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Male-sterile seed parents for the [*Pennisetum glaucum* (L.) R. Br.] breeding of landrace-based topcross hybrids of pearl millet for the arid zone. III. Matching A-lines and specific target environments

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Abstract

Growing environments of pearl millet [*Pennisetum glaucum* (L.) R. Br.] in the Indian arid zone are quite heterogeneous both in terms of environmental stresses and farming system needs. In this paper we described main target environments for pearl millet breeding programs within the arid zone, and then attempted to identify male-sterile (A) lines for developing suitable landrace-based topcross hybrids (TCHs) and conventional hybrids for the identified target environments. Target environments were defined as extreme stress, moderate stress and favourable environments based on the available environmental resources for, and limitations to, crop production in each target zone. TCHs based on 39 A-lines were clustered into five clusters for grain, stover and biomass yields, yield stability, responsiveness to environment, downy mildew and drought resistance and several other variables. The suitability of individual A-lines for different target environments was judged by their ability to produce TCHs with the adaptive traits considered as most important for each target environment. None of the A-lines produced hybrids that were equally well-adapted to all the three types of environments; most of the A-lines produced hybrids that showed a contrasting adaptation pattern to the different target environments. The A-lines ICMA 93111, ICMA 94555, ICMA 95111, HMS 9A and CZMS 44A produced highly stable dual purpose hybrids; and 842A, ICMA 95444, ICMA 97111, ICMA 97444 and 843A grain hybrids that were suitable for extreme stress environments. Hybrids made with ICMA 97333, ICMA 93111, ICMA 95555, ICMA 96333, 842A, ICMA 91444 and ICMA 92666 were suitable for moderate stress environments in that they proved high yielding, moderately stable and responsive hybrids to better environments. On the other hand, hybrids based on 5054A, ICMA 88006, ICMA 95222, ICMA 92333, ICMA 92444, ICMA 94555 and ICMA 97333, ICMA 96222, ICMA 97111, ICMA 91444 and ICMA 95444 were identified as most desirable for favourable environments. Utilisation of A-lines and their respective maintainers has been discussed for developing suitable hybrids and new parental lines of hybrids for arid zones.

Key words: Pearl millet, *Pennisetum glaucum*, adaptation, breeding, abiotic stress tolerance, disease resistance, male-sterile lines

Introduction

In pearl millet [*Pennisetum glaucum* (L.) R. Br.] landrace-based topcross hybrids (inbred male-sterile line × adapted landrace-derived pollinator population) are a potential alternative to conventional single-cross hybrids especially for arid zone. Landrace-based topcross hybrids can successfully combine the advantages of heterosis with the adaptation from their landrace parent, to both the environmental stresses and farming system requirements of the arid zone [1-2].

Breeding successful topcross hybrids (TCHs) will require not only the breeding of pollinators with the arid zone adaptation and traits needed by farmers, but also the identification of appropriate inbred male-sterile lines (A-lines). Such lines should exhibit grain and stover yield heterosis in combination with adapted pollinators, and produce hybrids with other traits needed in successful cultivars for the region (disease resistance, good seed set, good stover yield etc.). Papers 1 and 2 of this series [3-4] report on the evaluation of a set of 39 publicly available A-lines for the ability to produce topcross hybrids with a range of traits generally considered desirable for the arid zone.

However, breeding programs focusing on the arid zone are not targeting a single, homogeneous target environment, either in terms of prevalent environmental stresses or farming system needs, meaning that cultivar requirements will vary within the arid zone. The variation in the amount and distribution of rainfall from east to west across the state of Rajasthan creates a wide range of soil moisture availability across the arid zone. In addition, as the environment becomes drier, the relative importance of millet grain and stover changes [5]. Millet stover can be as valuable as grain where livestock products are the major source of household income in the farming system. Therefore, there needs to be a choice of A-line, as well as pollinator, for different target physical environments and for different target farmers, within the arid zone.

In this paper we describe the main target environments for pearl millet breeding programs within the arid zone, and establish likely criteria for successful landrace-based TCHs (and conventional hybrids), and by implication, for their A-lines, for each of the target environments and then attempt to identify A-lines that best meet these criteria.

Materials and methods

The details of test materials and procedures of data recording have been described in the first two papers of this series [3-4]. The study compared TCHs of a landrace-based pollinator (ERajPop TCP) on 39 publicly available A-lines. Evaluations of TCHs took place during 1998-2000 rainy seasons at nine location x year combinations in Rajasthan, and in managed disease and drought nurseries at ICRISAT, Patancheru.

Description and simulation of target environments: Although moisture stress is the most common stress in arid zone, its nature is not uniform within the entire arid zone. Drought stress is highly variable in its frequency, timing and intensity in different areas of arid zone. Different soil fertility status in arid zone areas may add further variation in the intensity of drought stress. These factors affect farmers' management strategies and utilization of the crop. Hence we classify arid zone environments in different target sub-regions in order to group them in a few largely homogeneous environments so as to identify most appropriate A-line and formulate breeding strategy for each sub-zone. Salient features of these target environments are described in Table 1. These target environments are:

Extreme stress environments: The seasonal rainfall is extremely scanty (often less than 250 mm) with highly irregular distribution. Soils are sandy with poor water storage capacity, with the result that crop-growing season is often short (<70 d). Moisture stress is likely to be very severe at one or other stage of crop, but there are no clear patterns to its occurrence. The nutrient status of soils is often poor, and crop growth often reduced by nutrient deficiencies as well as lack of soil water. Large areas of the districts of Barmer, Jaisalmer, Bikaner, Churu, Nagaur, and Jodhpur are represented in the severe stress target environment which correspond to 1A and 2A categories of agro-climatic zones of Rajasthan [6]. The Mandor and CAZRI locations in year 1999 and Nagaur in 2000 [3] with a mean yield level of 510 kg ha^{-1} were defined as representative of extreme stress environments.

Moderate stress environments: The annual rainfall is between 250 mm and 450 mm and soils are mainly sandy loam to loamy sand. Intermittent drought spells of varying periods are common during crop season but may be buffered somewhat by a greater soil water holding capacity. The duration of crop growing period is medium to medium short (70-85 days). Soil fertility is likely to be better because the better growth of cultivated legumes results in a greater contribution to soil fertility maintenance than in the extreme stress environments. The large areas of districts of Pali, Jalore, Sirohi, Ajmer and Jaipur represent the moderate stress growing environments corresponding to 2B and 3A agro-climatic zones of Rajasthan [6]. The locations Mandor 1998, Nagaur 1999 and CAZRI 2000 [3] with a mean yield level of 924 kg ha^{-1} were considered as representative of moderate stress environments.

Table 1. Distinguishing features of the major target environments for pearl millet within the arid zone, and the requirements for new cultivars for each target environment

Features of target environment	Desirable traits
1. Extreme stress environment	
Short growing season	Extra early maturity
Infertile soils with poor texture and structure	Modest grain and stover yield potential
High probability of drought	High level of drought tolerance
Highly variable crop productivity	High stability of grain and stover yields
Livestock are a major component of farming system	High tillering/thin stems for improved fodder palatability
2. Moderate stress environments	
Short to medium short growing season	Early to medium maturity
Relatively heavier soils with better fertility	Moderate to high grain and stover yields
Frequent intermittent spells of drought	Drought tolerance
Rare favourable crop season	At least average responsiveness to favourable growing conditions
Variable crop productivity	Average stability to grain and stover yields
Livestock are an important component of farming system	Dual purpose cultivars providing both grain and stover
Downy mildew in favourable years	Downy mildew resistance
3. Favourable environments	
Irrigation available to crop	Full season cultivars
Favourable crop growth conditions	Cultivars which are highly responsive to favourable growing conditions
Fertile soils	High grain and stover yields
Market-oriented farming	High potential productivity
High probability of downy mildew	Downy mildew resistance

Favourable environments: In these environments pearl millet is grown with supplemental irrigation and very often with the addition of organic and/or inorganic fertilizers, by larger, wealthier farmers, in much higher-input farming systems. The environmental resources are therefore favourable to support the potential productivity of high yielding cultivars and farmers will be seeking to obtain a maximum return for the inputs supplied. These environments are scattered throughout the arid zone but are mainly concentrated in Alwar, Bharatpur, Jaipur and Dausa districts of Rajasthan, wherever farmers have been able to access non-saline ground water. The three test environments of Nagaur 1998 (both early and late plantings) and CAZRI 1998 [3] with a mean yield level of 1457 kg ha^{-1} as representative of favourable environments.

Clustering of A-lines: In order to synthesize genotype performance by all of the various criteria by which they were assessed across different field evaluation environments and the various special evaluation environments, the testcrosses of all A-lines to the Early Rajasthan Population (ERajPop) topcross pollinator (TCP), were clustered into (an arbitrary) five clusters for each evaluation variable as described in detail by Bidinger *et al.* [3-4]. Biomass, grain and stover yields were clustered by TCH means for the three test environments for each of the extreme stress, moderate stress and favourable target environments. Downy mildew resistance [4] was clustered by TCH × pathotype means from the glasshouse seedling screen. Drought tolerance was clustered by the combined early and late stress drought tolerance index values and by the mean panicle harvest index from the combined drought nursery and stressed Rajasthan evaluation locations [4]. Potential productivity was clustered by the TCH means for crop growth rate and grain yield from a high input irrigated environment (drought nursery control treatment). Flowering, panicle number and harvest index were clustered as means of all of the Rajasthan evaluation locations [3].

Table 2. Cluster means for all variables for which the A-line TCHs were evaluated in multi-location field environments. Cluster 5 includes the best or highest ranked A-lines and cluster 1 the poorest or lowest ranked A-lines for each evaluation criteria

Evaluation variable	Cluster 1 mean	Cluster 2 mean	Cluster 3 mean	Cluster 4 mean	Cluster 5 mean	Overall mean
Extreme stress environments[1]						
Biomass ($kg\ ha^{-1}$)[1]	1618	1770	1898	2004	2181	1869
Grain yield ($kg\ ha^{-1}$)	314	444	492	555	616	510
Stover yield ($kg\ ha^{-1}$)	946	1005	1091	1176	1303	1124
Moderate stress environments[1]						
Biomass ($kg\ ha^{-1}$)	2855	3115	3337	3546	3967	3216
Grain yield ($kg\ ha^{-1}$)	779	876	946	1011	1102	924
Stover yield ($kg\ ha^{-1}$)	1559	1776	1973	2118	2315	1851
Favourable environments[1]						
Biomass ($kg\ ha^{-1}$)[1]	3603	3780	3917	4186	4548	4054
Grain yield ($kg\ ha^{-1}$)	1158	1351	1445	1537	1618	1457
Stover yield ($kg\ ha^{-1}$)	1876	2051	2262	2404	2586	2087
Responsiveness (b)[2]						
Biomass	0.75	0.87	0.98	1.15	1.38	NA
Grain yield	0.68	0.77	0.91	1.03	1.17	NA
Stover yield	0.64	0.81	1.03	1.24	1.55	NA
Stability (RMSE)[2]						
Biomass	84	73	56	40	24	NA
Grain yield	30	23	19	13	08	NA
Stover yield	45	38	32	25	14	NA
Yield components[2]						
Harvest index (%)	25.30	28.50	30.80	32.90	36.60	31.20
Panicle number m^{-2}	8.80	10.20	11.00	12.20	13.20	10.60
Other evaluations[3]						
Flowering (days)	52.70	51.20	50.00	48.10	46.90	49.20
DM infected plants (%)	31.60	25.10	22.00	16.10	6.40	11.50
Seed set (score)	2.20	3.80	5.20	5.50	7.20	6.40
DRI (drought nursery)	–3.55	–1.00	–0.20	+0.69	+1.43	0.00
PNHI (stress environments) (%)	57.80	61.20	62.80	65.50	67.50	64.30
Potential grain yield ($kg\ ha^{-1}$)	3321	3838	4076	4300	4641	4105

[1]Clustering based on different subsets of environments representing the extreme stress, moderate stress and optimum target environments.
[2]Cluster means presented are based on 36 A-lines only, using all nine field evaluation environments from 1998, 1999 and 2000.
[3]Cluster means presented are based on all 39 A-lines based on evaluations done in 1999, 2000 or 2001.

Matching of A-lines and target environments: The suitability of individual A-lines for different target environments was judged by their ability to produce TCH with the adaptive traits that are considered as most important for each target environment (see Table 1). Desirable A-lines for each target environment were those whose test crosses with ERajPop ranked in the first or second most desirable cluster for all or the majority of the desirable traits for that target environment. Also A-lines were considered for their ability to provide choices of maturity, grain vs. stover production etc. within the target zone.

Results and discussion

Clustering of A-lines: Clustering resulted in good differentiation among the lines on the basis of the performance or specific traits of their TCHs (Table 2). This provided a good opportunity to select from among A-lines that will meet most of the requirements of each target environment. The range in mean time to TCHs flowering across the nine evaluation environments was only 6 days between clusters 1 and 5, but the range in various productivity estimates was considerable larger (Table 2). Cluster mean productivity for grain yield ranged from 314 kg ha^{-1} to 616 kg ha^{-1} for extreme stress environments compared to 779 kg ha^{-1} to 1102 kg ha^{-1} for moderately stress environments and 1158 kg ha^{-1} to 1618 kg ha^{-1} for favourable environments (Table 2). The range in total TCH biomass accumulation was relatively narrower than that for grain and stover yields, due to considerable variation for harvest index (25.3% to 36.6%), and therefore in grain vs. stover productivity, among various clusters (Table 2).

Clustering was also effective in discriminating the A-lines for the responsiveness of their TCH to better environments (two-fold range between the lowest and highest clusters) and the stability of that response (three-fold range), for both grain and stover yields and total biomass (Table 2). The differences in cluster means for yield components also indicated a useful variability among A-lines in the phenotype of their TCH. For example, the tillering ability of the highest-tillering cluster was 1.5 times larger than that of the lowest-tillering cluster (Table 2). Clustering was equally effective for discriminating lines on the basis of their specific traits. The mean of various clusters for downy mildew incidence of the TCHs ranged from 6% to 32%, and the drought response index (DRI) from +1.43 to –3.55 (Table 2). The range in the potential productivity of TCHs included in various clusters was also quite large; from 3321 kg ha^{-1} of cluster 1 to 4641 kg ha^{-1} of cluster 5. Thus there should be good chances of selection of A-lines for improving both TCHs downy mildew resistance and drought tolerance and for developing TCHs with high potential productivity as per their importance in specific target environments.

Matching of A-lines and target environments priorities: The defined target environments (Table 1) vary widely in terms of the environmental resources for, and limitations to, production in each target zone. This necessitates selection for different crop traits in breeding programs targeting different defined target environments, in accordance with available resources and requirements in each of the environments. In extreme stress environments a high stability in grain and stover production, albeit at modest level, along with early maturity and high tillering are the priority traits of cultivars for these environments (Table 1). In moderate stress environments cultivars with better-than-average grain and stover productivity along with moderate stability are the priority traits, while genetic resistance to downy mildew, along with a high potential grain and stover productivity, and a longer maturity, are priorities for cultivars targeting such favorable environments.

None of the lines appeared to produce hybrids that were equally well-adapted to all the three groups of environments, i.e. none had uniform high rankings for yields of grain, stover and biomass in all groups of environments (Table 3). A few of the A-lines produced hybrids that were unadapted to all arid zone environments (e.g. ICMA 88004, ICMA 91333 and ICMA 94111). On the other hand, ranking of TCHs based on 5141A, 841A, ICMA 88006, ICMA 94222, ICMA 95111, and ICMA 95222 in three target environments for grain and stover yields (Table 3) showed a contrasting adaptation pattern to different target environments indicating that these lines clearly performed better in specific environments; which supports our original hypothesis of matching A-lines with specific target environments having different requirements. Hence suitability of individual lines for specific environment is considered.

A-lines for extreme stress environments: The major evidence of adaptation to stress environments is reported to be the ability of cultivars to accumulate a large amount of biomass under stress conditions [3,10]. Obviously, the preferred A-lines for extreme stress environments would be those that produce TCHs with a high and stable biomass. In addition, a high degree of drought tolerance and profuse tillering are important in increasing stability in production [8-10]. Finally, early flowering can further help in escaping the common terminal drought stress [11].

There were good differences among various A-lines in terms of biomass accumulation and stability of their TCHs (data not presented). TCHs made on 5141A, ICMA 93111, ICMA 92333, ICMA 94555, ICMA

95111, ICMA 95333, HMS 6A and CZMS 44A ranked in clusters 4 or 5 for biomass productivity (>2 t ha^{-1}) as well as stability. The lines 841A and MAL 2A, also produced TCHs with a high biomass, but were only moderately stable (cluster 3) (data not presented). In contrast TCHs on many other A-lines lacked either high biomass productivity (ICMA 88004, ICMA 91333, ICMA 92444, ICMA 95555, ICMA 93333 and RMS 3A) or stability (ICMA 94222, ICMA 91222 and ICMA 96222), and thus could not be considered as relevant for extreme stress environments of arid zone.

The lines that produced significant and stable biomass varied in their biomass partitioning (Table 4), resulting into different grain and stover yielding ability. ICMA 93111, ICMA 94555, ICMA 95111, HMS 9A and CZMS 44A produced dual purpose hybrids with high stability for both grain and stover yields (Table 3). Thus these lines appeared especially promising for the farming system in extreme stress environments where both grain and stover are equally important. On the other hand, ICMA 92333 and HMS 6A were better for stover production (cluster 4) than for grain yield (cluster 3). TCHs involving 5141A and 841A were in the best cluster both for grain and stover but had only low (841A) to moderate (5141A) grain yield stability (cluster 2 and 3). TCHs of both these A-lines also ranked poorly (cluster 1) for both panicle harvest index and drought tolerance (Table 4), which might have been the cause of their highly unstable grain yields. The TCH on ICMA 95333 looked very promising for yield and stability of stover production (Table 3), however its grain yield was very unstable, possibly due to its extremely late flowering (cluster 1; Table 3).

Several A-lines (842A, ICMA 95444, ICMA 97111, ICMA 97444 and 843A) produced hybrids with high and stable grain yield (Table 3), but only low to moderate biomass yields, due to their high harvest index (Table 4). Thus these lines are primarily suitable for producing grain type hybrids. Hybrids made with these lines also possessed high degree of drought tolerance (clusters 4 or 5 for DRI) and had high ranking for panicle harvest index (Table 4) which indicates a superior ability to set and fill grain under stress [12]. The earliness of these lines might have also contributed in their superior performance under stress as the TCHs on all but one of these were in the best two clusters for earliness (Table 4).

Given that growing season in this environment is very short, crop phenology plays an important role in escaping drought stress at the end of the season [11-12]. The line 843A was a very unique in terms of the phenology of its TCH, and hence was grouped in a separate cluster (Table 4). However, the short life cycle of 843A TCH resulted in low biomass productivity (cluster 2) and only moderate grain yield (cluster 3) (Table 3). Seven A-lines produced TCH in the second best cluster for earliness (mean flowering time of 48 days, only 1 day later than the 843A TCH); these were 5054A, 842A, ICMA 94222, ICMA 95111, ICMA 95444, ICMA 96333 and ICMA 97111 (Table 4). However, all these lines except ICMA 94222 and ICMA 95111 were also grouped in cluster 2 or 3 for biomass productivity (Table 3) confirming that earliness often has a tradeoff with biomass production. However, the converse is not necessarily true, as the lines that produced most desirable dual purpose hybrids (high grain and stover yield) in the extreme stress environments of arid zone were spread from cluster 2 (e.g. CZMS 44A, HMS 9A) to cluster 4 (ICMA 95111) for flowering time. Thus earliness should not be seen as a universal solution for extreme stress environments. Rather, other traits that help provide some stability in production under severe stress environments also need to be considered.

Among the remaining A lines, ICMA 88004 and ICMA 94111 appeared to possess good drought tolerance as their TCH were among the top rankers for PNHI (Table 4) but their grain and stover yields were low in the severe stress environments (Table 3). ICMA 96444 and ICMA 89111 hybrids were highly susceptible to stress, as indicated by their clustering in two most susceptible groups for DRI (Table 4) and were ranked in the second lowest cluster for grain yield in the severe stress (Table 3). The grain yield stability of their TCH was moderate to high but apparently at extremely low level of productivity. Hence none of these A-lines can be considered desirable for extreme stress environments.

From among the lines that were promising for severe stress environments (Table 5), hybrids on ICMA 95333, 843A and CZMS 44A were moderately susceptible to downy mildew (cluster 3 with mean downy mildew incidence of 22%) (Table 2). Though downy mildew is not considered as a serious threat to pearl millet in dry and harsh environments, the pathogen can still proliferate in short favourable periods and cause significant damage, especially during the early growth of millet. Hence the downy mildew resistance of these three A-lines needs to be improved before using them extensively in breeding hybrids for arid areas. Fertility restoration (data not presented) was adequate for all hybrids except one (based on ICMA 95333) suggesting that this trait is not a problem in developing suitable hybrids for harsh climate in arid zone environments.

A-lines for moderate stress environments: The requirements of hybrids for moderate stress environ-

Table 3. Cluster number (5 = highest/best; 1 = lowest/poorest) for TCH of 39 A-lines with the landrace-derived pollinator ERajPop for grain and stover yields in each of the severe stress, moderate stress and favourable environment subsets of the nine evaluation environments. Cluster number (5 = highest/best; 1 = lowest/poorest) for responsiveness to environment is based in intercept and regression coefficient values, and cluster number for stability (5 = highest/best; 1 = lowest/poorest) across environments is based on the root mean square for error of individual TCH regressions

A-Line	Severe stress environments		Moderate stress environments		Favourable environments		Responsiveness to environments		Stability across environments	
	Grain yield	Stover yield	Grain yield	Stover yield	Grain yield	Stover yield	Grain yield	Stover yield	Grain yield	Stover yield
5141A	5	5	1	2	3	2	3	1	3	4
5054A	3	4	3	3	5	4	5	4	2	2
81A	2	4	3	3	3	4	5	3	4	3
841A	5	4	2	1	3	1	4	2	2	3
842A	4	2	4	1	2	1	3	1	5	4
843A	3	2	2	1	2	1	3	1	4	3
ICMA 88004	2	2	2	2	2	1	5	4	4	2
ICMA 88006	3	3	3	5	5	5	5	5	3	3
ICMA 89111	2	3	1	2	2	1	4	3	5	4
ICMA 90111	2	4	1	4	2	5	2	3	4	2
ICMA 91333	2	3	2	1	3	1	5	2	5	5
ICMA 91444	4	4	5	4	4	3	3	3	3	2
ICMA 91777	2	4	1	4	1	2	2	3	4	1
ICMA 92333	3	4	3	3	5	3	5	3	4	4
ICMA 92444	3	1	2	2	5	2	4	3	4	4
ICMA 92666	4	3	3	4	2	2	1	4	4	3
ICMA 93111	4	5	4	4	3	3	4	3	5	4
ICMA 93333	2	1	3	3	3	1	4	4	5	4
ICMA 94111	1	1	3	2	2	1	5	2	3	4
ICMA 94222	4	4	3	1	3	2	3	1	3	1
ICMA 94444	2	4	3	4	2	3	4	4	3	1
ICMA 94555	5	4	2	2	4	2	4	3	4	4
ICMA 95111	4	4	3	2	1	1	1	3	4	4
ICMA 95222	3	3	2	2	5	4	5	3	4	1
ICMA 95333	3	5	3	3	2	3	3	3	1	5
ICMA 95444	5	2	3	1	4	1	3	2	4	4
ICMA 95555	2	2	4	3	2	1	4	3	4	4
ICMA 96222	4	4	2	4	5	1	3	4	1	1
ICMA 96333	3	2	4	3	3	2	5	4	3	4
ICMA 96444	2	3	2	1	2	1	3	3	3	4
ICMA 97111	5	1	2	1	5	2	3	2	4	5
ICMA 97333	2	4	5	5	4	2	3	3	4	3
ICMA 97444	4	2	3	1	3	2	4	3	4	4
MAL 2A	5	5	4	3	3	2	3	2	3	4
MAL 3A	4	3	1	2	5	3	5	3	3	4
ERajPop	3	4	5	2	5	3	5	3	1	1
CZ 44A[1]	4	5	2	3	-	-	4	4	4	4
RMS 3A[1]	3	1	3	1	-	-	2	4	4	5
HMS 6A[1]	3	5	4	2	-	-	4	4	4	3
HMS 9A[1]	4	4	2	1	-	-	2	4	5	3
ERajPop[1]	-	-	-	-	-	-	3	4	4	4

[1]Clusters are based on the severe and moderate stress environments only (1999 and 2000), as the test crosses on these A-lines were not grown in the favourable environments (1998). Cluster numbers for these A-lines are not directly comparable to the cluster numbers of the A-lines listed above in the table (which are based on 1998, 1999 and 2000 data). The cluster number of ERajPop for 1999 and 2000 is included for purposes of comparison, however.

ments include better than average productivity for both grain and stover, with moderate levels of stability and at least average response to better environments (Table 1). Several A-lines evaluated in this study met these requirements. Hybrids made on ICMA 97333, ICMA 93111, ICMA 95555 and ICMA 96333 ranked well for mean grain and stover yields and possessed moderate to high stability for both grain and stover yields (Table 3). Their moderate to high DRI or PNHI (Table 4) may have contributed to their stability. Their responsiveness to favourable growing conditions was also moderate to high (Table 3) making these four A-lines very suitable for moderate stress environments. All the A-lines identified above as suitable for moderate stress environments (Table 5) were able to protect their hybrids from downy mildew, as all of them were grouped in cluster 5 for downy mildew resistance. Hybrids on all of them had no problem is seed set as well (data not presented).

Several other A-lines possessed some, but not all, of the characteristics required for the moderate stress environments. For example, ICMA 88006 produced a TCH with high stover yield, but its performance was highly unstable and its mean grain yield was only moderate (Table 3). The hybrids based on 842A and ICMA 91444 were included in the best two clusters for grain yield with moderate to high stability, but they were very poor either in stover performance or stability (Table 3). Hence these two lines would be desirable for developing exclusively grain hybrids. Similarly, MAL 2A and ICMA 94444 looked more suitable for producing grain type hybrids in view of their clustering for their performance, stability and responsiveness with respect to grain and stover yields (Table 3). ICMA 92666, on the other hand, would provide TCH with high stover yield and stability but was one of the most unresponsive for grain production. Hence this line seems more suitable for developing hybrids that are better in stover production. Hybrids based on ICMA 90111, ICMA 91777 and ICMA 96222 had high stover yield per se (Table 3) but they were among the poorest for stover yield stability (cluster 1 and 2). Moreover their grain yield was poor in the moderate stress environments (Table 3); thus these lines have limited relevance for moderate stress environments.

The remaining A-lines produced hybrids that were not adapted to the moderate stress conditions, as they were included in the lowest two clusters for grain and stover productivity. These included HMS 9A, MAL 3A, ICMA 97111, 5141A, 841A, 843A, ICMA 89111, ICMA 91333, ICMA 96444, ICMA 88004, ICMA 92444, ICMA 94555 and ICMA 95222.

A-lines for favourable environments: Male-sterile lines capable of producing hybrids with high grain and high stover yields with a high degree of downy mildew resistance, are desirable for optimum growing conditions. They should also be highly responsive to better environments and have a high potential productivity to increase profitability and thus encourage the use of inputs. Several lines produced TCHs high biomass and grain or stover yields in the optimal environments; these included 5054A, ICMA 88006, ICMA 92333, ICMA 92444, ICMA 95222, ICMA 94555, ICMA 95444, ICMA 97333 and 81A. Among these, 5054A, ICMA 88006 and ICMA 95222 also produced hybrids that were ranked in the best two clusters for both grain and stover yields (Table 3), and were also highly responsive (except ICMA 95222 for stover yield) for both grain and stover productivity (Table 3). Thus, they should produce high yielding dual-purpose hybrids catering to farmers' needs for both grain and stover.

In contrast to the limited number of A-lines suitable for dual purpose hybrids (above), a larger number of lines looked promising for producing grain type hybrids. The most suitable were ICMA 92333, MAL 3A, ICMA 92444, ICMA 94555 and ICMA 97333, which produced high yielding grain hybrids (Table 3) that responded very well to better growing conditions (Table 4). Four other lines ICMA 96222, ICMA 97111, ICMA 91444 and ICMA 95444 also produced high yielding grain hybrids (Table 3), their response to better environments was, however, moderate (Table 4).

The grain yield of the TCHs of some of the older A-lines such as 5054A, 81A and ICMA 88006, were highly responsive to better environments (Table 3). Their ranking for potential yield was, however, not encouraging, as all produced hybrids that were only grouped in cluster 2 for potential productivity (Table 4). Either high yielding B-line materials were not available in the 1970s and 1980s when these lines were developed, or combining ability for potential productivity of A-lines was not a major selection criterion during their development. It was interesting to note, however, that potential productivity of hybrids based on some of the newly-developed lines (MAL 3A, ICMA 96222, ICMA 97333, ICMA 94555, ICMA 95222 and ICMA 95333) was considerably higher (clusters 4 and 5, Table 4). This suggests that the breeding of new A-lines has focused more on selection for high potential productivity, to increase the profitability and thus the use of inputs.

It was interesting to note that almost all A-lines identified as suitable for the optimum growing environments of the arid zone were included in middle cluster (3) for flowering with mean flowering of 50 days (Table 2). A combination of high grain yield with an

Table 4. Cluster number (5 = highest/best; 1 = lowest/poorest) for TCH of 39 A-lines with the ERajPop TCP, for a set of specific yield component and resistance criteria for which these were evaluated

A-line	Days to flower	Harvest index	DM resistance	DRI drought nursery	PNHI stress trials	Potential grain yield
5141A	2	3	1	2	1	1
5054A	4	3	5	1	1	2
81A	2	2	4	3	3	2
841A	3	4	5	2	1	2
842A	4	4	5	3	5	2
843A	5	4	3	4	5	4
ICMA 88004	3	3	5	5	5	3
ICMA 88006	3	2	5	5	4	2
ICMA 89111	2	2	5	1	2	5
ICMA 90111	1	2	4	2	2	2
ICMA 91333	2	3	5	3	4	3
ICMA 91444	3	3	5	5	3	3
ICMA 91777	1	1	5	2	2	4
ICMA 92333	3	3	5	3	4	3
ICMA 92444	3	4	5	4	3	4
ICMA 92666	3	3	5	4	5	4
ICMA 93111	3	2	5	3	2	4
ICMA 93333	3	3	3	4	4	4
ICMA 94111	3	3	5	3	4	4
ICMA 94222	4	4	5	3	5	3
ICMA 94444	3	2	4	3	4	4
ICMA 94555	3	4	5	2	4	4
ICMA 95111	4	3	5	5	4	2
ICMA 95222	1	2	4	2	3	4
ICMA 95333	1	2	3	4	4	5
ICMA 95444	4	5	5	4	5	2
ICMA 95555	3	3	5	3	3	2
ICMA 96222	3	3	4	4	4	5
ICMA 96333	4	3	5	2	5	5
ICMA 96444	2	3	4	2	4	4
ICMA 97111	4	4	3	5	4	3
ICMA 97333	3	2	5	5	5	4
ICMA 97444	3	4	5	4	4	2
MAL 2A	3	3	1	3	4	4
MAL 3A	3	3	2	3	4	5
ERajPop	4	3	5	3	3	3
CZ 44A[1]	2	3	3	4	4	1
RMS 3A[1]	3	3	5	3	3	1
HMS 6A[1]	2	3	5	5	4	2
HMS 9A[1]	2	2	5	3	3	5
ERajPop[1]	3	3	-	-	-	-

[1]Clusters for harvest index and flowering (only) are based on 5 environments only (1999 and 2000) and cluster numbers for these A-lines are not directly comparable to the cluster numbers of the A-lines listed above in the table (which are based on 1998, 1999 and 2000 data). The cluster number of ERajPop for 1999 and 2000 only is included for purposes of comparison, however. Values for these entries for DM resistance, drought response and potential yield are directly comparable to those of the other entries.

intermediate time of flowering has particular relevance for irrigated arid zone farming, as moderate flowering will optimize the use of water and permits the clearing the land in time for a *rabi* crop. The landrace-based pollinator also was a good restorer for all the suitable lines for optimum growing environments of arid zone with the exception of 81A (data not presented). Fertility restoration in landrace-based TCHs, hence, should not be regarded as a serious limitation in utilization of landraces as pollinators on the lines included in this study.

In high input areas, downy mildew susceptibility is a major limitation with many potentially useful hybrids. In this study, however, only MAL 3A was unable to provide adequate protection against DM pathogen (Table 4); all other lines (Table 5) were effective in protecting their hybrids. The highest downy mildew resistance (cluster 5) was observed in hybrids of 5054A, ICMA 88006, ICMA 92333, ICMA 92444, ICMA 91444, ICMA 94555, ICMA 95444 and ICMA 97333 (Table 4) with mean downy mildew incidence of only 6% (Table 2). Hybrids based on ICMA 95222, ICMA 96222, ICMA 90111 and 81A had moderate levels of downy mildew resistance (cluster 4) with 16% mean disease incidence (Table 2).

Breeding hybrids for the arid zone: This study showed that the suitability of A-lines tested here clearly differed for the three target arid environments within the arid zone (Table 5). As a short-term objective, preferred A-lines can be used to produce suitable hybrids for different target environments and categories of farming systems. In addition, using these A-lines in combining ability evaluations of new topcross (or inbred) pollinators would directly identify potentially suitable hybrids for specific target zones. Further, the B-lines of selected A-lines could be inter-mated and superior progeny selected in the target environment, to create new B-line populations with good adaptation to the various target environments in arid zone. This would be especially valuable for severe stress environments, for which less effort in male-sterile line breeding has been made in the past.

But as a long-term objective, there is need to redefine pearl millet breeding goals for arid zone environments. While it is clear that a major increase in millet yields can only occur through development of high yielding cultivars, supported by higher input management systems, breeding for a quantum yield increase under a high input management is not a realistic objective in the stress environments of arid zone, under both current and foreseeable conditions. For this target environment, the major breeding objective should be to improve yield stability, at a somewhat

Table 5. A-lines best meeting the requirements of the individual target environments within the arid zone, based on cluster ranks of the TCHs produced by the A-lines for traits considered most important for each target environment

Target environment	Most useful A-lines for the target environment
Extreme stress environments	ICMA 93111, ICMA 94555, ICMA 95111, HMS 9A, CZMS 44A, ICMA 92333, HMS 6A, ICMA 95333, 842A, ICMA 95444, ICMA 97111, ICMA 97444, 843A
Moderate stress environments	ICMA 97333, ICMA 93111, ICMA 95555, ICMA 96333, 842A, ICMA 91444, ICMA 92666
Favourable environments	5054A, ICMA 88006, ICMA 95222, ICMA 92333, ICMA 92444, ICMA 94555, ICMA 97333, ICMA 96222, ICMA 97111, ICMA 91444, ICMA 95444

higher yield level than the existing one, by selecting early segregating material, in the target environment, for development of adapted hybrid parental lines. This approach will also require greater interaction with farmers themselves at various stages of selection process, to assure that the lines selected meet farmers' needs. An early and continuing, interactive relationship with farmers will substantially reduce the time necessary to arrive at appropriate material that is well adapted to the target environment and to farmers' needs.

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