Relationships among Forage Yield and Quality Traits in Pearl Millet

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ABSTRACT

Pearl millet [*Pennisetum glaucum* (L.) R. Br.], owing to its high photosynthetic efficiency and biomass production ability, fewer disease and insect pest problems, and tolerance to multiple environmental stresses, is a valuable forage crop, especially in view of climate change consequences. Nine open-pollinated varieties (OPVs) and 27 top-cross hybrids made on three male-sterile lines (A-lines) were evaluated in Alfisols at ICRISAT, Patancheru in the rainy season for two years. When harvested at 50 days after sowing, top-cross hybrids out-yielded OPVs, on an average, by about 30%, most likely due to relatively earlier flowering and higher biomass accumulation. At 80 d harvest, the dry forage yield of OPVs was similar to those of the hybrids. Forage nitrogen (N), *in vitro* digestibility and metabolizable energy content were used as laboratory fodder quality traits. Significant differences among the OPVs and among the hybrids were observed for these three quality traits, both at 50 d and 80 d harvest. While forage N declined by 49% at 80 d harvest, *in vitro* digestibility and metabolizable energy declined by 16-18%. At 50 d harvest, forage N content, *in vitro* digestibility and metabolizable energy were all significantly negatively correlated with forage yield both in OPVs and hybrids. At 80 d harvest, forage yield was not associated with any of the three quality traits in OPVs. In hybrids, forage yield was significantly negatively correlated with forage N content, while it was significantly positively correlated with the other two quality traits. These results indicate better prospects of combining high forage yield with high levels of *in vitro* digestibility and metabolizable energy in hybrids than in OPVs of pearl millet.

Keywords: Hybrids, male sterility, OPVs, pearl millet forage, *Pennisetum glaucum*, trade-offs

INTRODUCTION

The inability of livestock producers to feed animals adequately throughout the year remains the major technical constraint in most livestock systems in developing countries (Ayantunde *et al*. 2005). With the improving economy of most of the developing countries, and hence the increasing consumption of livestock products, the feed and fodder situation is likely to be more challenging. For instance, a recent study has shown that by 2020 India would require 526 million tones of dry fodder, 855 million tonnes of green fodder, and 56 million tonnes of concentrates, up by 13-19% as compared to the consumption demand in 2003 (Dikshit and Birthal 2010). Meeting the greatly increasing demand for meat and milk (Delgado *et al*. 1999) in a way that poor livestock keepers benefit more from their animal assets will require sustainable options for enhancing feed and fodder production. Land and water scarcity are becoming increasingly serious constraints to mitigation of feed and fodder production in small-holder systems. It was recently pointed out that planted forages require the overwhelming bulk of the water used in livestock production (Singh *et al.* 2004). As a result, livestock-water productivity is very low unless water-use efficient, high-yielding and fast-growing forages are used.

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a widely cultivated warm-season cereal, primarily grown for grain production on more than 27 million ha in the arid and semi-arid tropical (SAT) regions of Asia and Africa. It is cultivated on a limited scale for forage production in the southern USA (Hanna and Gupta 1999). Recently, it has also been emerging as an important forage crop in Brazil, and a potential forage crop in the Middle East and Central Asia (Jeff Wilson, pers. comm.). Being a C_4 species with high photosynthetic rates and biomass production ability and varied adaptive features such as disease and insect pest resistance, and tolerance to drought, heat and soil salinity, pearl millet makes a high potential forage crop. A comparative study in two All India Coordinated Forage Trials conducted multilocationally under rainfed conditions, pearl millet gave an average dry forage yield of 8.5 tonnes ha^{-1}, which was 10-16% higher than sorghum and 21-30% higher than maize (see Rai *et al.* 2005). Pearl millet forage also had 8.7-8.9% crude protein, which was 45-64% higher than those in sorghum and 30-58% higher than those in maize. Tall African landraces grown without irrigation at Tifton, Georgia in the USA gave 8-10 tonnes ha^{-1} of dry forage yield, which was comparable to the dry forage yield of maize grown with irrigation (Gates *et al*. 1999). Some of the other studies have shown even higher forage yield in pearl millet. For instance, a comparative study in Korea reported 23.8 tonnes ha^{-1} of dry forage yield in pearl millet, which was 24% higher than sorghum and 54% higher than maize (Kim *et al*. 1990). Dry forage yield of up to 20 tonnes ha^{-1} in pearl millet have been reported in Brazil (Kichel *et al*. 1999). A recent crop management study in Iran reported up to 21 tonnes ha^{-1} of dry forage yield in pearl millet (Rostamza *et al*. 2011). Exceptionally high dry forage yield (30-35 tonnes ha^{-1}) under dense plantings (15 kg ha^{-1}) have been reported in pearl millet (Bukhari *et al*. 2011; Tariq *et al*. 2011), which could partly be due small sample size from the plots used to determine per ha yield.

Dual-purpose hybrids of pearl millet generally give 25-30% higher grain yield than the dual-purpose open-pollinated varieties (OPVs) (Rai *et al.* 2006). It is likely that forage hybrids will also have at least as much yield advantage over the OPVs, and hence the need to breed forage hybrids. A highly stable A_5 source of cytoplasmic-nuclear

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Table 1 Parentage/origin of three B-lines (maintainer counterparts of A-lines) and nine open-pollinated varieties (OPVs) of pearl millet.

Male-sterile line/OPV	Parentage/origin of B-line and OPV
ICMA 89111	[843B x (GNS x SS-48-40-4)-1-9-8]-30-B-B-1
ICMA 00999	(ICMB 89111 x 863B)-65-8-B-B
ICMA 03222	690-93B (B-line from Niger)
ICMV 05111	Forage variety bred at ICRISAT by random mating 16 non-pigmented S_2 progenies derived from four landraces from Nigeria (2 S_2s from IP 20485, 6 from IP 20550, 4 from IP 20555 and 4 from IP 20594).
ICMV 05222	Forage variety bred at ICRISAT by random mating 26 pigmented S_2 progenies derived from four landraces from Nigeria (13 S_2s from IP 20485, 7 from IP 20550, 1 from IP 20555 and 5 from IP 20594).
ICMV 05333	Forage variety bred at ICRISAT by random mating five medium-tall progenies (2 S_2, 2 S_3, 1 S_6) derived from a High-Tillering Genepool (IP 22269) developed at ICRISAT.
ICMV 05444	Forage variety bred at ICRISAT by random mating 10 S_2 progenies derived from two landraces from Burkina Faso (8 S_2s from IP 17213 and 2 S_2s from IP 17315).
ICMV 05555	Forage variety bred at ICRISAT by random mating 10 progenies derived from two accessions from India (1 S_2 from IP 15352, 4 S_2 and 5 S_6 from IP 22269).
ICMV 05666	Forage variety bred at ICRISAT by random mating 4 S_2 progenies of short height derived from the High-Tillering Genepool (IP 22269) developed at ICRISAT.
ICMV 05777	Forage variety produced at ICRISAT from a landrace (IP 6073) from Central African Republic.
ICMV 05888	Forage variety bred at ICRISAT by random mating 38 S_3 progenies derived from pearl millet variety CO-8 developed at Tamil Nadu Agricultural University, India.
ICMV 05999	Forage variety bred at ICRISAT by random mating 91 S_1 progenies derived from a forage population (RMFB) received from the All India Coordinated Pearl Millet Improvement Project, Mandor, Rajasthan, India.

male sterility on which more than 95% of the inbred lines are maintainers provides the greatest opportunity for genetic diversification of male-sterile lines (A-lines) (Rai *et al.* 2006). This, in turn, would dramatically enhance the scope of developing a large number of diverse hybrid combinations, thus increasing the probability of developing a diverse range of high-yielding forage hybrids. While ICRISAT so far has put greater emphasis on the breeding of dual-purpose OPVs and parental lines of dual-purpose hybrids, some of the A-lines from this research may provide the opportunities to breed forage hybrids. Recently, a few OPVs have been developed specifically for forage purpose. The objective of the research presented here was to examine the forage yield and quality of these OPVs and their top-cross hybrids made on A-lines initially produced as seed parents of dual-purpose hybrids.

MATERIALS AND METHODS

Experimental material

The experimental material consisted of nine OPVs and their 27 top-cross hybrids developed on three male-sterile lines (A-lines) (**Table 1**). Two pearl millet hybrids and a sorghum-Sudan grass hybrid were used as controls. These include an ICRISAT-developed pearl millet hybrid (PM Exp Hybr. 1) identified for high forage yield potential in a preliminary trial (KN Rai, unpub.), a released pearl millet forage hybrid (Proagro 1) developed by a private seed company, and a sorghum-Sudan forage hybrid (SSG 59-3). The OPV's had been specifically developed for forage purposes. However, A-lines used for producing the top-cross hybrids had initially been developed for use in breeding dual-purpose hybrids. Of these, ICMA 00999 had earlier been identified as the seed parent of PM Exp. Hybr. 1 (ICMA 00999 x IP 17315). ICMA 00999 is of medium height with average tillering. ICMA 89111 is the seed parent of two dual-purpose commercial hybrids released in India. It is dwarf in height, and is one of the few highest-tillering A-lines. ICMA 03222 is also a high-tillering line, but of medium height. Top-cross hybrids were produced by crossing each of the nine OPVs on each of the three A-lines. Bulk pollen collected from bagged panicles of more than 100 plants of an OPV was used to pollinate the bagged panicles of an A-line to produce a top-cross hybrid. Panicles in both A-lines and OPV's were bagged at the time of panicle emergence to avoid any contamination from unwanted pollen.

Field trials

Two experiments were conducted: OPVs in Experiment 1 and top-cross hybrids in Experiment 2. Both experiments included the same three common controls (PM Exp. Hybr.1, Proagro and SSG 59-3). Both experiments were planted side-by-side on Alfisols at Patancheru on 15 July in 2005 and on 17 July in 2006 in a randomized complete block design, replicated three times. The plots consisted of 6 rows of 4 m length spaced at 75 cm. Plots were overplanted and thinned 23 days after planting to single plants at 10 cm spacing. The crop was grown at the applied fertilizer level of 100 kg ha^{-1} DAP as a basal dose and 100 kg ha^{-1} urea top-dressed 30 days after planting. Time to 50% flower was recorded on plot basis when the main panicles of 50% of the plants had full stigma emergence. At 50 day (d) after planting, 2 m of the central four rows at the distal end were harvested, and green forage yield were recorded. The remaining 2 m were harvested at 80 d after sowing. Random samples of 20 plants from each plot from each harvest were weighed on the date harvested to determine green forage weight. These samples were oven-dried for 8 h each for three days at 50°C, and weighed again, to calculate dry forage yields of plots.

Forage quality analysis

Forage nitrogen concentration (N × 6.25 equals crude protein content), percentage *in vitro* digestibility and metabolizable energy content (Mega joule per kg) were analyzed by Near Infrared Spectroscopy (NIRS), calibrated for this experiment against conventional wet laboratory analyses. The NIRS instrument used was a FOSS Forage Analyzer 5000 with software package WinISI II. Validation procedures were blind-predictions of laboratory measurements by the NIRS equations developed in the calibration procedures. Laboratory analyses for the calibration and validation of the NIRS were done as follows. Nitrogen (N) was determined (Technicon Auto Analyzer) in duplicate samples and corrected for percentage dry matter (DM). For analysis of *in vitro* digestibility and metabolizable energy content, rumen inoculum was obtained from two rumen cannulated steers (local Indian breed) maintained on a ration of stover supplemented with concentrate. Briefly, a mixture of rumen fluid and particulate matter (approximately 60: 40) was collected into CO_2-filled thermos bottles, transferred to and homogenized in a household blender, strained and filtered through glass wool. All handling of rumen inoculum was carried out under continuous flushing of CO_2. Portions of about 200 mg air-dry stover sample were weighed (in duplicate) into 100-ml calibrated glass syringes (Menke and Steingass 1988) that were incubated according to the procedure of Blümmel and Ørskov (1993). *In vitro* digestibility was calculated based on gas volumes produced after 24 h of incubation following Menke and Steingass (1988) as: 15.38 + (0.8453 × ml of gas produced after 24 h per 200 mg sample) + (0.595 × % crude protein on a dry matter basis) + (0.181 × % ash on a dry matter basis). Metabolizable energy content was calculated following Menke and Steingass (1988) as: 2.2

+ (0.136 × ml of gas produced after 24 h per 200 mg sample) + (0.0057 × crude protein (g kg^{-1})).

Statistical analysis

Data were analyzed following a fixed model analysis of variance in an RCBD, and using the statistical package GenStat Release 8.1 (Payne 2002). Character correlations were worked out following Gomez and Gomez (1984), and broad sense heritability estimates were obtained following Thomson (1973).

RESULTS

Forage yield

The two years represented two significantly different productivity levels with the mean dry forage yield of OPVs and hybrids being 33-35% more in the 2005 than 2006, both at 50 d harvest (2.6 t ha^{-1} for OPVs and 3.4 t ha^{-1} for hybrids) and at 80 d harvest (9.2 t ha^{-1} for OPVs and 9.0 t ha^{-1} for hybrids) (data not presented). The difference among the OPVs over the two years (environments) for dry-forage yields at 50d harvest and at 80 d harvest as well as for time to 50% flower was highly significant (**Table 2**). The difference among the hybrids was also highly significant for time to 50% flower and for dry forage yield at 80d harvest (**Table 3**). Further partitioning of the mean squares showed that the differences among OPVs as well as among A-lines for their forage hybrid yield potential at 80 d harvest and for flowering time were also highly significant. This implied that the variation among hybrids due to OPV and A-line effects for dry forage yield significantly increased at 80 d harvest compared to those at 50 d harvest. The first order interaction between the OPVs and A-lines was also highly significant for dry forage yield at 80d harvest and for flowering time, but its contribution to total variability was much smaller than the main effects due to OPVs and A-lines. Interactions of main effect due to OPVs and A-lines with the years were either non-significant, or much less compared to the main effects.

Based on the 2-year mean, dry forage yield of all the top-cross hybrids at 50 d harvest was 3.9 t ha^{-1}, which was 30% more than the mean yield of all the populations (**Table 4**). The forage yield among the OPVs varied from 2.5 to 3.6 t ha^{-1}, while in case of hybrids it varied from 3.1 to 4.4 t ha^{-1}. Although statistically significant, there was little difference among the A-lines for their hybrid yield potential. At 80 day harvest, the mean forage yield of all the top-cross hybrids was similar to the mean forage yield of OPVs. The forage yield among the OPVs varied from 6.9 to 14.8 t ha^{-1} while in case of hybrids it varied from 7.0 to 13.8 t ha^{-1}. Considering the yielding ability both at 50 d and 80 d harvest, ICMV 05555 appeared to be the most promising OPV, and ICMA 00999 x ICMV 05222 as the most promising hybrid. This hybrid was comparable to the highest-yielding control (sorghum-sudan grass hybrid) at 50 d harvest and out-yielded the highest yielding control (PM Exp. Hybr. 1) by 17% at 80 d harvest, although this difference was not statistically significant.

There was a large difference among the OPVs for time to 50% flower, varying from 46 to 94 days (**Table 5**). The variability among the hybrids was from 45 to 77 days – probably resulting from the contribution for A-lines for relative earliness. Some of the hybrids made with the latest-flowering OPVs (i.e., ICMV 05111 and ICMV 05222) flowered 27 earlier than the corresponding OPV involved in the top-cross hybrids. The most promising hybrid (ICMA 00999 x ICMV 05222) flowered in 76 days, 18 days earlier

Table 2 Analysis of variance for dry forage yield and time to 50% flower in open-pollinated varieties (OPVs) of pearl millet, 2005-2006 rainy season, Patancheru.

Source of Variation	df	Mean square		
		Dry forage yield (50 d harvest)	Dry forage yield (80 d harvest)	Time to 50% Flower
Year (Y)	1	9.45	135.20	00.67
Rep/Y	4	0.52	13.98	9.72
OPV	8	1.00 **	36.24 **	1587.3**
Y x OPV	8	0.38	1.64	24.33 **
Residual	32	0.22	3.79	5.03

** Significant at 0.01 probability level

Table 3 Analysis of variance for dry forage yield and time to 50% flower in Top-cross hybrids of pearl millet 2005-2006 rainy season, Patancheru.

Source of Variation	df	Mean square		
		Dry forage yield (50 d harvest)	Dry forage yield (80 d harvest)	Time to 50% Flower
Year (Y)	1	45.98	411.43	5.19
Rep/Y	4	2.32	5.95	23.72
Hybrid	26	0.61	23.46 **	104.00 **
OPV	8	1.34	69.12 **	2252.26 **
A-line	2	1.16	7.16**	174.06**
OPV x A-line	16	0.18	2.67 **	33.62 **
Y x Hybrid	26	0.51	1.63 *	10.70 **
Y x OPV	8	0.37	2.95**	9.37**
Y x A-line	2	0.77	1.09	6.78**
Y x OPV x A-line	16	0.54	1.03	11.86
Residual	104	0.31	1.96	8.29

*, ** Significant at 0.05 and 0.01 probability levels, respectively.

Table 4 Mean dry forage yield of pearl millet open-pollinated varieties (OPVs) and their top-cross hybrids at 50 d and at 80 day harvest, Patancheru. Mean of 2 years.

Open-pollinated variety	Dry forage yield (t ha^{-1}) at 50 day harvest					Dry forage yield (t ha^{-1}) at 80 day harvest				
	OPV	Hybrid				OPV	Hybrid			
		ICMA 89111	ICMA 00999	ICMA 03222	Mean		ICMA 89111	ICMA 00999	ICMA 03222	Mean
ICMV 05111	2.5	3.5	4.0	3.6	3.7	10.3	13.1	13.0	11.9	12.6
ICMV 05222	2.8	4.0	4.1	3.7	3.9	11.9	12.5	13.8	11.4	12.6
ICMV 05333	3.3	4.4	4.2	4.0	4.2	10.6	10.0	10.5	9.8	10.1
ICMV 05444	2.6	3.4	4.0	3.4	3.6	10.8	11.8	12.7	10.7	11.7
ICMV 05555	3.2	4.2	4.1	4.1	4.1	14.8	11.4	11.0	9.7	10.7
ICMV 05666	2.7	4.2	4.4	4.1	4.2	10.9	9.8	9.7	10.2	9.9
ICMV 05777	3.1	3.6	3.7	3.1	3.5	13.1	12.6	12.7	11.7	12.3
ICMV 05888	3.6	4.0	4.1	4.1	4.0	7.7	8.1	7.1	8.3	7.8
ICMV 05999	3.6	4.2	4.0	4.0	4.1	6.9	7.0	7.4	7.9	7.5
Mean	**3.0**	**3.9**	**4.1**	**3.8**	**3.9**	**10.8**	**10.7**	**10.8**	**10.2**	**10.6**
Control										
PM Exp.Hyb.1	3.3	-	-	-	3.4	13	-	-	-	11.8
SSG 59-3	4.1	-	-	-	4.0	10.1	-	-	-	10.1
Proagro 1	3.9	-	-	-	3.9	9.2	-	-	-	8.4
LSD (0.05)	0.6	-	-	-	0.6	2.3	-	-	-	1.6

Table 5 Mean flowering time of pearl millet open-pollinated varieties (OPVs) and their top-cross hybrids, Patancheru. Mean of 2 years.

OPV	Population/ OPV	Time to 50% flowering (days)			
		Hybrids			
		ICMA 89111	ICMA 00999	ICMA 03222	Mean
ICMV 05111	94	67	75	69	71
ICMV 05222	94	76	76	67	71
ICMV 05333	65	56	58	55	56
ICMV 05444	78	70	71	65	68
ICMV 05555	70	50	55	53	53
ICMV 05666	60	48	49	52	49
ICMV 05777	74	67	77	71	72
ICMV 05888	46	47	45	47	46
ICMV 05999	48	45	46	47	46
Mean	**70**	**58**	**61**	**57**	**59**
Control					
PM Exp.Hyb.1	69	-	-	-	72
SSG-59-3	74	-	-	-	72
Proagro 1	52	-	-	-	53
LSD (0.05)	3	-	-	-	3

than its pollinator population and was 4 days later than the highest-yielding control (PM Exp. Hybr. 1). At 50 d harvest, days to flowering were significantly negatively related to forage yield in OPVs (r = -0.60; P = 0.04) and hybrids (r = -0.57; P = 0.001). At 80 d harvest, days to flowering tended to be significantly positively related to forage yield (r = 0.53; P = 0.08) of OPVs and highly significantly related to forage yield of hybrids (r = 0.87; P < 0.0001).

Forage quality

Forage N content, *in vitro* digestibility and metabolizable energy of OPVs are reported in **Table 6**. At both dates of harvest, significant differences (at least P < 0.01) were observed among OPVs for all three forage quality traits. As expected, all quality traits were substantially lower in forages harvested at 80 d compared to 50 d. The range in forage N content among OPVs was higher (range 0.58 percent units) at 50 d compared to 80 d (range 0.24 percent units). Digestibility in OPVs ranged from 56.3 to 61.2 (range 4.9 percent units) and from 45.2 to 51.4 (range 6.2 percent units) when harvested at 50 d and 80 d, respectively. Metabolizable energy in OPVs ranged from 8.08 to 8.65 (range 0.57 MJ/kg) and from 6.49 to 7.4 MJ/kg (range 1.05 MJ/kg) in forages harvested at 50 d and 80 d, respectively. There was no significant (P > 0.05) correlation between forage quality traits measured at 50 d and at 80 d. Broad-sense heritabilities (h^2) differed for forage quality traits measured at 50 and 80 d harvest. Forage nitrogen was a heritable trait at 50 d harvest (h^2 = 0.60) but not at 80 d (h^2 = 0.05). The opposite was true for *in vitro* digestibility and metabolizable energy, traits which were highly heritable at 80 d (h^2 = 0.90).

Nitrogen content, *in vitro* digestibility and metabolizable energy of forage hybrids are reported in **Table 7**. Except for N content in forages harvested at 50 d (P < 0.1), highly significant (P < 0.0001) differences were observed among hybrids in forage quality traits at both dates of harvest. As in OPVs, all forage quality traits were substantially lower when harvested at 80 d compared to 50 d. Except for N content of forage harvested at 80 d, forage hybrids had lower fodder quality traits than OPVs but these differences were only significant in forages harvested at 50 d. The ranges in forage quality traits in hybrids were of a similar order than in OPVs. Nitrogen content of forage hybrids harvested at 50 d and at 80 d were not correlated (P = 0.45) in contrast to *in vitro* digestibility (r = 0.65, P < 0.0001) and metabolizable energy contents (r = 0.66, P < 0.0001) measured at 50 d and 80 d harvests. The broad-sense heritability for forage nitrogen was poor at 50 d harvest (h^2 = 0.21) and zero at 80 d harvest. In contrast, at 50 d harvest reasonable heritabilities were observed for forage *in vitro* digestibility (h^2 = 0.51) and metabolizable energy (h^2 = 0.52). Higher heritabilities for *in vitro* digestibility (h^2 = 0.67) and metabolizable energy (h^2 = 0.78) were observed for forages harvested at 80 d.

In OPVs harvested after 50 d, flowering time was significantly positively related to forage N (r = 0.8; P = 0.002), *in vitro* digestibility (r = 0.73; P = 0.007) and metabolizable energy (r = 0.66; P = 0.02). When harvested at 80 d, flowering time was insignificantly negatively (P = 0.27) associated with forage N. In contrast, flowering time was highly positively associated with forage *in vitro* digestibility (r = 0.78; P = 0.003) and metabolizable energy (r = 0.84; P = 0.0006). Similarly, in hybrids harvested at 50 d, flowering time was positively related to forage N (r = 0.54; P = 0.002), *in vitro* digestibility (r = 0.66; P < 0.0001) and metabolizable energy (r = 0.60; P = 0.0005). When harvested after 80 d, flowering time was significantly negatively (r = - 0.61; P = 0.004) correlated to forage N but was highly positively associated with *in vitro* digestibility (r = 0.78; P < 0.0001) and metabolizable energy (r = 0.80; P < 0.0001).

Forage quality and forage yield

For OPVs harvested at 50 d, significant negative correlations were observed between forage quality traits and forage yields with forage N content, *in vitro* digestibility, and metabolizable energy accounting, respectively, for 86%, 61% and 43% of the variation in dry forage yield (**Fig. 1A-C**). In contrast, no significant relationships were observed between the quality traits and dry forage yield at 80 d harvest.

Table 6 Nitrogen, *in vitro* digestibility and metabolizable energy in pearl millet forage open-pollinated varieties (OPVs) harvested at 50 d and at 80 d. Mean of 2 years.

	Nitrogen (%)		*In vitro* digestibility (%)		Metabolizable energy (MJ/kg)	
	50-d	80-d	50-d	80-d	50-d	80-d
ICMV 05111	2.16	0.85	61.2	50.5	8.63	7.35
ICMV 05222	2.23	0.93	60.5	51.4	8.50	7.54
ICMV 05333	1.72	0.87	58.2	47.8	8.32	6.99
ICMV 05444	2.22	0.91	61.0	50.1	8.60	7.28
ICMV 05555	1.94	0.85	61.0	46.5	8.65	6.76
ICMV 05666	2.08	0.80	59.1	46.8	8.32	6.83
ICMV 05777	1.99	0.77	60.1	49.7	8.51	7.30
ICMV 05888	1.65	0.85	56.3	45.9	8.08	6.65
ICMV 05999	1.76	1.01	57.9	45.2	8.30	6.49
Mean	**1.97**	**0.87**	**59.5**	**48.3**	**8.43**	**7.02**
Control						
PM Exp. Hyb. 1	1.89	0.76	59.9	47.5	8.50	6.97
SSG-59-1	1.80	0.75	56.6	48.1	8.06	7.04
Proagro 1	1.72	1.37	55.4	49.5	7.987	7.07
LSD (0.05)	0.29	0.19	3.3	2.3	0.5	0.35
h^2	0.60	0.05	0.40	0.90	0.23	0.90

Table 7 Nitrogen, *in vitro* digestibility and metabolizable energy in pearl millet forage hybrids harvested at 50 d and at 80 d. Mean of 2 years.

Hybrid	Nitrogen (%)		*In vitro* digestibility (%)		Metabolizable energy (MJ/kg)	
	50-d	80-d	50-d	80-5	50-d	80-d
ICMA 89111 x ICMV 05111	1.97	0.81	58.4	48.2	8.27	7.09
ICMA 89111 x ICMV 05222	1.74	0.87	56.8	50.1	8.13	7.35
ICMA 89111 x ICMV 05333	1.70	0.95	55.8	44.8	7.94	6.48
ICMA 89111 x ICMV 05444	1.88	0.97	58.7	49.0	8.37	7.18
ICMA 89111 x ICMV 05555	1.86	0.89	57.5	46.6	8.19	6.81
ICMA 89111 x ICMV 05666	1.80	1.04	57.5	45.2	8.22	6.51
ICMA 89111 x ICMV 05777	1.97	0.91	58.4	48.6	8.26	7.12
ICMA 89111 x ICMV 05888	1.75	1.03	56.5	46.1	8.14	6.63
ICMA 89111 x ICMV 05999	1.67	1.08	56.1	43.3	8.05	6.18
A-line Mean	**1.82**	**0.95**	**57.3**	**46.9**	**8.17**	**6.82**
ICMA 00999 x ICMV 05111	1.88	0.84	59.9	50.6	8.52	7.50
ICMA 00999 x ICMV 05222	1.80	0.83	57.7	49.4	8.26	7.31
ICMA 00999 x ICMV 05333	1.61	0.78	57.3	46.9	8.23	6.91
ICMA 00999 x ICMV 05444	1.89	0.76	57.9	48.3	8.26	7.10
ICMA 00999 x ICMV 05555	1.90	0.91	58.8	47.3	8.39	6.89
ICMA 00999 x ICMV 05666	1.76	0.79	56.2	46.7	8.02	6.83
ICMA 00999 x ICMV 05777	1.78	0.81	59.7	49.9	8.53	7.34
ICMA 00999 x ICMV 05888	1.78	1.05	57.7	46.1	8.25	6.67
ICMA 00999 x ICMV 05999	1.78	1.08	58.3	45.2	8.33	6.49
A-line Mean	**1.80**	**0.87**	**58.2**	**47.8**	**8.31**	**7.00**
ICMA 03222 x ICMV 05111	1.96	0.86	58.1	47.0	8.23	6.87
ICMA 03222 x ICMV 05222	2.01	0.90	58.7	47.5	8.31	6.91
ICMA 03222 x ICMV 05333	1.80	1.04	56.0	42.7	7.96	6.12
ICMA 03222 x ICMV 05444	1.96	0.95	58.5	46.0	8.30	6.71
ICMA 03222 x ICMV 05555	1.60	0.75	54.4	44.5	7.80	6.48
ICMA 03222 x ICMV 05666	1.74	1.16	55.6	47.7	7.91	6.85
ICMA 03222 x ICMV 05777	1.94	0.95	58.4	47.0	8.27	6.80
ICMA 03222 x ICMV 05888	1.70	1.05	54.9	45.4	7.85	6.52
ICMA 03222 x ICMV 05999	1.66	1.09	53.7	44.0	7.67	6.27
A-line Mean	**1.82**	**0.97**	**56.5**	**45.7**	**8.03**	**6.61**
Overall mean	**1.81**	**0.93**	**57.3**	**46.8**	**8.17**	**6.81**
LSD (0.05)	0.3	0.23	2.7	2.7	0.34	0.38
h^2	0.21	0	0.51	0.67	0.52	0.78

For forage hybrids harvested at 50 d, trade-offs between forage quality and yield were less than in OPVs with forage quality traits accounting for at most 26% (r = -0.51) of the variation in forage yields (**Fig. 2A-C**). When harvested at 80 d, forage N content was inversely related to forage yield (r = -0.69), while forage *in vitro* digestibility and metabolizable energy were significantly positively associated with forage yield.

DISCUSSION

Forage yields of OPVs and top-cross hybrids

The 2-year evaluation of the nine OPVs and their 27 top-cross hybrids showed that at 50 d harvest none of the OPVs reached the dry forage yield levels of some of the highest-yielding pearl millet and sorghum-Sudan grass hybrids used as controls. However, there were several top-cross hybrids that were comparable to or out-yielded sorghum – Sudan grass hybrids (high-yielding control) up to 7%. Most of these hybrids flowered by up to 25 days earlier than sorghum-Sudan grass hybrid and thus had accumulated much of the biomass by the time of the 50 d harvest. At the 80 d harvest, pearl millet Exp.Hybr.1 had the highest yield among the controls, out-yielding sorghum-Sudan-grass hybrid by 28%, thus confirming its superior yield performance observed in earlier trials in India (Rai *et al*. 2005). In Korea, Kim *et al*. (1990) also observed that pearl millet can out-yield sorghum. There were two OPVs (ICMV 05555 and ICMV 05777) that yielded 14.8 t and 13.0 t ha^{-1} of dry forage, respectively, which were comparable to, or had slight yield advantages, over the PM Exp.Hybr.1 (13.0 t ha^{-1}). These OPVs were also comparable to PM Exp.Hybr.1 in flowering time. No hybrid out-yielded the highest-yielding OPV (ICMV 05555), and there were only three hybrids that had 13.0-13.8 t ha^{-1} dry forage yield, which was comparable to the forage yield of PM Exp.Hybr.1. Lack of clear forage yield advantage of hybrids over the highest-yielding OPVs is not unexpected as these hybrids had been made on male-sterile lines initially bred for developing dual-purpose hybrids intended primarily for grain production. This would suggest that to breed high-yielding forage hybrids, male-sterile lines with high forage yield will need to be developed. Such breeding is currently underway at ICRISAT with potential inbred lines identified for their conversion into A-lines. Generally, pearl millet yield levels reported in the current work agree with yields reported by Gates *et al.* (1999) and Kichel *et al*. (1999).

Fodder quality traits

Low N content is often considered the primary constraint particularly in mature forages and crop residues. Rumen microbes require a minimum of about 1 to 1.2% of nitrogen (N) in the diet otherwise feed intake and utilization might be severely depressed (Van Soest 1994). All pearl millet forages harvested at 50 d were well above this threshold with N content ranging from 1.65 to 2.23% in OPVs and from 1.60 to 2.01% in hybrids. Feed manufacturers in India providing the so-called complete total mixed rations for dairy animals use about 2 to 2.2% of feed N for medium to high-yielding dairy cattle and buffaloes (Miracle Feds and Fodder Pvt. Ltd.). Thus, some of the best pearl millet forage OPVs and hybrids could, when harvested at 50 d, provide sufficient feed N for medium to high-yielding dairy cattle and buffaloes even when fed as sole feed. However, forage N heritability was low (h^2 = 0.21) in hybrids harvested at 50 d, limiting opportunities for increasing forage N content through hybridization. Forage N content did generally fall below the minimum microbial N requirements when harvested at 80 d in both OPVs and hybrids even though some cultivars could still provide the minimum required N level.

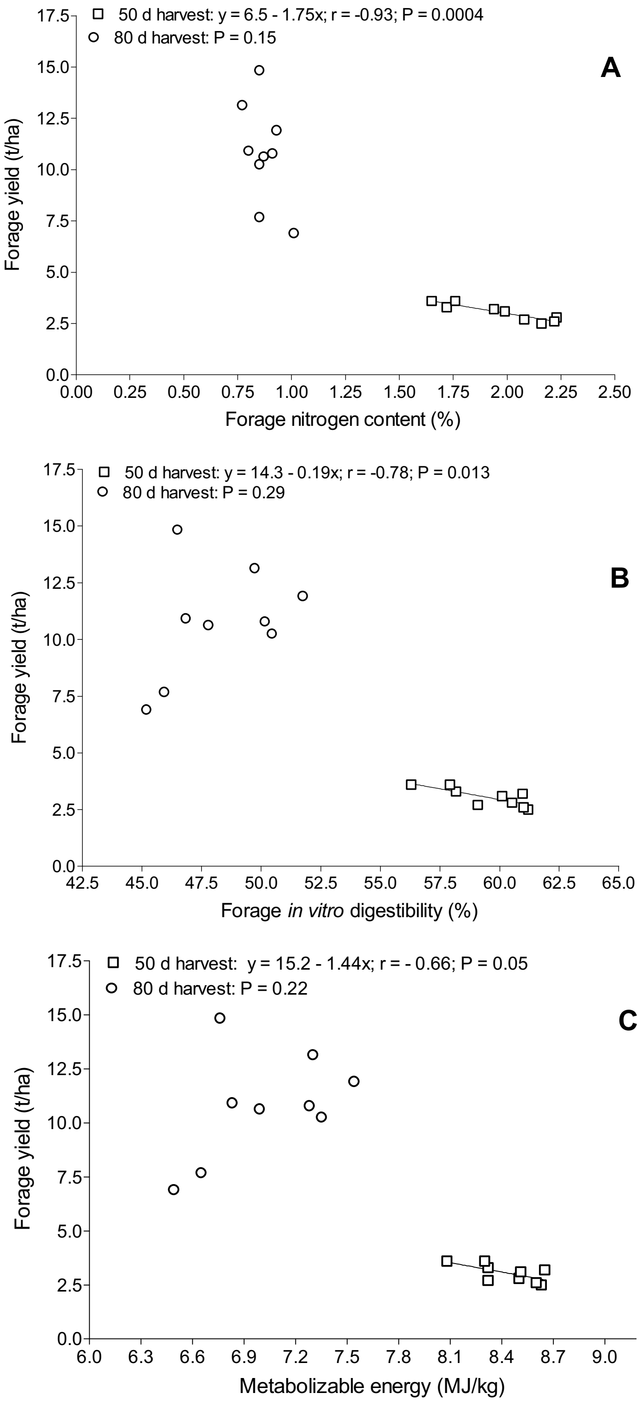

Fig. 1 (**A**) Relationships between forage nitrogen content and forage yield in pearl millet hybrids; (**B**) Relationships between forage *in vitro* digestibility and forage yield in pearl millet hybrids; (**C**) Relationships between forage metabolizable energy content and forage yield in pearl millet hybrids.

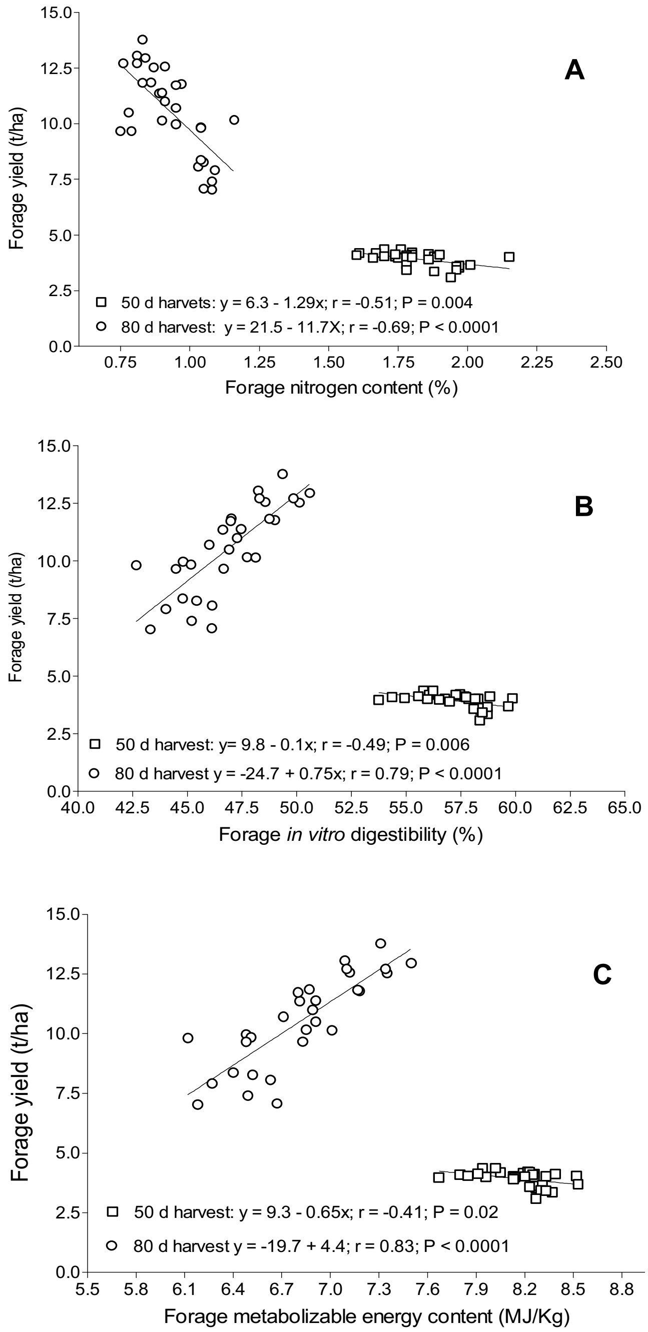

Fig. 2 (**A**) Relationships between forage nitrogen content and forage yield in pearl millet OPVs; (**B**) Relationships between forage *in vitro* digestibility and forage yield in pearl millet OPVs; (**C**) Relationships between forage metabolizable energy content and forage yield in pearl millet OPVs.

But the broad-sense heritability for forage N content in mature forage (80 day harvest) was close to zero in OPVs and hybrids probably severely limiting genetic interventions into manipulation of N content of mature pearl millet forage. These findings are in agreement with Hash *et al.* (2006) who reported zero heritability for N content for pearl millet stover, which should in composition resemble pearl millet forages harvested at 80 d. Besides the lack of heritability, high forage N came with penalty for forage yields in both OPVs and hybrids harvested at 50 d and for hybrids harvested at 80 d (see also below).

Significant cultivar differences were observed for all three quality traits at both stages of harvest and among OPVs and hybrids. Forag*e in vitro* digestibility among the cultivars varied by at least 4 to 5% percentage units (**Tables 5, 6**). It has been shown in grasses that a 3 to 4 percentage unit difference in digestibility was associated with 17 to 24 percent differences in animal performance (Vogel and Sleper 1994). In sorghum stover, a cultivar-dependent difference of 5 percentage units (47 to 52%) in *in vitro* digestibility translated to a 25% and higher price premium (approximately 4 Indian Rupees per kg of dry stover compared to 3 Rupees corresponding roughly to 8 versus 6 US cents in 2011) in the higher digestible stover in a year-long survey of stover traders in Hyderabad (Blümmel and Rao 2006). The cultivar-dependent variation in *in vitro* digestibility observed among the pearl millet forages will have implications for livestock productivity, as can be further corroborated by calculations about variation in forage metabolizable energy (ME) content, which is an estimate of feed quality that is closer to the net energy (NE) actually available to the animal than estimates obtained through digestibility measurements, since the ME takes into account the energy losses in urine and methane which digestibility measurement do not (McDonald *et al*. 1988). NE requirement, for example, for milk production can be calculated from ME by the use of an efficiency factor k ($k > 0 < 1$), which, in turn, depends on the ME content of a feed. Thus, one kg of forage of the OPV with the highest (8.65 MJ/kg) and lowest (8.02 MJ/kg) ME at 50 d harvest would promote 1.70 and 1.56 liter of cow milk. Similarly, ME difference at 80 d harvest would result in milk difference of 1.43 and 1.18 liter per kg of forage consumed. Analogous relationships can be established for variation in ME content observed in hybrids. In other words, difference in forage ME observed among cultivars and among forages from different dates of harvest will have implications for livestock productivity.

Relationships between forage yield and fodder quality

It is to be noted that high digestibility and ME content can come with a penalty on forage yield, particularly when harvested early (i.e. at 50 d) both in OPVs and hybrids (see **Fig. 1B/C** and **2B/C**). Interestingly, digestibility and ME and yield were positively associated in mature forage (80 days) and these associations were quite strong for the hybrids (**Fig. 2B/C**). Similar significant associations have been observed for pearl millet stover (Blümmel *et al*. 2007). Since at the same time broad-sense heritabilities for digestibiliy and ME in forages harvested after 80 days were quite high, breeding for combination of high digestibility and/or ME and forage yield seems feasible. In India both feed quantity and quality are lacking. However, a comprehensive survey of feed resources in India showed that feed quality presents a higher constraint than feed quantity, which was estimated to be short by 6% while digestible crude protein and energy (feed quality traits) were estimated to fall short by 61 and 50%, respectively (NIANP 2003). Still, great differences exist in feed resources particularly between irrigated and rain-fed areas, and in the latter lack of feed quantity can be a more immediate concern than feed quality, for example during droughts (NIANP 2003). In the context of the present work, actual on-farm feed resources will effect decisions about when to harvest pearl millet forages and what to prioritize, forage quality or yield. Within a date of harvest, scope exists to select cultivars with high forage quality traits and high forage yield for which apparently there are greater opportunities in hybrids than in OPVs (compare **Figs. 1, 2**).

Forage hybrids included in this study were produced by using A-lines that had been initially bred for use in breeding dual-purpose hybrids, and genetically heterogeneous OPVs as pollen parents of heterogeneous top-cross hybrids that would have variability both for forage yield and quality. It would seem that by breeding A-lines with high forage attributes (both yield and quality) and selecting for specific combining ability for forage attributes in the OPVs, more productive parental lines can be developed that will enable developing high-yielding hybrids with improved forage quality. The availability of an A_5 system of cytoplasmic-nuclear male sterility on which >99% of the inbred lines are maintainers (Rai *et al.* 2008), provides a useful genetic resource for genetic diversification of A-lines and the consequent forage hybrids.

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