Forage Potential of Sorghum and Pearl Millet

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Abstract

Sorghum *and* Pennisetum *are two of the gifted genera of the tropical regions that provide food, feed, stover (dry straw) and fuel to millions of poor farmer families and their livestocks. Single-cut sorghum and multi-cut pearl millet varieties are also cultivated for green fodder (forage). In addition, the interspecific sorghum × sudangrass annual multi-cut hybrids are grown for green fodder. The interspecific pearl millet × napiergrass hybrids are perennial and yield green fodder throughout the year.*

Pearl millet uses less water per unit of forage production, tolerates both lower and higher soil pH and higher aluminium concentration, and is rich in minerals as compared to sorghum. However, sorghum has a wider range of adaptability and is more widely grown. Geographical preferences, limited market demand, variable prices, and lack of private industry and institutional research support have led to limited pearl millet forage research and cultivar adoption.

Forage quality is paramount to palatability or acceptability and animal intake. Plant morphology, anatomical components, digestibility, protein, mineral, cellulose and lignin contents, and anti-nutritional factors like hydrocyanic acid in sorghum and oxalic acid in pearl millet determine animal performance – milk and meat production.

Development of multi-cut annual forage sorghum and pearl millet hybrids rather than varieties could have a catalytic effect on forage yield and quality. Diversification of sorghum seed parents (white-grained rather than the currently used red-grained male steriles) and development of sudangrass pollinators with high sugar content and foliar disease resistance offer good opportunities for the exploitation of full potential of the interspecific hybrids. Crop scientists, chemical technologists, and animal health and nutrition experts have a role to play in good quality forage research and cultivar development. Inter-institutional partnerships could forge strong interlinks for strengthening sorghum and pearl millet forage research and development.

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Sorghum and *Pennisetum* are two of the gifted grass genera of the tropics. Each genus includes an important species used for food, feed, forage, fuel and as building material in many parts of the world, while the remaining, lesser known species in these genera are important forage producers. Sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) are usually grown for grain in areas where environmental conditions, especially rainfall, temperature and soil fertility are too harsh to grow maize (*Zea mays*) (Hanna and Cardona 2001). The dry fodder or stover is also used to feed animals.

Forage sorghums, by definition, include annual cultivars of sorghum and sorghum-sudangrass (*S. bicolor* × *S. sudanense*) hybrids. *Sorghum sudanense* is also grown for annual forage.

Forage *Pennisetum*, by convention, includes the annual pearl millet and the perennial napier-*bajra* (*P. glaucum* × *P. purpureum*) hybrids. As an indispensable grain crop of the arid and semi-arid tropics, pearl millet provides both grain and stover. Dinanath grass (*P. pedicellatum*) is also cultivated for forage.

Adaptation

Both sorghum and pearl millet make efficient use of soil moisture by remaining semi-dormant during stress and responding rapidly to available moisture (Hanna and Cardona 2001). Drought tolerance capacity measured in terms of water-use efficiency of forage pearl millet (280 kg water kg^{-1} dry matter) is better than forage sorghum (310 kg water kg^{-1} dry matter) (Chapman and Carter 1976, de Lima 1998). Pearl millet produces more green and dry fodder yield than sorghum (Table 1) under limited moisture regimes (Singh et al. 1989).

Table 1. Response of different forage crops to irrigation regimes[1].

	Green fodder yield (t ha^{-1})			Dry fodder yield (t ha^{-1})		
Crop	0.25[2]	0.50	0.75	0.25	0.50	0.75
Sorghum	25.7	28.5	28.5	8.1	9.1	10.1
Pearl millet	33.4	32.7	34.7	9.5	10.8	11.4
Maize	38.6	41.7	42.5	8.4	9.2	10.6
Teosinte	37.1	40.0	39.2	7.5	8.0	9.0
Cowpea	19.4	23.3	22.6	4.1	4.9	4.7
Cluster bean	17.9	20.5	17.7	6.3	6.6	6.4

1. Mean response during summer, 1982 and 1983.
2. IW/CPE (irrigation water/cumulative pan evaporation) ratio.

Source: Singh et al. (1989).

Both sorghum and pearl millet make efficient use of soil fertility by producing higher biomass, and thus take advantage of the growing conditions. Pearl millet roots tolerate lower soil pH and higher Al^{+3} concentration than those of sorghum (Ahlrichs et al. 1991). However, pearl millet does not tolerate waterlogged soils. Sorghum has a wider range of adaptability than pearl millet (Hanna and Cardona 2001). Forage sorghum is recommended for both calcareous and saline soils, while forage pearl millet grows well in calcareous soils (ICAR 1989).

Fodder production

Traditional areas for stover production

Sorghum is the third most important grain crop in India, next only to rice (*Oryza sativa*) and wheat (*Triticum aestivum*). Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh and Rajasthan are the principal sorghum-growing states of India (Table 2). They account for 88.5% of total sorghum area (10.75 million ha), producing an estimated 88.7% of stover (22.52 million t).

Pearl millet is the fourth most important grain crop in India. It is used as a dual-purpose annual crop mainly in the drier areas of the arid and semi-arid tropics. Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana are the principal pearl millet-growing states in the rainy season (Table 2). They account for 90.7% of total pearl millet area in the country (9.43 million t ha), producing on an average an estimated 90% of 14.76 million t of stover.

Non-traditional areas for forage production

Statistics on sorghum forage area or forage production are not available. But private seed industry produced 36,600 t of sorghum-sudangrass hybrid seed during 2002–03 for supply in packages of 1, 3 and 5 kg. Estimated at 20 kg ha^{-1}, 36,600 t should cover an area of 1.8 million ha which should yield about 90 million t of green fodder or forage. Almost all grain sorghum cultivating states grow forage sorghum varieties, and/or sorghum-sudangrass hybrids during rainy season as well as hot dry (summer) season. Forage sorghums are principally cultivated in Punjab, Haryana, Delhi, western and central Uttar Pradesh and adjoining areas of Madhya Pradesh. Other forage sorghums include sudangrass for which area estimates are not available.

Table 2. Area and production of sorghum and pearl millet grain and stover in India, 1995–2000.

State	Area (million ha)	Grain (million t)	Stover[1] (million t)
Sorghum			
Maharashtra	5.33	4.82	12.05
Karnataka	1.95	1.67	4.17
Madhya Pradesh	0.85	0.73	1.82
Andhra Pradesh	0.81	0.57	1.42
Rajasthan	0.57	0.21	0.52
Tamil Nadu	0.40	0.38	0.95
Uttar Pradesh	0.39	0.34	0.85
Gujarat	0.28	0.25	0.62
India	10.75	9.01	22.52
Pearl millet			
Rajasthan	4.35	1.78	3.92
Maharashtra	1.75	1.29	2.84
Gujarat	1.05	1.21	2.67
Uttar Pradesh	0.83	1.07	2.35
Haryana	0.57	0.57	1.25
Karnataka	0.38	0.24	0.53
Tamil Nadu	0.21	0.27	0.59
Madhya Pradesh	0.14	0.13	0.29
Andhra Pradesh	0.12	0.10	0.22
Other states	0.03	0.03	0.07
India	9.43	6.71	14.76

1. Estimated from harvest index.
Source: NRCS (2001), Bhatnagar (2003).

Pearl millet is cultivated for forage, but no estimates of either the forage pearl millet area or production are available. While forage hybrids are not produced, no statistics of seed production of forage varieties are available. Considerable scope, therefore, exists for the development of high-yielding and high quality forage hybrids and varieties of pearl millet. Only a few states grow forage pearl millet in summer season: Gujarat, Uttar Pradesh, Uttaranchal, Madhya Pradesh, Haryana and Rajasthan.

Interspecific hybrids of napier-*bajra*, a perennial forage crop, are planted throughout the country for which no statistics are available. Other forages like *P. purpureum* and *P. pedicellatum* are also grown, but area statistics are not available.

Silage production

Although sorghum (Kalton 1988) and pearl millet (de Andrade and de Andrade 1982) are excellent for producing silage, particularly in regions with dry spells during the rainy season, pearl millet can produce higher silage yields with higher protein than sorghum (Table 3).

Forage quality

Some of the constituents that affect palatability or acceptability and animal performance include protein and lignin content, lignin type and chemistry, mineral content, plant morphology, anti-nutritional components such as hydrocyanic acid (HCN), anatomical components and forage digestibility (Hanna 1993). Preliminary studies indicate that pearl millet forage is more succulent and has higher crude protein (CP) than sorghum or maize with other chemical constituents being comparable (Table 4). The CP in pearl millet stover is less than in sorghum but more than in wheat and rice straw (Table 5). The dry matter and cell wall digestibility of pearl millet stover is also less than that of sorghum. Pearl millet does not contain HCN but contains oxalic acid, an anti-nutritional component that can have adverse effect on milk production and milk fat in cows (Hanna and Gupta 1999).

Lignin concentrations in brown-midrib (*bmr*) mutants are consistently lower than their normal counterparts in both sorghum (by 21.8%) and pearl millet (by 20%) (Cherney et al. 1988). The in vitro digestibility of *bmr* sorghum (642 g kg^{-1} dry matter) and pearl millet (726 g kg^{-1} dry matter) are higher than the normal genotypes of sorghum (568 g kg^{-1} dry matter) and pearl millet (659 g kg^{-1} dry matter). Most digestible and partially digestible tissues in both sorghum leaves and pearl millet stems are degraded by fiber-digesting

Table 3. Silage production and quality of sorghum, pearl millet and maize.

Crop	Silage yield (t ha^{-1})	Dry matter yield (t ha^{-1})	Dry matter (%)	Silage quality: Crude protein (%)	Silage quality: IVDMD[1] (%)
Sorghum	19.2	5.76	30	7.0	58.0
Pearl millet	31.0	8.68	28	12.0	53.4
Maize	27.0	8.10	30	7.8	60.0

1. IVDMD = In vitro dry matter digestibility.
Source: Kichel et al. (1999).

Table 4. Chemical composition (% of dry matter) of pearl millet, sorghum and maize forages.

Constituent	Pearl millet	Sorghum	Maize
Crude protein	8.2	5.9	6.7
Dry matter	19.5	31.6	28.8
Neutral detergent fiber	67.9	70.7	66.4
Acid detergent fiber	38.3	44.4	38.5
- Lignin	7.8	7.6	6.8
- Cellulose	27.7	34.6	28.6
- Silica	2.8	2.2	3.1
Hemicellulose	29.6	26.3	27.9
Cell content	32.1	29.3	33.6

Source: Singh et al. (1977).

Table 5. Chemical composition and in vitro nutrient digestibility (% of dry matter) of pearl millet and sorghum stover compared to other cereals.

Constituent	Pearl millet	Sorghum	Rice	Wheat
Crude protein	3.2	4.3	2.1	2.6
Neutral detergent fiber	79.5	79.5	74.7	76.2
Acid detergent fiber	55.6	54.2	53.6	51.8
- Lignin	12.8	9.0	8.2	9.7
- Cellulose	39.4	41.0	37.0	36.3
- Silica	3.4	4.2	8.4	5.8
Hemicellulose	23.9	25.5	21.1	24.4
Cell content	20.5	20.3	25.3	23.8
In vitro dry matter digestibility	48.9	53.3	51.4	51.9
In vitro cell wall digestibility	35.7	41.2	31.2	36.9

Source: Singh et al. (1977).

bacteria to a greater extent in *bmr* mutants than in normal genotypes. Geneticists are now attempting to incorporate the *bmr* trait into a range of backgrounds in sorghum and pearl millet (Cherney et al. 1991).

Genetic variability

Success in crop improvement depends largely on the extent of desirable genetic variability available for selection. Therefore, collection, evaluation, documentation, utilization and conservation of genetic resources assume considerable significance.

Sorghum

The National Bureau of Plant Genetic Resources (NBPGR) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India evaluated 1500 accessions from global collection for forage yield and its components under different agroclimatic conditions in India. The results indicated a wide range of variability for forage yield and its component traits (Table 6) besides a few quality traits like stalk juiciness and midrib color, suggesting ample scope for genetic enhancement of forage potential of sorghum.

Sorghum improvement at ICRISAT has developed a diversified set of hybrid parents, and grain and dual-purpose varieties. A population improvement program has developed sorghum lines with brown-midrib (*bmr*), high stem sugar, and grain yield that tiller under stress conditions, such as drought and stem borer infestation (Reddy et al. 1994). Mass selection for *bmr* gene, tillering, and high grain and biomass yield has produced pure lines which have four to five tillers. These lines were evaluated along with male-sterile lines, restorers and varieties at Patancheru (Table 7). Results indicate that high-tillering varieties combined high forage yield with high stem sugar and good ratoonability.

Table 6. Estimates of some quantitative traits of 1500 selected world collections of sorghum during rainy season 1986 in three locations in India.

		Mean±SE		
Character	Range[1]	Delhi	Jhansi	Akola
Plant height (cm)	38.0–373	144.8±1.14	206.5±1.54	133.0±1.23
Stem thickness (cm)	1.2–11.60	4.84±0.038	4.34±0.036	–
Number of leaves (on main stem)	4.0–25.90	11.23±0.072	13.65±0.086	9.51±0.067
Length of 5th leaf (cm)	14.0–118.50	51.10±0.301	67.05±0.452	55.022±0.395
Width of 5th leaf (cm)	1.4–11.00	5.41±0.04	5.79±0.039	6.12±0.052
Basal tillering	–	–	1.025±0.007	–
Culm branching	–	–	0.733±0.029	–
No. of nodes on main stem	3.00–19.30	9.30±0.069	–	–
Days to 50% flowering	41.0–191.00	91.40±0.57	102.79±0.87	100.83±0.50
Total leaf area (cm^2) on main stem	–	–	–	2517.13±51.82
Forage yield ($kg\ m^{-2}$)	0.40–9.88	–	1.79±0.025	–

1. Across three locations.
Source: Mathur et al. (1991).

Table 7. Performance of the selected sorghum breeding lines for grain yield, fodder yield and quality attributes at ICRISAT, Patancheru, India during rainy season 2002.

Breeding material	Stem sugar[1] (%)	Fresh fodder yield (t ha^{-1})	Grain yield (t ha^{-1})	Ratooning ability (%)	Best lines for stem sugar
Hybrid seed parents	14–18	17–35	0.8–3.3	36–81	ICSB 472 (17.9%), ICSB 401 (16.3%), ICSB 405 (16.1%), ICSB 731 (15.9%)
Varietal/restorer lines	13–20	26–46	0.6–4.5	15–77	GD 65003 (20%), Entry #64 DTN (19.7%), GD 65080 (19%), ICSV 96143 (18.1%)
Dual-purpose varieties	14–20	28–40	0.1–2.8	19–79	S 35 (19.6%), GD 65179 (18.5%), FM 345 (17.5%), GD 65122 (17.3%)
High-tillering varieties	13–21	23–52	0.3–1.9	34–95	FM 48 (20.7%), GD 65174-1 (18.3%), GD 65239 (18.1%), FM 665 (18%)

1. As % on fresh stalk basis = 0.1516 × 0.8746 brix degrees.

Pearl millet

ICRISAT has assembled more than 21,000 accessions of pearl millet consisting of landraces and breeders' products. Evaluations by NBPGR and ICRISAT covering large number of accessions from many countries revealed considerable variability for various fodder components such as plant height (49–443.3 cm), number of tillers $plant^{-1}$ (1–9.3), stem thickness (6–31.2 mm), number of leaves (4.3–37), leaf length (19.3–130 cm) and leaf width (1.1–8.6 cm) (Table 8). Gupta (1969) observed considerable variability for desirable fodder quality components such as protein, phosphorus (P), calcium (Ca) and anti-nutritional factors like oxalic acid in a sample of world collections of pearl millet.

Cultivar options

Forage hybrids and varieties of sorghum (Table 9) and pearl millet (Table 10) are popular with the farmers. Until 2000, 53 varieties and hybrids of forage sorghum comprising 40 single-cut and 13 multi-cut types were released in India (Table 11). They include 37 single-cut and 6 multi-cut forage sorghum varieties, 3 single-cut forage sorghum hybrids, 5 sorghum-sudangrass hybrids,

Table 8. Variability for forage components in a sample of world collection of pearl millet, at NBPGR, Issapur, New Delhi, India.

	1987[1]		1988[2]	
Trait	Range	Mean±SE	Range	Mean±SE
Days to 50% flowering	34.0–119.0	76±0.41	34.0–136	75±0.38
Plant height (cm)	49.0–367.0	215±0.92	95.6–443.3	273.5±0.98
Number of tillers plant^{-1}	1.0–9.3	2.3±0.02	1.0-–9.0	2.1±0.03
Number of productive tillers	1.0–6.0	1.7±0.01	1.0–8.6	1.6±0.02
Stem thickness (mm)	6.0-–30.8	19.2±0.07	9.5–31.2	15.3±0.01
Number of nodes	–	–	5.3–37.0	13.5±0.07
Internode length (cm)	3.5-–26.3	15.4±0.07	4.0–39.0	19.5±0.09
Number of leaves	5.7–22.3	12.6±0.05	4.3-–37.0	13.8±0.07
Leaf length (cm)	22.3–130.0	68.9±0.33	19.3–126.3	75.2±0.35
Leaf width (cm)	1.7–8.5	3.6±0.02	1.1–8.6	4.3±0.02
Ear exsertion (cm)	0.0–16.3	2.1±0.06	0.0–43.0	3.1±0.11
Spike length (cm)	8.8–85.3	27.5±0.23	10.0–78.3	24.2±0.18
Spike thickness (mm)	5.7–47.8	20.6±0.10	10.8–47.7	20.2±0.01
1000-seed mass (g)	2.5–19.3	8.6±0.06	–	–

1. Based on 1938 accessions from world collections.
2. Based on 2458 accessions from world collections.

Source: Mathur et al. (1993a, 1993b).

1 multi-cut sudangrass variety and 1 multi-cut sudangrass hybrid. Compared to forage sorghum, only 10 pearl millet cultivars including 1 multi-cut variety and 3 hybrids have been recommended for forage cultivation. Eleven napier-*bajra* hybrids are available for perennial forage cultivation. While there is a great demand for sorghum-sudangrass forage hybrids, the non-availability and need for multi-cut sorghum hybrids has been long recognized. Efforts are also required to develop multi-cut forage pearl millet cultivars (both varieties and hybrids). During rainy season, a successful harvest fills granaries, and provides stover, while failed harvests assure forage at least.

Varieties

Both sorghum and pearl millet are grown during rainy season (June to September), while only sorghum is cultivated during postrainy season (October to March). A choice of landraces and improved cultivars are available for rainy season, but only a single variety of sorghum (Maldandi) dominates during postrainy season. Forage sorghum and pearl millet are grown

Table 9. Product and cultivar preferences of sorghum in India[1].

State	Season	Product			Cultivar	
		Grain	Stover	Forage	Grain	Forage
Maharashtra	Rainy	P	P	S	H>V	V
	Postrainy	P	P	–	V	–
	Summer	–	–	P	H	H+V
Karnataka	Rainy	P	P	S	H>V	V
	Postrainy	P	P	–	V	–
	Summer	–	–	P	H	H+V
Madhya Pradesh	Rainy	P	P	P	H>V	V
	Summer	–	–	P	–	H+V
Andhra Pradesh	Rainy	P	P	–	H>V	–
	Postrainy	P	S	–	V	–
	Summer	–	–	S	–	H+V
Rajasthan	Rainy	P	P	P	H	V
	Summer	–	–	P	–	H
Tamil Nadu	Rainy	P	P	–	H	–
	Postrainy	P	S	–	V	–
	Summer	–	–	S	–	H
Uttar Pradesh	Rainy	S	P	P	H	H+V
	Summer	–	–	P	–	H+V
Gujarat	Rainy	P	P	P	H	V
	Summer	–	–	P	–	H
Punjab	Rainy	–	–	P	–	H>V
	Summer	–	–	P	–	H>V
Haryana	Rainy	–	–	P	–	H>V
	Summer	–	–	P	–	H>V

1. P = Primary importance; S = Secondary importance; H = Hybrid; V = Variety.

during summer season (March to June). High density cultivation of landraces offers a single-cut, and staggered plantings ensure continuous supply of fodder during the off-season. On the other hand, improved varieties are amenable for multi-cut and management practices. Again, many sorghum varieties are available for forage, but the choice is limited for pearl millet – a single variety of pearl millet (Rajko) dominates the multi-cut forage scenario.

Intra-specific hybrids

Covering 54.8% of cultivated sorghum and 53.3% of pearl millet, high-yielding grain hybrids and varieties provide grain and stover during rainy

Table 10. Product requirement and cultivar types of pearl millet in India[1].

State	Season	Product: Grain	Product: Stover	Product: Forage	Cultivar: Grain	Cultivar: Forage
Rajasthan	Rainy	P	P	–	H<V	–
	Summer	P	–	P	H	V
Maharashtra	Rainy	P	S	–	H>V	–
	Summer	P	–	–	H	–
Gujarat	Rainy	P	S	–	H	–
	Summer	P	S	P	H	V
Uttar Pradesh	Rainy	P	P	–	H>V	V
	Summer	–	–	P	–	V
Haryana	Rainy	P	P	–	H>V	V
	Summer	–	–	P	–	V
Karnataka	Rainy	P	S	–	H	–
Madhya Pradesh	Rainy	P	P	–	H>V	V
	Summer	–	–	P	–	V
Tamil Nadu	Rainy	P	P	–	H	–
Andhra Pradesh	Rainy	P	P	–	H>V	–

1. P = Primary importance; S = Secondary importance; H = Hybrid; V = Variety.

season. Dual-purpose hybrids of sorghum (Madhya Pradesh and Uttar Pradesh) and pearl millet (Rajasthan, Uttar Pradesh and Tamil Nadu) are preferred in some states of India. During summer, parts of Gujarat grow dual-purpose pearl millet hybrids, while parts of Maharashtra and Rajasthan go for grain hybrids.

Multi-cut forage hybrids of sorghum are grown during summer, but not pearl millet multi-cut hybrids. There are indications of the possibility of producing topcross forage hybrids that are comparable in forage yield to sorghum-sudangrass hybrids.

Interspecific hybrids

Unlike sorghum, sorghum-sudangrass hybrids tiller profusely, produce succulent stems, have high leaf to stem ratio, re-grow quickly, withstand multi-cuts, and are low in HCN and tannins. Single and three-way interspecific hybrids have been developed in both public and private sectors. However, three-way cross hybrids are predominantly cultivated because private seed industry produces and supplies the hybrid seed. Red-grained

Table 11. Released varieties and hybrids of forage sorghum and pearl millet in India, 1973–2000.

Crop/Type	Single-cut	Multi-cut
Forage sorghum		
Varieties	JS 263, JS 291, JC 6, JC 69, J Set 3, JJ 4, Pusa Chari 1, Pusa Chari 6, Pant Chari 3, Pant Chari 4, Pant Chari 5, HC 6, HC 136, HC 171, HC 260, HC 308, SL 44, CSV 13, CSV 14R, SPV 669, SSV 74, K 7, CO 8, Jumbo, Speed Feed, UP Chari 1, UP Chari 2, GFS 3, GFS 4, GJ 37, GJ 40, RSLG 262, Improved Ramkel, Parbhani Sweta, Rajasthan Chari 1, Rajasthan Chari 2, Rajasthan Chari 3	MP Chari, Pusa Chari 9, Pusa Chari 23, Ruchira, CO 27, DFJ 1
Hybrids	COH 4, PCH 106, CSH 13	–
Sorghum-sudangrass		
Hybrids	–	Proagro 988, MFSH 3, GFSH 1, Hara Sona, Safed Moti Hybrid
Sudangrass		
Varieties	–	SSG 59-3
Hybrids	–	Punjab Sudax Hybrid Chari 1
Pearl millet		
Varieties	Giant *Bajra*, PCB 15, PCB 141, Raj *Bajra* Chari 2, AFB 2, CO 8	DFB-1
Hybrids	FMH 3, GHB 15, GHB 235	–
Napier × *bajra* hybrid		
Hybrid		NB 21, NB 37, CO 1, CO 2, CO 3, PBN 83, PBN 233, Pusa Giant, Yashwant, Annapurna, Swetika

three-way sorghum-sudangrass hybrids are cultivated, though there is no difference between white- and red-grained sorghum forage hybrids.

Round-the-year supply of green fodder paved the way for developing perennial napier-*bajra* hybrids in India. The napier-*bajra* hybrids combine quick re-growth, non-hairiness, narrow long leaves, thin stems, high leaf-stem ratio, high forage quality, low oxalic acid and high forage yield. Above all, napier-*bajra* hybrids can be grown on a wide variety of soil types, and in mixed, relay and intercropping systems.

Genetic enhancement of forage yield and quality

Forage yield improvement

Breeding becomes simpler when the relevant component characters are identified, inheritance patterns understood and effective breeding method(s) are chosen. Khairwal and Singh (1999) reviewed inheritance, heritability, correlations, and general and specific combining ability effects of several economic traits in pearl millet. Tiller number and stem girth were positively related with plant height, indicating that indirect selection could be effective in increasing forage yield. Dry fodder yield is positively correlated with grain yield, indicating that simultaneous selection could be effective. Resistance to rust, a foliar disease, is negatively correlated with green and dry fodder yield which augurs well for improving forage quality. Several forage-related characters like plant height, tiller number, internode number, biomass and growth index are under additive and non-additive genetic control. Also several forage-related traits like quick regeneration, tillering, plant height, thin stems and non-hairy leaves appear to be under Mendelian inheritance. Genetic improvement of forage yield and quality should, therefore, be possible through conventional inbred line development, testing for combining ability, identifying fertility-sterility reaction, developing male-steriles, and breeding varieties and hybrids.

Forage quality improvement

Quantitative traits

The primary objectives of forage quality improvement are to increase feed intake and digestibility, and reduce anti-nutritional attributes (Smith et al. 1997). In vitro dry matter digestibility (IVDMD) is under genetic control and is correlated with CP, neutral detergent fiber (NDF), acid detergent fiber (ADF) and water-soluble carbohydrates (WSC). Recurrent and divergent selections have been extensively used to improve IVDMD through decreasing cell wall concentration [measured by NDF, more recently by in vitro fiber digestibility (IVFD)], reducing lignin concentration (measured by ADF), increasing ready energy (measured by WSC) and/or increasing CP. A great deal of forage quality research is being done in other crops which could be adapted to design forage sorghum and pearl millet quality research relevant to the semi-arid tropics.

Divergent selection for IVDMD has been reported to result in 1.0 to 4.7% gains per year in several species including grasses and legumes (Casler 2000), suggesting that rapid genetic progress for IVDMD is possible. Divergent selection for IVDMD did not result in correlated response for in vitro digestibility of fiber in smooth bromegrass (*Bromus* sp) (Casler 1987) or in vitro digestibility of cell wall polysaccharides in alfalfa (*Medicago sativa*; lucerne) (Jung et al. 1994). Divergent selection for CP increased IVDMD in timothy (*Phleum pratense*; herd grass) (Suprenant et al. 1990). Divergent selection for Kalson lignin (KL) with high or low EthFA (etherified ferulic acid) revealed that both reduce IVFD, but are independent of each other (Casler and Jung 1999).

Recurrent selection for dry matter disappearance in *Cynodon dactylon* through in situ nylon-bag dry matter digestibility (NBDMD) revealed an average genetic gain of 2 g kg^{-1} yr^{-1} between 1963 and 1993 (Hill et al. 1993). Recurrent selection for combining low ADF and high CP in alfalfa decreased ADF and NDF, and increased CP, IVDMD and IVFD (Vaughn et al. 1990).

Selection for WSC in perennial rye grass (*Secale cereale*) revealed greater genetic variation for WSC than for IVDMD, and large non-additive component and positive correlation with IVDMD than for forage yield (Humphreys 1989a, 1989b).

Selection for increased CP led to correlated response for increased digestibility (Suprenant et al. 1990). Genetic progress for increased CP has been documented in several species (Casler 2000). Traditional breeding methods may be useful in improving protein quality; improving degradable proteins is easier and less expensive than non-degradable proteins.

Qualitative traits

While several forage yield and quality traits are under polygenic control and quantitatively inherited, few genes with large and direct effects (oligogenes) could be effectively used to improve forage quality, albeit indirectly. Such material could be exploited through pure line, pedigree and backcross breeding or through population improvement.

Dwarfing genes. Dwarfing genes have been isolated in sorghum and pearl millet. Dwarfing genes are recessive. They shorten the internode length and increase the leaf:stem ratio. Burton and Fortson (1966) isolated d_1 and d_2 dwarfs, while Appa Rao et al. (1986) identified d_3 and d_4 dwarfs in pearl millet. Burton (1983) incorporated d_2 dwarfing gene into forage seed and pollen parents leading to the development of dwarf forage hybrids. This resulted in 11% increase in leafiness and 17–21% increase in IVDMD, but 30% decrease in forage yield (Burton et al. 1969). While forage pearl millets are used for grazing, and hay and silage production in USA and elsewhere, they are chaffed and fed to animals in India. Reducing plant stature would, therefore, adversely affect forage yields and commercialization of forage pearl millets in India. Therefore, attempts should be directed at developing semi-dwarf and normal height forage varieties and hybrids with better forage digestibility for wider acceptability.

Trichomeless gene. Genes that affect leaf surface and epidermal features may also affect forage quality. Trichomeless gene in pearl millet increases palatability, but reduces digestibility of intact leaves (Burton et al. 1977). Bloomless gene in sorghum, on the other hand, increases digestibility of intact leaves (Cummins and Dobson 1972). Trichomeless is controlled by a recessive gene. But bloomless is controlled by two non-allelic recessive genes and sparse-bloom by three non-allelic recessive genes, segregating independently (Peterson et al. 1982). It should, therefore, be possible to transfer trichomeless and bloomless genes into elite lines through backcross breeding.

Stay-green genes. Whether grown for grain and stover (dual-purpose) or for forage, the incorporation of stay-green character is a boon for improving the quality of fodder. Stay-green character is governed by a recessive gene, which slows down senescence. Stay-green gene has a pleiotropic effect arresting the decline in protein content of the aging leaves (Humphreys 1994). Stay-green sorghum lines have been developed at ICRISAT through pedigree breeding.

Glossy genes. Appa Rao et al. (1987) identified three different non-allelic genes in pearl millet governing the glossiness of leaves. Seedling marker 'glossy' was found to be associated with shoot fly resistance and drought tolerance in sorghum.

Sweet stalks. The value of forage sorghum or pearl millet depends on the sugars left in the stover or accumulated in green forage. This is particularly true of pearl millet stover which has low feeding value and is considered inferior to that of sorghum and several other cereals. Considerable variation was observed for juiciness and sweetness of the stalks of sorghum and pearl millet in germplasm collections from Tamil Nadu (Appa Rao et al. 1982) and Rajasthan in India. Several Cameroon landraces of pearl millet also have sweet stalks. Brix varies from 3 to 16% (Harinarayana 1987). Pearl millet accessions from Tamil Nadu are late and tall, but could be used to improve stored energy of stover or green fodder. Sweetness is controlled by a single recessive gene in sorghum (Bangarwa et al. 1987).

Brown midrib genes. Lignins interfere with digestibility. Low lignin mutants offer an opportunity to increase the overall digestion of plant fiber which comprises 30–80% dry matter (Cherney et al. 1991). Low lignin mutants are characterized by brown midrib. There are four *bmr* loci in maize, one *bmr* locus in pearl millet and several *bmr* loci in sorghum and sudangrass (Cherney et al. 1991). Brown midrib loci have been reported to improve IVDMD by reducing lignin in sorghum stems by 51% and in leaves by 25% (Porter et al. 1978) and NDF concentration by 13% (Fritz et al. 1981). All *bmr* genes are recessive. Selection should, therefore, be done in selfed progenies of backcrosses where *bmr* genotype is the donor. At ICRISAT, several sorghum lines with high biomass were selected for *bmr* trait (Table 12).

WW Hanna, University of Georgia, Tifton, Georgia, USA (personal communication) has also developed several pearl millet forage seed and pollen parents incorporating the *bmr* gene. Low lignin lines with *bmr* gene have also been isolated at ICRISAT.

Forage quality improvement through anti-nutritional attributes

Sorghum contains tannins, phenolics and HCN that affect forage quality adversely. Tannins in moderate quantities bind with the proteins and prevent bloating in animals, but when in excess, they lower CP and IVDMD. Tannins are negatively correlated with CP, IVDMD and ADF. Plants with tan plant color, which is controlled by a recessive gene, have low tannin (8%), while purple plants have 10 to 18% tannins (Gourley and Lusk 1978). Phenolics

Table 12. Characteristics of sorghum lines selected for dark midrib color at ICRISAT, Patancheru, India during rainy season 2002.

Cultivar	No. of entries	Midrib color[1]	Brix (%)	Days to 50% flowering	Plant height (m)	Agronomic desirability[2] (score)	Fresh fodder yield (t ha^{-1})	Grain yield (t ha^{-1})	Head length (cm)
B-lines (white grain)									
ICSB 293	23	1.5	13.8	75	2.0	1.5	20.8	4.0	29.8
ICSB 301	31	1.0	14.3	77	1.7	2.5	15.2	3.2	30.5
ICSB 418	41	1.5	17.3	74	1.4	2.0	19.0	2.5	21.7
ICSB 472	46	1.5	20.3	81	2.1	1.5	27.4	2.5	14.4
ICSB 474	47	1.0	17.5	75	2.6	3.0	15.3	1.6	18.2
ICSB 507	54	1.5	15.5	80	1.7	2.5	24.5	2.0	23.8
ICSB 664	66	1.5	22.9	78	1.4	2.5	26.9	1.7	18.6
ICSB 702	71	1.5	13.8	75	1.8	2.0	23.7	3.4	28.0
ICSB 731	73	1.5	18.0	78	2.4	1.5	34.6	3.3	24.3
ICSB 765	80	1.5	17.0	69	1.4	2.5	15.1	2.3	21.0
B-lines (red grain)									
IS 10475B	47	1.5	13.8	62	1.1	3.0	9.8	2.9	29.8
Varieties (red grain)									
ICSV 96114	34	1.5	17.3	69	1.6	2.5	17.6	3.1	25.3
GD 65025	81	1.5	22.0	83	2.3	2.5	34.4	0.6	19.8

1. Score at harvest on a 1 to 5 scale where 1 = more brown and 5 = more white.
2. Score on a 1 to 5 scale where 1 = best and 5 = poor.

interfere with the digestion of structural carbohydrates and NDF (Reed et al. 1988). When absorbed into blood, HCN causes cellular asphyxiation and eventual death (Hoveland and Monson 1980). HCN is under genetic control of a major dominant gene, reinforced by multiple genes with additive effects (Duncan 1996). Pearl millet contains lignins that affect palatability and oxalic acid which affects digestibility.

Management factors

Improvement of forage productivity and quality is as much amenable to management as to genetics and breeding. Some of these management factors relate to cultural practices while others relate to applied nutrients. Effects of various management factors on sorghum crop residue have been summarized in a recent review (Reddy et al. 2003).

Cultural practices

Besides plant population and harvesting time, sowing time and irrigation have been found to have the greatest effects on fodder yield and quality. For instance, significant reduction in green fodder, dry matter content and CP yield was observed with delay in planting from 25 October to 25 November at Urulikanchan, India (Khandale and Relwani 1991). The effects of irrigation during summer on forage yields have been reported to be variable, depending on the genotype, soil type and potential evapotranspiration. Irrigation (7 cm) at different IW/CPE (irrigation water/cumulative pan evaporation) ratios of 0.25, 0.50 and 0.75 revealed that maize yielded the highest green fodder while pearl millet yielded the highest dry fodder when compared to sorghum, teosinte (*Euchlaena mexicana*), cowpea (*Vigna unguiculata*) and cluster bean (*Cyamopsis tetragonoloba*) at all irrigation regimes (Singh et al. 1989). But Singh and Singh (1986) reported that sorghum outyielded maize and pearl millet at IW/CPE ratios of 1.0, 0.6, 0.3 and 0.15.

It has also been observed that transplanted pearl millet produces more stover yield than direct-seeded crop, irrespective of the seedling age (Upadhyay et al. 2001). The response increased with increased nitrogen (N) (0 to 80 kg ha^{-1}) application (Singh 1985), but P had no effect (Upadhyay et al. 2001). Jayanna et al. (1986) observed that increased seed rate (20 to 40 kg ha^{-1}) had no effect on tillering forage sorghum, but the green fodder yield increased with increasing seed rate in non- or low-tillering forage sorghums. Green fodder yield of pearl millet increased up to a seed rate of 12 kg ha^{-1}, after which it declined with increase in seed rate (Sharma et al. 1996). Pearl millet stover yield and plant height increased with increasing plant density (Singh 1985). Highest green fodder and dry matter yields were obtained when harvested at either 60 or 75 days after sowing (DAS) than at 45 DAS. However, opposite trend was observed with crude fiber (%) being lowest when harvested at 45 DAS (Ram and Singh 2001a, 2001b). Compared to single-cut, multi-cut pearl millet produced high forage yield coupled with good quality forage (Chauhan et al. 1990), though the magnitude varied from genotype to genotype (Table 13).

Table 13. Nutrient production (t ha^{-1}) of pearl millet as influenced by cutting.

	Single-cut				Multi-cut			
Component[1]	Comp 5	Comp 1	PHB 10	Mean	Comp 5	Comp 1	PHB 10	Mean
Green fodder	61.2	62.2	40.5	54.6	74.1	73.6	56.4	68.0
Dry fodder	9.7	10.1	7.4	9.1	15.5	14.7	11.8	14.0
DDM	5.7	5.5	3.9	5.0	9.1	8.1	6.1	7.8
Crude protein	0.80	0.79	0.55	0.71	1.28	1.16	0.87	1.10
DCP	0.45	0.40	0.26	0.37	0.72	0.59	0.41	0.57
TDN	5.4	5.3	3.8	4.8	8.6	7.7	6.0	7.4

1. DDM = Digestible dry matter; DCP = Digestible crude protein; TDN = Total digestible nutrients.
Source: Chauhan et al. (1990).

Intercropping of fodder sorghum with legumes such as cowpea, soybean (*Glycine max*), horse gram (*Dolichos uniflorus*), and velvet bean (*Mucuna deeringiana*) resulted in better green forage, dry matter and CP yields than fodder sorghum alone (Sood and Sharma 1992, Mishra et al. 1997, Ram and Singh 2001a, 2001b). Forage sorghum-chickpea (C*icer arietinum*) produced highest green fodder under normal conditions, but under drought, pearl millet-pearl millet ratoon prevailed over sorghum + pigeonpea (C*ajanus cajan*)-fallow or pearl millet-safflower (C*arthamus tinctorius*) (Ali and Rawat 1986). Compared to sole crop, pearl millet mixed or intercropped with cowpea or soybean produced more CP, ether extract (EE), minerals, crude fiber and N-free extract (NFE) (Singh and Narwal 1987, Yadav and Sharma 1995).

Nutritional amendments

Nitrogen application has been found to have greatest effect on forage yield and quality. Several studies have shown that forage sorghum responded well to increased levels of N by producing significantly higher green forage, dry matter content and CP (Patel et al. 1992, Sood and Sharma 1992, Vashishatha and Dwivedi 1997, Ram and Singh 2001a, 2001b, Reddy et al. 2003). The response of fodder pearl millet was positive for forage production up to 120 kg N ha^{-1} (Randhawa et al. 1989, Sharma et al. 1996). Application of N also improved forage quality, CP, mineral matter, EE and NFE (Table 14). Increase in N application was also accompanied by increase in stover production, plant height and tillers plant^{-1} (Singh 1985). But forage pearl millet following postrainy berseem (*Trifolium alexandrinum*) required less N application than pearl millet following wheat, oat (*Avena sativa*) or turnip (*Brassica rapa*),

Table 14. Response of forage pearl millet to nitrogen application[1].

Genotype/ Fertilizer	GFY (t ha^{-1})	DFY (t ha^{-1})	Plant height (cm)	No. of tillers m^{-1}	Leaf: stem ratio	Crude protein (%)	Mineral matter (%)	Ether extract (%)	Crude fiber (%)	NFE (%)
Genotype										
L 72	51.1	9.6	241	19.3	0.66	7.0	9.4	1.45	26.5	56.3
C 5	58.3	17.6	266	19.6	0.54	6.6	7.8	1.34	32.1	53.6
PCB 15	53.6	10.0	248	18.3	0.62	7.2	10.0	1.30	9.2	52.9
CD at 5%	4.4	1.2	–	–	–	–	1.1	–	–	–
Nitrogen (kg ha^{-1})										
0	38.3	8.5	230	19.2	0.69	5.3	8.7	1.30	32.1	55.4
50	53.3	12.1	253	18.1	0.64	6.2	8.0	1.31	30.1	55.2
100	63.6	14.0	265	20.0	0.58	7.1	9.9	1.39	26.4	55.5
150	62.4	14.7	266	18.6	0.55	7.6	11.5	1.44	22.4	57.2
CD at 5%	5.1	1.4	–	–	–	–	1.28	–	–	–

1. GFY = Green fodder yield; DFY = Dry fodder yield; NFE = Nitrogen-free extract.
Source: Randhawa et al. (1989).

resulting in a saving of 50% N (Harika et al. 1986). Following the application of P, pearl millet produced more green and dry fodder yield than sorghum, maize, cowpea or cluster bean (Ram et al. 1988). Sulfur (S) application increased CP, sugars, methionine, cell contents, S:P ratio, and S:zinc ratio (Tripathi et al. 1992a) and decreased NDF, ADF, N:S ratio and Ca:P ratio up to 40 kg S ha^{-1} in forage sorghum (Tripathi et al. 1992b). Treatment of forage sorghum with *Azospirillum lipoferum* (Pahwa 1986) or with *Azotobacter* (Patel et al. 1992, Reddy et al. 2003) resulted in significant increase in dry matter production than without *Azospirillum* or *Azotobacter*. The rhizosphere was enriched with N, and resulted in a saving of 15 kg N ha^{-1}.

Commercialization potential

Economics of seed production

In India, forage sorghum-sudangrass seed is produced during the postrainy season, while grain/forage pearl millet seed is produced during the hot summer season. The chief seed production area is in Nizamabad district of Andhra Pradesh. Some seed production is also evident in Bellary district of Karnataka. Congenial climate, pest-free environment, assured irrigation and the desire to maximize economic returns have all contributed to successful seed production in Nizamabad.

A system of one-year rotation, rice-pearl millet in alluvial soils is followed. In the two-year rotation, first year sequence of maize-turmeric (*Curcuma domestica*)-pearl millet (seed crop) is followed by maize-forage sorghum (seed crop) during the second year. The intensive cropping, particularly seed production, ensures stability and high economic returns to the farmer. Forage sorghum as well as grain pearl millet acreage continue to spread following good monsoon, but tend to shrink following partial failure of monsoon.

Forage sorghum seed production is profitable with yields ranging from 2.5 to 4.0 t ha^{-1} under irrigation. Forage pearl millet seed production is small, compared to sorghum-sudangrass or grain pearl millet seed. Some case studies regarding forage pearl millet hybrids will provide an insight into profitability of seed production. Area planted to pearl millet seed fluctuates widely as water becomes more and more limiting. Secondly, compared to forage sorghum, the seed yields of forage pearl millet hybrids are significantly lower, and vary between 1.0 and 2.5 t ha^{-1}. Farmers undertake pearl millet seed production with the express understanding that it is a catch crop between postrainy season turmeric and rainy season maize/rice.

Seed trade

The sale price of forage sorghum-sudangrass fluctuates between Rs 15 kg^{-1} and Rs 20 kg^{-1} (US$0.25–0.45 kg^{-1}), depending on the market demand. Though the margin of profits is not substantial, the volume and the recurring demand sustain the interest of the seed industry. The recent entry of a large number of marginal traders has discouraged the registered seed industry. There is a need to curb unregistered trade firms not supported by scientific and technical personnel, and to encourage seed companies with research, production, processing and marketing support.

The sale price of Rs 30–50 kg^{-1} (US$0.70–1.10 kg^{-1}) of forage pearl millet hybrid seed is not attractive to the farmers in view of limited harvests (cuts) and low forage yield. Low seed yields, limited area and lack of recurring demand are discouraging the seed industry to venture into forage pearl millet research and development.

Future outlook

Any-time forage

Sorghum and pearl millet either alone or in mixed or intercropping system are cultivated for stover and forage. Sorghum stover scores over pearl millet, but forage pearl millet is rich in protein, Ca, P and minerals, and oxalic acid content is within safe limits. Being any time forage, pearl millet, unlike sorghum, can be grazed, or cut and fed at any growth stage. However, forage sorghum is more popular than forage pearl millet. Low green fodder yield, poor ratoonability (ability to regenerate), limited market demand, variable prices and lack of private industry support and research support have discouraged pearl millet as forage. Concerted efforts are, therefore, required to ameliorate this situation.

Geographical preferences

Sorghum and pearl millet green fodder is fed to ruminants in northern India, while stover is common in sorghum and pearl millet growing areas in southern India. Intensive cropping, short growing season, poor growth of perennial grasses during winter, nutritional quality and the need for continuous supply of green fodder created demand for forage sorghum and forage pearl millet in northern India. Sorghum varieties and sorghum-sudangrass hybrids are grown for forage in northern India while in southern India, perennial grasses are cultivated as annual forage is required for supply between harvests, and for supplementing the stover. Development of annual multi-cut high-yielding forage sorghum and pearl millet is needed to correct the regional imbalances.

Multi-cut varieties

To overcome limited ratoonability, forage sorghum and pearl millet varieties are repeatedly planted (staggered) for sustaining the green fodder supply chain. High plant density ensures high yields, thinner stems and more palatability. Efforts should, therefore, be directed at designing forage sorghum and forage pearl millet that tiller, grow tall and ensure multi-cuts.

Varietal choice

Many forage sorghum varieties are under cultivation, but there are very few forage pearl millet varieties. Recurring demand and/or volume turnover are product-driven, while public and private seed industry are market-driven. Development of multi-cut annual forage sorghum and pearl millet hybrids, rather than varieties, will be of interest to the seed industry. There is also scope for the development of intra- and interspecific forage hybrids.

Forage sorghum

Development of multi-cut, intra-specific, single-cross, white-grained forage hybrids would offer the widest choice for realizing forage potential of sorghum. These hybrids provide a better alternative to forage varieties grown during the rainy season. Diversification of interspecific, sorghum-sudangrass hybrids for increased productivity and nutritional quality also requires attention. Sorghum-sudangrass three-way hybrids are by far the most popular forage hybrids, and are based on red-grained sorghum male-sterile lines. Limited variability in red-grained sorghum seed parents, and sudangrass pollinators further impose restrictions on the exploitation of the interspecific forage hybrids. Focused efforts to improve the seed parents and pollinators for forage traits like high tillering, fast growth, stay-green and brown midrib characters, resistance to foliar diseases and stem borer, high stalk sugars, forage intake and digestibility in animals will add further diversity to the forage cultivar development. Large-seeded, red- or white-grained high-density panicles should be deployed in seed parents. The sudangrass pollinators can be improved for resistance to foliar diseases and high sugar content.

Forage pearl millet

Single-cut pearl millet varieties with limited forage potential of 30 t ha^{-1}, and 0.27 to 2.24 t day^{-1} ha^{-1} are currently dominating the forage market. Development of intra-specific forage hybrids that combine the ability for repeated harvests (multi-cuts), earliness to first harvest (cut), short harvesting intervals, quick regeneration, the built-in tillering potential, high green fodder yield, high quality factors and low anti-nutritional factors like oxalic acid and nitrates has tremendous opportunity to improve pearl millet as a forage crop. Efforts should also be directed at identifying seed parents for high seed yield. Alternatively, the feasibility of F_1 male sterile seed parents and three-way forage hybrids should be examined.

The interspecific napier-*bajra* hybrids give year round forage production. Improving the nutritional quality of pearl millet and napier grass could enhance opportunities for clonal selection. The hybrids of *P. glaucum* × *P. purpureum* × *P. squamulatum* developed by GW Burton, Agricultural

Research Station, Coastal Plain Experimental Station, Tifton, Georgia, USA and tested in India (Ramamurty and Shankar 1998) had shown promise for forage yield and quality among perennial grasses. Probably, such tri-species hybrids could be developed in sorghum as well!

Nutritional quality

Forage quality as determined by CP, IVDMD, NDF and ADF reflecting degradable and non-degradable proteins, structural and non-structural carbohydrates, lignin and celluloses, and anti-nutritional attributes such as HCN, oxalic acid, tannins and phenolics have received greater research attention elsewhere in the world, but not in the arid and semi-arid tropics. Forage quality research is complex, expensive and laboratory dependent calling for multidisciplinary approach and multi-institutional alliances.

Public-private partnerships

Inter-institutional partnerships involving international agricultural research centers (IARCs), national agricultural research systems (NARSs) and private agricultural research systems (PARSs) could forge strong interlinks for sustaining forage sorghum and pearl millet research. Crop scientists, chemical technologists, and animal health and nutrition experts have a role to play in the forage development scenario.

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