Sorghum (Sorghum bicolor) research in India

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ABSTRACT

Sorghum (Sorghum bicolor (L.) Moench) research significantly contributed towards the Green Revolution in dryland areas. The compound growth rate per annum (3.22%) of its productivity (yield/ha) between 1967-68 and 1980-81 is commendable which surpassed the population growth rate in India. This compound growth rate in productivity progressed further @ 1.90 between 1980-81 and 1994-95 over and above the productivity achieved in 1981-82 base year. These rates have further significance as there had been negative growth rate in area where 5 million ha of its assured rainfall and deep soil area was diverted to the oilseeds (sunflower, soybean and castor), pulse (green gram) and cotton. Hence while strong research base of sorghum could enable enhanced production of 11 million tonnes from much reduced area of 12.6 million ha compared with early sixties area of 18 million ha and production of 9 million tonnes, its sparing of 5 million ha area to other crops profoundly helped the country to meet its additional requirement of oilseeds, pulses and cotton and obviously saving of foreign exchange both in terms of less oilseed import and more export of cotton.

Key words: sorghum, hybrid, growth rate, germplasm resources, crop improvement, production, physiology, protection

Sorghum (Sorghum bicolor (L.) Moench) in India represents about 30% of world acreage and 83% that of in South-East Asia. It is a major dryland cereal grown as a dual-purpose crop for food, feed and fodder primarily in Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Rajasthan, Tamil Nadu, Uttar Pradesh and Gujarat. Dual-purpose sorghum is grown both during the rainy season (kharif) (7 million ha) as well as winter season (rabi) (5.6 million ha). Rabi sorghum is grown under receding moisture condition leading to terminal drought in a contiguous areas spread in Maharashtra, Karnataka and Andhra Pradesh where winter is relatively warmer. Besides, it is primarily utilized as a green-forage crop in northern India to sustain its large cattle population for agriculture and dairy industry. A rough estimate of this additional area is about 3 million ha.

GERMPLASM RESOURCES

Sorghum originated in East Africa with its secondary centre of origin in India. Due to its wide range of adaptation in tropical and temperate climates and free gene exchange among various races, the crop is endowed with wide range of variability. Initial efforts to collect local germplasm in India supplemented by germplasm collected from Africa and the USA was intended to augment the breeding process. Over 10,000 genetic stocks from 44 countries were assembled at the IARI, New Delhi, with the assistance of Rockefeller Foundation and evaluated during 1963-67. Systematic efforts were made to catalogue and classify them. Though collection of germplasm from all over the world remained an objective, study of variability, classification and description-based genetic criteria and preparation of a catalogue of vegetative, reproductive and other attributes of each genetic stock were the major objectives. Based on biometrical classification, sorghum germplasm could be divided into 9 major categories, which corresponded with the major groups as outlined by Snowdon in his early classification in 1936. Grain characters of about 12,000 entries were subsequently catalogued and germplasm lines with desirable alleles for seed characters were identified. These 12,000 varieties were also screened for resistance to shootfly and stem-borer and selected 322 lines for midge. Based on repeated field screening, 20 lines were identified resistant to shootfly, 26 resistant to stem-borer and 22 tolerant to midge.

Indian tropical varieties though tall and photosensitive, possess valuable dominant genes for yield and plant height, and resistance to shootfly and stem-borer, bold grain and high biomass productivity but low harvest index, whereas temperate cultivars, though dwarf possess valuable dominant genes for earliness, and photo-insensitivity.

The entire germplasm collection which was assigned International Sorghum (IS) numbers from 1 to 16,676 available with All-India Co-ordinated Sorghum Improvement
Project (AICSIP) was handed over to the International Crop Research Institute for Semi-Arid Tropics (ICRISAT), Hyderabad, in 1974. By 1995, the ICRISAT had 37,359 accessions in its germplasm bank.

CROP IMPROVEMENT

Varietal improvement before sixties

Most of the varieties till sixties were the result of pureline selection practised in local land races. The hybridization and selection up to a limited extent among improved land races could not bring genetic improvement to a perceptible level but basic traits for local adaptation were preserved. In spite of the availability of more than 100 improved strains the yield levels remained low, representing marginal increase of 10–15% over the base populations. Notable among the varieties developed during this period and cultivated till recently are the CO series in Tamil Nadu; the Nandyal (NJ), Guntur (G) and Anakapalle series in Andhra Pradesh; PJ rainy season (kharif) and winter season (rabi) selections, Saonar, Ramkel, Aispuri, the Malandangi and Dagadi (compact headed) selections in Maharashstra; Bilichigan, Fulgar (rabi selections), white, Fulgar Yellow, Kanvi, Nandyal, Hagari and Yanigar varieties in Karnataka; Budh Perio (BP 53), Sundhia and Chasatio in Gujarat; selections of Gwalior and Indore in Madhya Pradesh; RS selections in Rajasthan and a few others. The local cultivars for specific uses (popping, parching, sweet grain and papad making) were also identified. Their continued cultivation in spite of low yields was due to local preference for taste and lack of exposure to wide genetic diversity existing elsewhere and lack of utilization of novel genes to evolve more productive forms.

Growing these cultivars under low management though provided an insurance against risk of insect and diseases, kept the sorghum production at subsistence level. These cultivars have greater survival value, high risk coverage and low productivity. Under adequate moisture and low population, these cultivars may produce large ears reflecting their individuality but their performance under high plant density remains poor. Due to longer duration, crop losses approach to the failure in the years of low rainfall and early cessation of rains. Under low plant population these varieties behaved as grain type and under high plant population as fodder type.

Without conceptual change in the existing plant-breeding programmes in individual states, the new varieties evolved till sixties were similar to locals in plant architecture. The research aptitude during those days was towards low yield-low risk. As the small productivity gains are masked by weather aberrations under rainfed agriculture, a breakthrough was anticipated by bringing large quantum jumps rather than lagging productivity gains.

Genotypic alteration as a foundation of progress

The potentiality of local cultivars to produce the total dry matter is quite high, but unjudicious partitioning of biological yield into economic yield limits their utility in input-intensive agriculture. Excessive height, longer duration and low harvest index of local cultivars provided the poor plant framework unamenable to achieve quantum jump. Therefore optimization of crop growth matching with seasonal conditions provided a leading principle to maximize the yield level.

In contrast to tropical cultivars, temperate ones are dwarf, early maturing and high in harvest index. As wide range of germplasm could be available in India during the sixties, the gene transfer from temperate germplasm to tropical cultivars through hybridization was possible to bring genotypic alteration in yield-limiting factors of local cultivars.

Exotic dwarfs (caffrorum, caffrorum-feterita and shallu) and Indian tall parents used in sorghum improvement represented 2 extremes for height, maturity and panicle shape.

The crosses among these 2 groups of parents were non-heterotic and posed difficulty in recombining the components of long and compact panicles.

Desirable recombination between parents having the main differences in either height or maturity was anticipated. The F₁ superiority and increased additive genetic variance in long panicked temperate x compact panicked tropical crosses for most of the panicle characters related to yield indicated the possibility of reinforcement of the components of long and compact panicles. It gave an indication that tropical varieties from African countries may provide an alternative in varietal improvement.

Further study involving large number of parental genotypes and their derived advanced generation progenies of temperate x tropical crosses established a curvilinear relationship of plant height with grain yield and flowering with grain yield where days to flower contributed 72% variation in grain yield. This led for a computer simulation to optimize the height and maturity to maximize the yield. A conclusion was drawn that productive progenies can be obtained at height of 175–180 cm, flowering at 68–70 days and with reduced leaf numbers. This phenotypic optimum which is an intermediate optimum was greatly helpful in sorghum breeding in India, since subsequently evolved most popular hybrids pertain to this optimum combination of height and flowering conferring the wider adaptability. The model imposes restriction on the vegetative phase by controlling plant height and time to flower and consequently improves the grain : straw ratio. Such varieties would mature in 105–110 days and match the duration of normal rainy season (July–September) in the major sorghum-growing tract. Consequently, it ensures higher productivity and stability of production due to matching crop-growth period with the length of growing season.

Conventional pedigree, bulk and backcross methods were extensively used. Single crosses limited the exploitation of variability, low recombination and quick fixation of linkage
blocks due to inbreeding in segregating generation. The re-
combination can be enforced through intermatting in pop-
ulation improvement programmes or by adopting multiple
crosses. The utility of such crossing in self-pollinated crops
was questioned, since the extent to which it disintegrates
the natural gene complexes, the characteristic of self-pollinated
species, is not known precisely.

Performance of first phase of varieties: Besides release
of 'Swarna’ (‘CSV 1’), a pureline selection from ‘IS 3924’
in 1968, 6 more varieties derived from temperate x tropical
crosses were released in first phase in 1974.

‘CSV 1’, ‘CSV 2’ and ‘CSV 3’ are early maturing (100–
105 days), and tend to yield 138–207% higher than locals.
‘CSV 4’ and ‘CSV 5’ are relatively dwarf varieties, mature
in 110–115 days during rainy season (kharif) and combine
excellent grain quality, tan plant pigment, resistance to grain
deterioration even when caught in rains and resistance to
most of the leaf diseases, downy mildew and striga. These
furnished the male parents of commercial hybrids released
subsequently. ‘CSV 6’ is a relatively tall (220 cm) variety
and highly tolerant to shootfly and stem-borer. ‘CSV 7R’ is
particularly adapted to early winter season planting and
yielded higher than locals.

Development of multiple resistant dual-purpose vari-
eties: Genetic enhancement and recombination of multiple
resistance in high-yielding background gained the major pri-
ority from the lesson learnt after the introduction of varie-
ties and hybrids released in sixties and early seventies, and
transformation of tropical late-maturing cultivars into more
productive short-duration forms. Though new varieties could
demonstrate high yield gains over locals, one of the imme-
diate consequences was grain deterioration due to grain
maturity coinciding with late rains reducing the food qual-
ity of grain and profitability. Increased susceptibility to
shootfly, leaf-spot diseases and reduction in fodder yield
due to short stature were also immediately experienced.

These factors reflected on the acceptability of the new varie-
ties by the farmers. Introduction of these early-maturing
cultivars also accentuated midge damage on late locals
particularly in Maharashtra which became the management
problem but helpful in replacing late local varieties by early-
duration cultivars. Shootfly could be managed by recom-
mending early planting in kharif but remained a challeng-
ing problem in rabi. Hence research on genetic basis of re-
sistance to major pests, eg shootfly and stem-borer, and ma-
jor diseases, eg leaf-spot diseases, grain moulds, downy mi-
dew and charcoal rot, were intensively carried since mid-
seventies and incorporation of resistance to these biotic
stresses.

Once excessive height and maturity was corrected, the
intermediate derivatives served as bridge population for fa-
vourable gene transfer. The sources of resistance to grain
mould and leaf diseases were located in Zerazera germplasm
from Ethiopia. Mechanism of resistance was studied and
resistance was consciously transferred in high-yielding back-
ground. The resistance to these diseases was located in ‘CS
3541' which is a dwarf derivative of ‘IS 3541’, a Zerazera
from Ethiopia. Tan plant pigment conferring resistance to
most of leaf diseases was discovered and incorporated in
kharif nurseries. This became our innovative contribution
in various states, the production potential of ‘CSV 15’ got
confirmed (Fig 1, top right). Besides these all Indian releases,
number of varieties were released with specific adaptation’
to states.

<table>
<thead>
<tr>
<th>Hybrid or variety</th>
<th>Year of release</th>
<th>Grain yield (kg/ha)</th>
<th>Fodder yield (kg/ha)</th>
<th>Plant height (cm)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'CSV 1'</td>
<td>1964</td>
<td>3 020</td>
<td>7 500</td>
<td>150</td>
<td>95-100</td>
</tr>
<tr>
<td>'CSV 5'</td>
<td>1975</td>
<td>3 414</td>
<td>9 300</td>
<td>174</td>
<td>105-110</td>
</tr>
<tr>
<td>'CSV 6'</td>
<td>1977</td>
<td>3 376</td>
<td>8 100</td>
<td>161</td>
<td>95-100</td>
</tr>
<tr>
<td>'CSV 9'</td>
<td>1981</td>
<td>3 865</td>
<td>9 800</td>
<td>182</td>
<td>105-110</td>
</tr>
<tr>
<td>'CSV 10'</td>
<td>1984</td>
<td>3 633</td>
<td>12 000</td>
<td>233</td>
<td>105-110</td>
</tr>
<tr>
<td>'CSV 11'</td>
<td>1986</td>
<td>3 832</td>
<td>9 700</td>
<td>188</td>
<td>105-110</td>
</tr>
<tr>
<td>'CSV 13'</td>
<td>1991</td>
<td>3 924</td>
<td>14 400</td>
<td>261</td>
<td>105-110</td>
</tr>
<tr>
<td>'CSV 14'</td>
<td>1992</td>
<td>3 840</td>
<td>8 800</td>
<td>181</td>
<td>103</td>
</tr>
<tr>
<td>'CSV 10'</td>
<td>1985</td>
<td>2 836</td>
<td>1 010</td>
<td>194</td>
<td>112</td>
</tr>
<tr>
<td>'CSV 11'</td>
<td>1985</td>
<td>3 211</td>
<td>9 600</td>
<td>174</td>
<td>109</td>
</tr>
<tr>
<td>'CSV 13'</td>
<td>1986</td>
<td>3 402</td>
<td>9 800</td>
<td>172</td>
<td>112</td>
</tr>
<tr>
<td>'SPY 462'</td>
<td>1985</td>
<td>3 308</td>
<td>9 700</td>
<td>208</td>
<td>110</td>
</tr>
<tr>
<td>'CSV 15'</td>
<td>1996</td>
<td>3 600</td>
<td>12 100</td>
<td>232</td>
<td>110</td>
</tr>
</tbody>
</table>
Winter sorghum is grown under unique stored moisture condition over 5.6 million ha in a contiguous belt. Moisture stress, poor soil fertility and susceptibility to shootfly, lodging including charcoal rot and cold are found to be major yield constraints. The progress in varietal improvement in rabi is low due to limited use of scientific resources commendable to the crop area and yield constraints.

Concept of temperate x tropical crosses and kharif (high grain number) x rabi type was also adopted for improvement of rabi sorghum. However, due to difficulties in recombining grain and fodder yields, low translocation in ‘GS 3’, inferior grain quality and susceptibility to biotic stresses equivalent to popular ‘Maldandi’ cultivar, the genetic improvement is limited to the development of few varieties such as ‘CSV 7R’, ‘CSV 8R’, ‘Swati’ and ‘CSV 14R’. All these cultivars possess resistance equal to local ones and marginal advantage in grain yield. The performance of these varieties is given in Table 3.

Hybrid improvement in kharif: The discovery of cyto-

Table 2 Sorghum varieties and hybrids specifically released for cultivation in states after 1970

<table>
<thead>
<tr>
<th>State</th>
<th>Variety or hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh</td>
<td>‘Mothi’ (‘IS 6928’), ‘NTJ 1’, ‘NTJ 2’, ‘N 14’</td>
</tr>
<tr>
<td>Rajasthan</td>
<td>‘SPV 245’, ‘SPV 96’</td>
</tr>
<tr>
<td>Madhya Pradesh</td>
<td>‘SPV 235’, ‘JJ 741’, ‘JJ 938’</td>
</tr>
</tbody>
</table>

Table 3 Performance of rabi sorghum hybrids and varieties presently under cultivation

<table>
<thead>
<tr>
<th>Hybrid or variety</th>
<th>Year of release</th>
<th>Grain yield (kg/ha)</th>
<th>Fodder yield (kg/ha)</th>
<th>Plant height (cm)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘CSH 8R’</td>
<td>1977</td>
<td>2 173</td>
<td>3 675</td>
<td>102</td>
<td>115</td>
</tr>
<tr>
<td>‘CSH 12R’</td>
<td>1986</td>
<td>2 564</td>
<td>4 665</td>
<td>201</td>
<td>115</td>
</tr>
<tr>
<td>‘CSH 13R’</td>
<td>1991</td>
<td>3 260</td>
<td>5 417</td>
<td>184</td>
<td>113</td>
</tr>
<tr>
<td>‘CSH 15R’</td>
<td>1996</td>
<td>3 194</td>
<td>5 570</td>
<td>196</td>
<td>110</td>
</tr>
<tr>
<td>Variety</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘CSV 8R’</td>
<td>1979</td>
<td>2 230</td>
<td>4 791</td>
<td>157</td>
<td>120</td>
</tr>
<tr>
<td>‘Swati’</td>
<td>1985</td>
<td>2 156</td>
<td>5 277</td>
<td>168</td>
<td>117</td>
</tr>
<tr>
<td>‘CSV 14R’</td>
<td>1992</td>
<td>2 270</td>
<td>5 537</td>
<td>165</td>
<td>117</td>
</tr>
<tr>
<td>‘M 35-1’</td>
<td></td>
<td>2 080</td>
<td>6 110</td>
<td>151</td>
<td>119</td>
</tr>
</tbody>
</table>
lems through genetic enhancement and use of improved derivatives. Conversion of known high-yielding derived lines, as female parents was suggested to have greater impact on hybrid performance.

As new CMS and dwarf derivatives became available, further hybrid breeding was based on these genetically enhanced indigenous bred parental lines. ‘CSH 5’ based on ‘2077A’ x ‘CS 3541’ was one such hybrid which brought quantum jump in productivity and qualitative changes in grain mould tolerance. ‘CS 3541’, a dwarf variety, was earlier released as ‘CSV 4’ in 1974 furnished the male parent and thus varietal programme could be precursor of parental line improvement. This parent also resulted in another early-maturing hybrid ‘CSH 6’ in combination of already available ‘CMS 2219A’. These hybrids were released in 1975 and 1976 respectively. ‘CSH 5’ and ‘CSH 6’ became widely adapted in the country with accepted grain and fodder yields, as well as tolerance to grain mounds and leaf diseases as added advantages over ‘CSH 1’.

The next breakthrough was experienced with the release of ‘CSH 9’ (Fig 1, bottom left) by utilizing derivative x derivative combination in the form of a new highly potential ‘CMS 296A’ and already available R line ‘CS 3541’, though number of new CMS and R lines were tried in hybrid combinations. The selection of parental lines was based on per-se performance and combining ability and expression of yield heterosis in long panicle x compact panicle crosses due to the increased number of seeds/primary branch. The hybrid maintained 18–20% more yield than ‘CSH 5’ and ‘CSH 6’ hybrids and became best selling hybrids till to date, with 13 000–18 000 tonnes seed sale per annum.

The hybrids ‘CSH 5’, ‘CSH 6’ and ‘CSH 9’ showed 12, 11 and 28% yield advantage over ‘CSH 1’ and a perceivable superiority in terms of fodder yield and resistance to grain mounds and leaf diseases. With both enhanced grain and fodder yields, these hybrids were considered dual purpose and were widely accepted by the farmers across the country. At this stage, efforts were made to increase grain and fodder yields in hybrids with partial success. ‘CSH 10’, a tall hybrid based on ‘296A’ x ‘SB 1085’ was bred to supplement the fodder production without grain yield advantage over ‘CSH 9’. At this stage the ICRISAT also contributed its first hybrid based on ‘CMS 296A’ bred in the Indian programme which was released as ‘CSH 11’. Though both these hybrids appear to be promising could not find popularity with farmers due to seed-production problem or small seed size and lodging. The yield performance of these hybrids is presented in Table 1.

Since yield level of ‘CSH 9’ has now been plateaued around 4.0 tonnes/ha, further diversification in terms of additional fodder yield and early maturity brought out in the form of ‘CSH 13 (K and R)’. It is adapted to both kharif and rabi seasons and showed an additional 45% dry fodder yield and better mould tolerance than ‘CSH 9’. ‘CSH 14’ is another example of diversification for earliness by 8–10 days. ‘CSH 14’ (Fig 1, top right) bred on a new set of parental lines (‘AKMS 14A’ and ‘R 150’) has been replacing ‘CSH 1’ rapidly due to its 33% higher grain yield and better adaptability.

**Breeding for rabi hybrids:** Two hybrids ‘CSH 7R’ (‘36A x 168’) and ‘CSH 8R’ (‘36A x PD 3-1-11’) were developed and released for rabi cultivation in 1977 and 1978 respectively. ‘CSH 8R’ was under cultivation for few years but due to economic reason, seed-producing agencies could not continue to support it further.

The renewed efforts enabled to develop 2 more hybrids ‘CSH 12R’ and ‘CSH 13R’ in 1986 and 1991 respectively, but both are based on kharif ‘CMS 296A’. The commercial heterosis realized over ‘CSH 8R’ is given in Table 4.

The yield advantage of ‘CSH 13R’ over ‘M 35-1’ noticed in research farms was realized in on-farm trials also. The hybrid is highly tolerant to moisture stress, charcoal rot and leaf-spot diseases and is suitable for both dry and irrigated conditions. Though the hybrid ‘CSH 13R’ for the first time could show the breakthrough in the yield over ‘M 35-1’ (1.8–2.0 tonnes/ha), it does not have adequate level of primary resistance to shootfly and thus required to be planted at conventional time of planting in the first fortnight of October when shootfly population becomes low.

The current breeding programme aims at optimum plant type which should combine resistance to moisture stress, shootfly, charcoal rot and should be capable to rapidly grow under receding temperature, stay green and translocate effectively to sink in ‘GS 3’ under receding moisture condition. Selection for high biomass productivity and harvest index under such a situation may provide a desirable type. In rabi plant height and panicle components (primary branches and 100-seed weight) contribute to yield. However, grain quality lower than popular local ‘M 35-1’ was a highly determinant of acceptability of hybrids by the farmer. With this understanding of rabi-adapted traits, recently number of parental lines were developed and are being utilized in

**Table 4 Commercial heterosis in winter season (rabi) hybrids**

<table>
<thead>
<tr>
<th>Hybrid</th>
<th>Grain yield (kg/ha)</th>
<th>Commercial heterosis (%)</th>
<th>Fodder yield (kg/ha)</th>
<th>Commercial heterosis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>‘CSH 8R’</td>
<td>‘CSH 12R’</td>
<td>‘CSH 8R’</td>
</tr>
<tr>
<td>‘CSH 8R’</td>
<td>2 173</td>
<td>100</td>
<td>85</td>
<td>3 675</td>
</tr>
<tr>
<td>‘CSH 12R’</td>
<td>2 564</td>
<td>118</td>
<td>100</td>
<td>4 665</td>
</tr>
<tr>
<td>‘CSH 13R’</td>
<td>3 260</td>
<td>150</td>
<td>127</td>
<td>5 417</td>
</tr>
</tbody>
</table>
hybrid programme. This programme received impetus recently under the ‘Promotion of Research and Development Efforts on Hybrids in Selected Crops’.

Breeding of rabi-based CMS lines is of recent origin started at the UAS, Dharwad; MPKV, Rahuri, and NRCS, Hyderabad. Two released varieties, ‘SPV 86’ and ‘Swati’, were utilized as rabi base in crossing programmes at these centres resulting in number of CMS lines, ‘53A’, ‘104A’, ‘116A’ and ‘117A’ from Mohol; ‘42A’, and ‘3662 A’ from Rahuri; and ‘2A’, ‘P 5A’, ‘7A’ and ‘9A’ besides ‘SB 323A’ and ‘SB 401A’ from Dharwad. Among these, ‘42A’, ‘104A’, ‘116A’ and ‘117A’ have characteristic rabi plant type with desired seed quality and others towards kharif type. Though all these lines have shootfly-resistant parent in their parentage, they lost shootfly resistance during the course of development except ‘CMS 104A’ which possesses intermediate level of resistance.

On the other hand, varietal programmes provided various tall restorer lines with bold grain and desired level of resistance to biotic and abiotic stresses. Restorer lines, eg ‘RS 585’, ‘RS 615’, ‘SPV 492’ and ‘SPV 727’, in addition to ‘M 148-138’ were used in most promising hybrids. All these being tall, result in tall hybrids due to dominance interaction and ensure adequate fodder yield, intermediate level of shootfly resistance and acceptable grain quality.

Present emphasis is on development of hybrids on rabi-based CMS and restorer lines. The most promising hybrids presently in advance testing are ‘SPH 606’, ‘SPI 634’, ‘SPH 677’, ‘SPH 695’, ‘SPI 922’, ‘SPI 1010’ and ‘SPI 1026’.

The hybrid ‘SPI 677’ for the first time was developed on rabi CMS and R lines from a cross ‘104A’ x ‘RS 585’ jointly by the NRCS and MPKV. Both lines being bold-seeded with 1000-seed weight 32 and 35 g respectively, the hybrid also has bold grains. Based on 3-year performance, it was found 22% superior to popular variety ‘M 35-1’ and 11–22% better than released and experimental hybrids. The hybrid is also tolerant to shootfly. Based on overall performance, this hybrid was released as ‘CSH 15R’ in 1995 for Maharashtra, parts of south–east Karnataka and adjacent parts of Andhra Pradesh. During 1995–96 the performance of ‘CSH 15R’ and ‘CSH 13R’ over 14 locations in 3 major rabi-growing states was 2730 kg/ha compared with 2377 kg/ha yield of ‘M 35-1’ (control). Other hybrids such as ‘SPI 606’, ‘SPI 634’, ‘SP 641’, ‘SP 695’ with marginal yield superiority of about 11% over ‘M 35-1’ were low in shootfly tolerance.

Under irrigated condition, the hybrid ‘CSH 15R’ and ‘SPI 695’ were significantly superior in yield to ‘M 35-1’. Additional resistance to leaf-spot diseases and aphid is required to suit irrigated condition in rabi. Presently, ‘CSH 13R’ under high-input management (80–120 kg N/ha and 2 irrigations) gave a yield of 4.2 tonnes/ha, which will retain its competitiveness with other rabi crops. The average increase in grain yield under irrigation over unirrigated condition was 1.1 tonnes/ha.

Specific adaptation of hybrids to Maharashtra and Karnataka was observed, since low temperature in Maharashtra affects the fertility restoration in hybrids, and therefore performance of ‘CSH 13R’ and ‘SPI 634’ was better in Karnataka and Andhra Pradesh than in Maharashtra. If hybrids with higher shootfly resistance are to be bred in future, both CMS and restorer lines should be highly resistant and R lines fully fertility restoring under low temperature. Current approach involves diversification of varietal maturity (100–115 days) to suit soil depth (0.45m –1.0 m)-based moisture regime under which rabi sorghum is grown. Early-maturing variety ‘Sel 3’ and hybrid ‘SPI 922’ specifically adapted to shallow soil regime.


Some of these lines are being used in land race-based hybrids but future success will depend on evolving genetically diverse CMS and restorer lines and exploitation of additive and non-additive gene actions in hybrid combinations to bring genetic improvement in required characters over and above recently released hybrids. Male parents of test hybrids ‘SPI 1010’ and ‘SPI 1026’ showed such improvement.

Adoption rate of high-yielding variety, certified seed production and impact on productivity

The advent of hybrid technology and assured quality seed supply were instrumental in the large-scale adoption of kharif hybrids. Area under high-yielding variety was gradually increased from 0.18 million ha in 1966–67 to 1.31 million ha (8.1%) in 1974–75 and 3.05 million ha in 1980–81. Since 1975–76, there has been a constant increase in the total area up to 1990–91. In spite of fall in total acreage under sorghum cultivation from 15.8 million ha in 1980–81 to 11.6 million ha in 1995–96, the adoption under high-yielding varieties increased to 7 million ha. The acceleration in coverage is associated with the release of new hybrids in the past. Though initial coverage started with ‘CSH 1’ released in 1964, other significant increases were stimulated by the release of ‘CSH 5’ and ‘CSH 6’ in mid-seventies and later by the release of ‘CSH 9’ in early eighties.

There has been skewness in adoption rate in various states. The coverage under high-yielding varieties was rapid in Maharashtra, Karnataka and Tamil Nadu. Presently, highest adoption is in Tamil Nadu (90%), Maharashtra (72%).
Fig 1 Varieties and hybrids of sorghum. Top left, ‘CSV 15’, a dual-purpose, rainy-season variety, is gaining popularity among farmers because of its high yield, adaptability and resistance to grain moulds; bottom left, ‘CSH 9’ is a popular hybrid in the country with more than 13 000 tonnes seed sale per annum. It shows superiority to all the earlier hybrids in grain and fodder yields and grain quality as well as resistance to leaf disease; top right, ‘CSH 14’ is a rainy-season hybrid, bred on a new set of parental lines. It gives 33% higher grain yield and shows better adaptability than ‘CSH 1’; bottom right, ‘SPV 462’, a rainy-season variety, gives grain yield of 3 308 kg/ha and fodder yield of 9 700 kg/ha.
Madhya Pradesh (65%), Andhra Pradesh (46%) and Gujarat (41%). The high-yielding varieties area in Karnataka is not growing beyond 30% due to sharp reduction in kharif area. The coverage in Maharashtra was 4.03 million ha in 1992-93 and most of it is expected to be in kharif season.

Based on the seed produced by State Seed Corporations in 1995–96, the hybrid ‘CSH 9’ has emerged as best selling hybrid in the country with its 75% share (13,780 tonnes). ‘CSH 5’ is another hybrid with production of 2,070 tonnes. Among early hybrids, ‘CSH 14’ with 1,117 tonnes and ‘CSH 6’ with 805 tonnes are important. The commercial production of ‘CSH 1’ declined due to its replacement by ‘CSH 14’. The production of ‘CSH 13’ has recently been started.

Area under kharif sorghum is constantly at decline, reducing from 10.25 million ha in 1974–75 to 6.86 million ha in 1994–95. However, area under rabi cultivation is fairly constant. This resulted in 3.56 million ha decline in area over 2 decades as a consequence of low competitiveness of kharif sorghum due to reduction in per caput consumption in rural and urban areas, grain deterioration in kharif, option of growing more remunerative crops (soybean, sunflower, greengram and cotton), low minimum support price declared by Government of India and gap between farmers and potential yields. In spite of it, total production increased from 6.11 to 7.51 million tonnes in kharif, 2.72 to 3.63 million tonnes in rabi during the same period of time, realizing a total increase from 8.83 to 11.14%, ie 26 million tonnes increase in production over 2 decades. Between 1974 and 1994, this gain is particularly due to increase in productivity from 598 to 1,093 kg in kharif and 454 to 639 kg in rabi.

The all-India average yield from 546 kg in triennium ending (TE) 1968–70 to 1,097 kg in TE 1992–94, whereas yield (kg/ha) in major sorghum-growing state Maharashtra increased from 587 kg to 1,542 kg between TE 1968–70 and 1992–94.

**Nutritional quality**

The quality of sorghum grain is slightly inferior (protein 10%, lysine 2%) than other cereals which led research for improving lysine content utilizing 2 Ethiopian high-lysine sorghum genotypes (‘IS 11167’ and ‘IS 11758’). It was possible to derive high-yielding dwarfs, early-maturing, photoinensitive selections, combining high level of protein (13.5%) and lysine (2.7–3%). The high lysine content of 3% could be recovered in shrivelled seed genetic background in ‘N 81’, ‘N 92’, ‘N 93’ and ‘N 94’. However, a moderate level of lysine (2.3–2.5%) could be recovered in plump seed background in some selections such as ‘N 19’, ‘N 49’, ‘N 55’ and ‘N 59’. Recently, high-lysine content could be recovered in 16 shrivelled grain mutants produced by using mutagens like ethyl methane sulfonate, nitrosomethyl urea.

**Cytoplasmic diversity**

The milo cytoplasm discovered in the USA was intensively utilized in the development of CMS lines. Virtually all the released hybrids are presently based on this cytoplasm and whose diversification led to the identification of Indian source of cytoplasm such as Malandadi (M 31-2A and M 35-1A), VZM sources (VZM 2A) and Guntur source (G 1). A similar set of different cytoplasm (A2, A3 and A4) was identified in the USA with consequent redesignation of milo cytoplasm as A1. These Indian and American cytoplasm were characterized. The fertility restoration decreases in succession from A1 to A4, the A2 being mildest compared with A3 and A4. The recent work on restoration enabled development of about 34 breeding lines with a wide range of plant height and maturity. The hybrids involve A, B and R. However, the genotype and environment interaction identified with A2 cytoplasm enabled production of hybrid based on 2 lines also where a maintainer line becomes sterile in winter and fertile in summer.

**Biotechnology: tissue culture and protoplast system**

Using the tissue culture system, the NRCS has already produced somaclones for desirable economic characters. A very efficient, rapid and reproducible tissue culture system was standardized. Using any of the ex-plants like mature seeds, immature seeds, immature inflorescences, leaf base and shoot tips, rapid friable, embryogenic callus could be obtained in almost all types of genotypes. The medium for induction of embryogenic callus is LS 2.5. Similarly, efficient regeneration could be obtained, irrespective of the genotype either in MS or in N6 using 3-week-old calli. Standardization of protoplast system is essential for utilization of any of the transformation techniques in a more efficient manner than other alternative methods especially in cereals. The mesophyll protoplasts can be used in combination with suspension-derived protoplasts in somatic hybridization. This provides a method for inter-varietal, inter-specific and inter-generic transfer for desirable characters. At present, serious attempts are being made with partial success in the standardization of a reproducible protoplast system. Embryogenic callus and suspensions could be obtained so far.

**Alternate uses of grain and stalk**

Sorghum grain in India is primarily used as food, but it is used as feed in other countries. The kharif sorghum may provide a cheap source of feed for poultry and cattle industry as well as raw material for industrial starch and alcohol production. The PKV, Akola, already perfected the liquid glucose-and alcohol-production technologies and provides consultancy to set up industries. The purity of alcohol produced from sorghum is more than that from other sources.

**Sweet sorghum:** In order to diversify the uses and make the sorghum production more remunerative, research to develop sweet-stalked sorghum was initiated almost 2 decades back with the ICAR support at Research Institute, Phalton, and at SAUs and more recently at the NRCS. A sweet-stalked variety ‘SSV 84’ was released in 1992 with 51.4 tonnes/ha.
green cane yield, 17.8% brix content, 1.88 tonnes/ha CCS, and 1.364 kg/ha grain yield. This variety may be utilized for raw sugar (jaggery) production due to crystallization problem. Such sorghum can be grown as rainfed crop in areas where sugarcane cannot economically be produced. With the ethanol-production technology now available from grain and juice of sweet sorghum, whole plant utilization has now become possible to gain higher returns from sorghum.

Among the genotypes currently under multilocation test ‘AKSS 15’ and ‘AKSS 16’ with total sugar (TS) index 1.44 and CCS 1.43 tonnes/ha are promising. In IVT, ‘RS 608’ with 1.525 tonnes/ha TS index and 1.73 tonnes/ha CCS was found most promising. Other promising varieties were ‘GCSV 236’ and ‘RM 48’ with TS index 1.52 and 1.46 tonnes/ha respectively compared with 1.29 tonnes/ha TS index in ‘SSV 84’. The genotypes ‘RS 608’, ‘GCSV 238’, ‘RM 48’, ‘NSS 102’ and ‘AKSS 21’ were suitable for ethanol production; from their stalk juice 15.0-15.5% ethanol was recovered from them.

Forage sorghum: The average yield in the demonstration plots at farmers’ fields was 40-50 tonnes/ha green fodder with best yield up to 60 tonnes/ha. The forage sorghum varieties developed before the seventies includes ‘Hundi’, ‘Nilva’, ‘CO 11’, ‘Impi Jowar’ and ‘Vidisha 60-1’. The genetic studies on various aspects carried out at the CCS HAU, Hisar, provided sound basis for genetic improvement of forage sorghum in India. With the start of All-India Co-ordinated Project, there was a growing interest to develop widely adapted varieties for all sorghum-growing regions. As a result of accelerated efforts on genetic improvement in green- and dry-fodder yields, quality and resistance to biotic and abiotic factors, a number of single-cut varieties released. Initially ‘JS 20’, ‘JS 263’, ‘JS 29/1’, ‘MP Chari’ in 1973 and ‘SL 44’ in 1976 were released for north-western region but other varieties such as ‘Haryana Chani’ (‘JS 73/53’) and ‘Pusa Chari 1’ were released in 1976 and ‘Methi Sudan’ (‘SSG 59-3’) in 1978 for all sorghum-growing regions of the country.

Subsequent improvement in green- and dry-fodder yields, quality and resistance to leaf-spot diseases and stemborer resulted in the release of various varieties for all-India cultivation. Among them, green-fodder yield of ‘RC 2’, ‘UP Chari 1’ and ‘UP Chari 2’ varied (33-38 tonnes/ha). The yield potential of ‘HC 136’, ‘HC 171’, ‘HC 260’, ‘PC 6’, ‘PC 9’, ‘PC 23’ and ‘RC 1’ is much higher (45-55 tonnes/ha) which made them more popular and acceptable. Of them, ‘HC 171’ is a tan-pigmented and resistant to leaf-spot diseases. Besides these, ‘Jawahar Chari 6’ and ‘Jawahar Chari 69’ for Madhya Pradesh; ‘K 7’ for Tamil Nadu in 1982; ‘Pant Chari 3’ and ‘Pant Chari 4’ for Uttar Pradesh; ‘MKV Chari 1’ and ‘MKV Chari 2’ for Marathwada were also released after 1991. Recently ‘S 308’ was released in 1995 for all sorghum-growing regions, with green-forage yield of 49 tonnes/ha, dry-fodder yield of 145 tonnes/ha and tolerance to various leaf-spot diseases. There was constant emphasis on enhancing seed yield in this programme.

Among the multicut varieties, ‘Meethi Sudan’ (‘SSG 59-3’) is the most popular owing to its high regeneration capacity, profuse tillering, thin stem and high yield potential (green forage 75 tonnes/ha, dry fodder 21 tonnes/ha) in 4-5 cuts. ‘Pusa Chari 23’ (‘PC 23’) is also a Sudan grass variety with 55 tonnes/ha green-fodder yield. Multi-cut hybrids were introduced in nineties with the release of ‘Proagro Chari’ (‘X 988’) in 1992, ‘MFSH 3’ in 1993 and ‘Hara Sonae’ (‘855 F’) in 1995 by private sector. The average green yield of these hybrids in 3-4 cuts is 60-70 tonnes/ha. For all-India cultivation, the first public sector hybrid ‘PC 106’ (‘CMS 2219 A’ x ‘PC 23’) was recently released (October 1996) which yields 70 tonnes/ha green fodder in 3-4 cuts. It has sweet stalk and tolerance to foliar diseases. The state releases of multi-cut forage sorghum include variety ‘GFS 1’ for Gujarat and hybrid ‘Punjab Sudax Chari 1’ released in 1995 for Punjab. This hybrid yields 70-75 tonnes/ha green fodder under irrigated condition. Efforts on multi-cut sorghum x Sudan grass hybrid breeding may be more rewarding in future owing to commercial interest of seed sectors to produce and supply the seed in constraint to limited interest, in seed production of varieties. There is further need to develop tan plant type hybrids to ascertain resistance to leaf-spot diseases.

Genetic enhancement for pest resistance

Significant progress was made in identifying sorghum genotypes resistant to one or more key pests or diseases. This approach conferred considerable stability in sorghum production. Using these altered genotypes as the basis, both varietal and hybrid improvement programmes are presently oriented towards incorporation of greater levels of resistance against key pests and diseases to further enhance the levels of stability in production. It was only from the late sixties onwards that host-plant resistance was given major emphasis as a control tactic. A concentrated effort to identify potential resistant germplasm accessions and transfer in good agronomic background by strengthening multiple resistance in high-yielding varieties and hybrids was initiated. Promising resistant sources as well as derivatives possessing multiple resistance not only to insects but also to diseases were utilized in the breeding programmes.

Shootfly: Promising sources identified as resistant to shootfly were found potential and stable across locations (‘IS 1054’, ‘IS 1055’, ‘IS 1151’, ‘IS 2123’, ‘IS 2146’, ‘IS 2312’, ‘IS 4664’, ‘IS 5469’, ‘IS 5490’, ‘IS 5604’, ‘IS 5613’, ‘IS 8315’, ‘IS 18551’). Breeding programmes utilized them as donors to incorporate resistance in a good agronomic background. A greenhouse cage technique was developed for rearing and critical evaluation. Simultaneously, the mechanism of resistance as well as the morpho-physiological and biochemical traits associated with resistance were also studied. Antixenosis was found to be the predominant mechanism,
followed by low levels of antibiosis. Short and pointed trichomes and glossy leaves alone or in combination are less preferred for oviposition by shootfly females. Antibiosis to larval hatch is attributed to such factors as hindrance by leaf trichomes for larval movement, greater silica deposition and cell lignification and some biochemical deficiency in the leaves for causing damage and its growth and development. Resistance was partially dominant and dominant under low and high infestation conditions respectively. Antixenosis for oviposition was a low heritable trait. Additive genetic variance was noticed for deadhearts, while tillering consequent to deadhearts was controlled by non-additive genes. Monogenic recessive and 2 duplicate recessive genes were found governing antixenosis for oviposition and deadhearts respectively. Understanding from these studies greatly aided in utilizing them in the development of commercial sorghum cultivars. Morphological traits such as glossiness and trichomes are correlated characters and governed by single recessive genes.

**Stem-borer:** By screening world sorghum germplasm accessions, few sources and mechanisms of resistance were identified. Only modest levels of resistance to stem-borer are known in 'IS 1044', 'IS 1054', 'IS 2123', 'IS 2205', 'IS 5613', 'IS 8315' and 'IS 18551', but they are tropical in origin and exceptionally tall, late maturing, susceptible to lodging, photo-sensitive, low yielding and poor in harvest index. Antibiosis is considered as the predominant component of resistance with low levels of antixenosis. However, greater levels of tolerance to stem tunneling was incorporated into the commercial grain sorghum cultivars.

Inheritance has been found polygenic and partially dominant over susceptibility. Resistance to foliar damage is controlled by additive and additive x additive genes; deadhearts by additive and non-additive genes; stem tunneling predominantly by additive genes and to a lesser extent by non-additive genes; and number of holes and length of tunneling by non-additive genes.

**Midge:** Varietal resistance to midge began in mid-sixties. Few sources of resistance were identified, viz 'DJ 6514', 'IS 2579C', 'SGIRL-MR 1', 'IS 2664C', 'AF 28', 'TAM 2566' and 'IS 12666C'. Among them, 'DJ 6514', and 'AF 28' were found stable and compatible for resistance. Short and tight glumes which remain closed during anthesis, conferred resistance. Inheritance is governed either by more than 1 gene or 2 recessive pairs of genes and dominance and additive x additive gene effects. Both 'DJ 6514' and 'AF 28' were extensively used in the resistance breeding programme and as a result 'DSV 3' was identified, possessing high degree of stable resistance and released in Karnataka, and is being extensively cultivated in midge-endemic areas there.

**Head bug:** Few germplasm accessions were identified possessing high degree of resistance to head bug infestation and population build-up, viz 'IS 17610', 'IS 17645' and 'IS 21444'. However, these genotypes are late flowering and agronomically poor for their utilization in the programme.

**Genetic enhancement for disease resistance**

Promising sources of resistance identified were tested for their stability across locations in multilocation-testing programme in the AICSIP by utilizing the hot-spot locations. In order to detect the virulence among the pathogen races, national sorghum disease nurseries were established, where 'E 35-1' was found resistant to many diseases, including grain moulds. Similarly, an Australian line, 'QL 3' from downy mildew nursery bred for sugarcane mosaic virus resistance has shown immunity to downy mildew. These sources were utilized extensively in the breeding programmes.

Grey leaf spot susceptibility is dominant, while the resistance is governed by a single gene; charcoal-rot resistance being a polygenic threshold character is partially dominant and governed by duplicate epistasis genes with low heritability. However, the stalk infection (%), number of nodes crossed and susceptibility index of charcoal rot are governed by high degree of dominance, and lodging is governed by recessive genes in spite of frequent dominant genes. While the grain mould resistance is governed by both additive and non-additive genes. Downy-mildew resistance is dominant and governed by 3 or 4 genes, rust resistance by 1 or 2 genes and 3 major genes, but susceptibility is dominant; zonate leaf-spot resistance being dominant is governed by 3 genes: sooty stripe susceptibility was partially dominant with a single pair of recessive gene conferred resistance.

**Sources of resistance:** The sources available for different diseases are: grain moulds ('IS 3443', 'IS 3547', 'IS 14332', 'IS 10892', 'IS 14380', 'IS 24995', 'IS 24996', 'E 35-1', 'RSP 48-1', 'RSP 49-1', 'GMRP 8', 'GMRP 9', 'GMRP 26', 'GMRP 27', 'GMRP 44', 'GMRP 55', 'GMRP 56' and 'RS 29'); charcoal rot ('E 36-1', 'Q 1014', '296B', '2219B', 'RS 29', 'CRP 3', 'CRP 4', 'CRP 11', 'CRP 22', 'CRP 25', 'CRP 27', 'RSCR 6-3-1', 'RSCR 7', 'RSCR 12'); downy mildew ('IS 27042' ('DMRS 1'), 'QL 3', 'CS 3541', 'IS 3443', 'IS 18757', 'IS 22230', 'IS 22231', 'IS 27042'); ergot ('IS 3443', 'IS 3547', 'IS 14332', 'CS 3541', 'SRT 18B', 'SRT 26B'); rust ('IS 8185' and 'IS 14322', 'E 36-1' and 'RS 29'); foliar diseases ('IS 3443', 'IS 3546', 'IS 8283', 'IS 18758', 'SB 401B', 'SRT 18B' and 'RS 29')

**Multiple disease resistance:** Multiple disease resistance to grain moulds, charcoal rot, ergot and foliar diseases was reported in 'IS 3443', 'IS 3547' and 'IS 14332'; downy mildew, sugary disease, rust and grain moulds in 'CO 25', 'TNS 23' and 'TNS 28'; grain mould. downy mildew, rust, anthracnose, zonate leaf spots, ergot and charcoal rot in 'IS 3443', 'IS 3547', 'IS 8283', 'IS 14332', 'SB 1089' and 'CSV 4'. Similarly, other sources were identified for various diseases include 'IS 7528', 'IS 8185' and 'IS 8283'.

**Striga management**

In India, *Striga* causes crop loss of 15–100% depending on the severity. Low fertility and good drainage in deep Vertisols promote greater establishment of *Striga*. A striga-
resistant variety, 'CO 20' was developed using an africana resistant line, 'Bonganahilo'. Subsequently, few other Sfriga-resistant lines were identified, viz 'SPV 168', 'SPV 103', 'SPV 221', 'SAR 1' and 'SAR 2'. Low-stimulant production in sorghum which confers resistance to Sfriga was inherited as a monogenic as well as a quantitative character.

CROP PRODUCTION

Indian sorghums show a wide range of variability for duration, panicle length and quality. In absence of genotypic changes, earlier efforts improved the yield levels only marginally. Practically there was no improvement in yields of local cultivars due to poor response to agronomic inputs. The real thrust to research on sorghum-production technology was given with the start of the accelerated hybrid sorghum project at national level during 1962 and subsequently the AICSIP during 1969 towards crop-production technologies both for kharif and rabi sorghum-based sequences and intercropping systems.

Kharif sorghum management

With the evolution of short-duration and highly-responsive genotypes from the mid-sixties onwards intensive research efforts were made to develop new and improved technologies to realize maximum potential of the genotypes.

Nitrogen: In general the heterotic hybrids are more efficient in total uptake and translocation of nutrients. The hybrids and high-yielding varieties were more responsive to N than locals, giving 53–81% more yield even at no N compared with locals. The hybrids and improved varieties responded well to higher levels of N up to 150 kg/ha, while the locals were very poor in yield response. Based on the results from several multi-location trials, application of 80–100 kg N/ha was recommended for kharif hybrids and improved varieties.

Results on time of N application were not found constant. Sorghum yields reduced if basal application of N omitted or reduced below 50% of total N. Reasons for variable results are attributed to soil texture, crop duration, rainfall and quantity of N applied. Application of N 50% basal and 50% as top-dressing at flower-primordia initiation during rainy season is generally recommended. Soil application of N proved superior to foliar application and placement of N fertilizer in soil to broadcast application.

Phosphorus: A mean optimum level of P₂O₅ 40 kg/ha was suggested in rainfall situations. Overall quantity of response is 7–20 kg P₂O₅/ha. Many soils in the sorghum-growing area are deficient in P. The P application is also essential for maintaining the soil health to sustain the productivity level over a long period. Placement of P fertilizers in the soil before sowing or broadcast and incorporation into soil during the land preparation was recommended and the total quantity is applied at a time.

Potassium: The response to potassium application was not consistent. In majority of the cases response was not significant. Though sorghum depletes high quantity of potassium from the soil, less response to applied K is due to the fact that the soils in the sorghum-growing areas are rich in native potassium. However, application of about 30 kg K₂O/ha is generally recommended to be applied basal during kharif to maintain the soil health and its productivity.

Micronutrients: Recent studies at AICSIP indicated significant yield response to application of both zinc and iron. In the soils with clear deficient symptoms, application of zinc as zinc sulphate @ 25 kg/ha to the soil before sowing or 0.2% zinc sulphate solution as foliar spray is recommended. Similarly, iron is recommended to be applied as iron sulphate either to the soil or to the foliage.

Plant density: The traditional varieties were not responsive to higher plant densities. The hybrids and the high-yielding varieties are highly responsive to higher plant densities. A plant population of about 180 000/ha, which can be achieved by keeping the row-to-row spacing at 45 cm and plant-to-plant at 12 cm during the rainy season. A seed rate of 8–10 kg/ha is suggested followed by thinning of excess plants at 15 days age to maintain optimum plant population. It is also further advised to maintain only 1 plant/hill.

Planting time: Based on the results from the trials carried out till mid-seventies the optimum time of planting for kharif sorghum was at the onset of monsoon. Subsequent studies in the recent past in the project clearly indicated that planting of rainfed kharif sorghum performs far superior when it is planted about a week before the onset of monsoon. Planting before the onset of monsoon resulted about 22.1% increase in grain yield irrespective of genotype and fertilizer management and as such the present recommendation is to plant kharif sorghum about a week before the onset of monsoon.

The traditional method of hand-weeding, hoeing and intercultivation by bullock-drawn implements is the most effective for controlling the weeds and thereby increasing the yields. Chemical control methods are suggested only as alternative to the hand-weeding. A selective herbicide, atrazine is very effective to control the weeds in the early growth stages of the crop. This chemical is recommended to be applied @ 0.5 kg ai/ha as pre-emergence application.

Management of dual-purpose genotypes

The dual-purpose sorghum genotypes identified to yield grain at normal rate and yield higher quantity of fodder responded for higher plant stand and higher dose of nitrogen fertilizers. Application of 120 kg N/ha with a plant stand of about 0.21 million/ha was recently found optimum for realizing about more than a tonne dry fodder without any reduction in the grain yield.

Cropping system

During the second part of fifties some efforts were made to make cropping systems more scientific.

Sequence cropping: Successful sequence cropping had
been realized after evolution of new genotypes making available highly desirable plant types to fit into double cropping. Sequence cropping can be dealt as kharif sorghum-based, rabi sorghum-based and intensive cropping systems. Kharif sorghum-based systems are feasible in areas of fairly good rainfall and deep black soils. Rabi sorghum-based systems are common in areas of deep black soils with late monsoon and low rainfall. In these areas growing a kharif crop is uncertain. Only during years of good rainfall a short-duration pulse crop is recommended for kharif season. In the above 2 systems the crops are grown largely under rainfed conditions. In the areas with irrigation facilities sorghum is well fitted in 3-crop intensive cropping system. Investigations on nutrient management of highly significant systems, viz. intensive (sorghum-wheat-greengram, sorghum-gram-sorghum, sorghum-wheat-groundnut, greengram-sorghum-groundnut) and double crop (sorghum-safflower, sorghum-chickpea, sorghum-sunflower, greengram-sorghum and cowpea-sorghum), largely indicate a saving of about 30 kg N due to inclusion of a pulse crop in the sequence.

**Intercropping:** Intercropping or mixed cropping in rainy-season sorghum is an age-old practice. Significant advantages both in yield and remuneration due to intercropping over sole cropping were reported. Performance of different intercropping systems as expressed by land-equivalent ratios is given in Table 5.

In intercropping systems crop compatibility is of foremost importance and primarily determined by the minimum competition of component crops both temporal and spatial. Even before fifties legumes were found as the best group of compatible crops for sorghum. Further studies were also carried out keeping in view the changing price structure of crops. The considerations are changing from insurance against risk to higher productivity and finally higher remuneration.

Studies on compatible genotypes of companion crops were started along with the evolution of new genotypes. 'CSH 6' with remarkable plasticity in performance, short stature and duration was reported the best for intercropping system with pigeonpea as its companion crop. Medium-duration genotypes 'C 11', 'BDN 2' and 'LRG 36' of pigeonpea are ideal. 'CSH 9' is also being presently recommended in the areas of black soil with assured rainfall in view of its per-se yield potential with 3:3 row ratio to permit higher yield recovery of companion pigeonpea.

In traditional intercropping component crops were grown at a lower population than their respective sole population. Additive series show superiority to replacement series and it is suggested to maintain full population of base crop. In order to accommodate this, a full population in paired-row pattern was suggested as an alternative to row spacing of 45 cm. Sorghum yield is not affected much due to planting geometries. However, intercrops yields are found greater in paired-row systems.

In a cereal-legume system extensive studies were carried on fertilizer management and the results were not consistent. Reports are available both in favour and against additional application of fertilizers to the companion crop. The overall indications are that the intercropping system required no additional fertilizer application and recommended dose for the base sorghum as sole system is adequate under rainfed conditions. However, if the system is maintained irrigated, optimum requirement of fertilizers for the respective companion crops should be met with to realize best results.

**Ratooning systems:** Sorghum can be successfully ratooned. There are evidences of advantages in yield increases and related management techniques. Since continuous culture of a single crop may lead to injurious build up of pests and diseases, the ratoon cropping was in general, discouraged. Ratooning of green-forage sorghum is a common practice for multi-cut forage genotypes. In Karnataka the practice of harvesting sorghum at its flowering stage during kharif and allowing it to ratoon as grain sorghum is in vogue.

**Rabi sorghum management**

Rabi sorghum cultivation faces several production constraints. Natural factors like climate and soil and also non-availability of best adaptive cultivars are the most important. Since rabi crop is largely grown on soils with residual moisture, the crop faces terminal drought and in some of the areas low temperature too. Till recent past neither high-yielding variety nor a potential hybrid was available for cultivation in rabi. The native races and local cultivars are highly non-responsive to agronomic inputs and the yield levels stagnated at a very low level (< 500 kg/ha). During the recent years intensive efforts in the field of genetic improvement, a couple of hybrids and improved varieties with reasonable potential were released for cultivation in rabi. Simultaneous efforts in the field of production technology resulted in the improved management practices for rabi.

The traditional planting time in October and November

<table>
<thead>
<tr>
<th>Land-equivalent ratio (LER)</th>
<th>Companion crop grown with sorghum</th>
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<tbody>
<tr>
<td></td>
<td>Groundnut</td>
</tr>
<tr>
<td>Partial LER for sorghum</td>
<td>0.97</td>
</tr>
<tr>
<td>Total LER of system</td>
<td>1.33</td>
</tr>
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was not found suitable. The new group of genotypes required advanced planting time. The period from middle of September to the middle of October was found be optimum time for planting. Delayed planting leads to lower yields because of low minimum temperatures and severe terminal drought.

The optimum plant population for rabi rainfall cultivation was found to be 135 000/ha. In irrigated culture the population can be increased up to 180 000/ha. Generally, the response to applied fertilizers in rabi is low. The fertilizer dose of 60 kg N and 30 kg P₂O₅/ha is recommended for irrigated conditions and 80 kg N and 40 kg P₂O₅/ha for irrigated conditions. In hybrids ('CSH 13 R' and 'CSH 15R') and also the variety ('Swathi') a higher fertilizer dose of about 100 kg N/ha is suggested in irrigated situations. With combinations of higher fertilizer dose and irrigation, higher yields to a tune of about 5 tonnes/ha were realized from these genotypes. Deep placement of fertilizers in the soil was found to increase the yields by about 200 kg/ha.

In rabi sorghum-based systems, full yields of sorghum can be obtained with the application of only 50% of recommended fertilizers when sorghum is grown following a normally fertilized pulse crop grown in kharif. Row proportions of 6 : 3 and 4 : 2 of sorghum and safflower were found relatively better in rabi season. This system is widely practised in parts of Maharashtra under absolute rainfed conditions. Under severe terminal drought, threatening a total failure of crop, thinning up to 50% is suggested as a mid-season correction. It is advisable to thin alternate rows before the emergence of ear retaining 50% rows.

In kharif, present thrust is on increasing the profitability of intercropping systems and reducing the cost of production by way of using low-cost inputs as biofertilizers etc to make kharif produce competitive in the market. In rabi, the priority was on to enhance the fertilizer-use efficiency and moisture-use efficiency. Research efforts are being especially made to develop appropriate production management for shallow, medium and deep soils.

In sorghum-based cropping systems the main thrust is on working out efficient integrated nutrient management for different sequence systems keeping the objectives of profitability, productivity and sustainability. The historical changes in the process of progress in technological development from subsistence to profitable, and to commercial farming are always taken into consideration for formulating research programmes.

**CROP PHYSIOLOGY**

**Physiological approaches for improving productivity and adaptation to stress environments**

Cultivars grown during the pre-high-yielding variety era were basically tall, long duration, photoperiod-insensitive and low yielding with poor harvest index. The introduction of early duration, short, high yielding, photo-insensitive, temperate (ms CK60) genotypes into the Indian sorghum programme brought out the transformation in our agriculture. Intensive efforts of sorghum research work during past 3 decades led to the development and release of a series of hybrids ('CSH 1' to 'CSH 15R') and varieties ('CSV 1' to 'CSV 15'). The modern high-yielding varieties were basically early to medium, semi-tall, photoperiod-insensitive and complete their grain ripening before cessation of monsoon. Besides, these are characterized by early seedling vigour, high-growth rates, more allocation of photo-assimilates to sink development, tolerance to abiotic stresses, high current photosynthesis rates, high harvest index (0.45–0.50) etc that resulted in higher yield potential (4–5 tonnes/ha).

**Biomass accumulation, growth and components of yield**

Dry-matter production and distribution pattern indicated that in traditional varieties, the dry-matter accumulates in the stem after flowering, while in temperate dwarfs mainly in the ear. Non-heterotic hybrids were superior to their parents up to flowering only. Hybrids had high leaf-area index (LAI) and leaf-area duration (LAD) than locals. Physiological basis of hybrid vigour in 'CSH 1' indicated heterosis in growth parameters, viz net assimilation rate (NAR), LAI, LAD and crop-growth rate (CGR), that resulted in higher yield in hybrid than its parents. Sorghum showed high degree of plasticity in plant density vis-a-vis grain yield relationships.

'CSH 1' consistently outyielded local varieties under both stress and normal conditions, but 'CSH 2' showed more reduction in yield than 'CSH 1' under rainfed conditions because of its late flowering, restriction in stem elongation and delayed panicle emergence. However, 'CSH 2' outyielded 'CSH 1' under no-stress conditions only. For obtaining higher yields higher sink size and flowering by the end of rainy season were the desirable attributes for rainfed sorghum. Reduction in light intensity, ie 75% of normal, decreased both biomass and grain yields in sorghum cultivars.

Investigations on nature of yield plateauing in kharif sorghum revealed that increase in source (LAI) was accompanied by increase in biomass production, but grain yields declined beyond certain critical LAI. Both grains/panicle and 1,000-grain weight declined as population increased from 0.05 to 0.25 million/ha. Yield limitations in 'CSH 9' occurred at 2 500 grains/panicle and 1 000-grain weight of around 25 g. For improving yield potential of hybrids, more number of grains per unit land area with stability in grains/panicle and consistency in grain size are the desirable features. While in inbreds, increasing the grains/panicle will be the criterion for enhancing the potential yields. Both in hybrids and inbreds the grains/m² were positively correlated with grain yield. Modern experimental hybrids recorded higher yields due to high harvest index, grains/panicle and biomass. Further, grain yield in these hybrids showed positive correlation with harvest index, grain number, dry matter of stems, leaves and panicle and total biomass. There was a genetic variation in photosynthesis rate in a set of experimental hybrids and inbreds.
Dry-matter production in hybrids and varieties both at seedling and maturity had a significant positive correlation with grain yield. Improved varieties have also shown similar potential of dry-matter production and efficiency of partitioning. In low-yielding sorghum genotypes, the source, ie low L.A., LAR and LAD, was the major limitation to grain yield, besides poor partitioning. It was suggested that selection for high yield could be based on the harvest index, dry weight of panicles and grains/panicle. Genotypes 'SB 2407', 'SB 2432', 'SB 3304', 'SB 2431' and 'CSV 13' produced higher biomass despite having low leaf area. It resulted in high water-use efficiency. Advanced experimental hybrids recorded 19, 11 and 17% higher 1 000-grain weight, grain yield and harvest index respectively than inbreds. In another study the advanced hybrids had distinct superiority in biomass production and 1 000-grain weight to inbreds.

**Photoperiod and temperature interactions in relation to adaptation**

Control of reproductive cycle by photoperiod or temperature is an important component of adaptation in sorghum to its environment. Sorghum being a native to the tropics and now is well adapted to temperate world. This is mainly due to conversion programme. In this programme the tall, photoperiod-sensitive, exotic varieties of sorghum are converted to short-photoperiod, insensitive types that are capable of flowering under rather wide range of environmental conditions. For post-rainy season, the genotypes should be highly sensitive to photoperiod and relatively insensitive to temperature. Under these conditions, the early-sown genotype will extend its life-cycle, whereas the late-sown one will shorten its life-span thereby escaping terminal drought.

**Responses and reaction to water stress and adaptation to drought**

Among the rohi genotypes, 'Hegari 1' produced higher biomass but yielded less than 'M 35-1' because of lower sink size and test weight. While 'PJ 4R' also gave less straw as well as grain yield. Water-stressed crop showed lower stomatal conductance and leaf water potential than irrigated one. Mild water stress did not affect phenology. Minimum leaf injury (firing) during drought could be useful index of drought. 'M 35-1' accumulated less proline than others.

Water stress reduces the grain yield more (54-73%) in non-glossy cultivars than in glossy ones (46-54%). Glossy-leaved genotypes had higher leaf-area index and growth rates than non-glossy ones under stress. Rainy-season 'CSH 6' showed lower capacity to decrease osmotic potential, ie low osmotic adjustment than post-rainy-season 'M 35-1' and 'CSH 8R' under stress. Further, early-maturing genotypes give similar yield but less dry matter than late ones under terminal stress in rohi season. Osmotic adjustment, remobilization of stem reserves to the panicle, rapid phenological development (not delayed by stress) and deep roots are all useful parameters for improving productivity of rohi sorghum.

Winter sorghum showed higher water-use efficiency than rainy-season one. Screening of genotypes in medium soils led to the identification of drought resistance donors such as 'IS 12611', 'DVK 73', 'SPV 824', 'ICSV 218' and 'SPV 678'. These entries were characterized by more green leaf area after flowering and more dry-matter accumulation towards sink. Drought-screening programme at Palem, Parbhani and Anantapnr for rainy-season situation resulted in identification of useful donors like 'IS 12611' and 'IS 2312' in germplasm and 'SPH 263', 'DKV 73', 'SPV 815', 'SPV 772', 'SPV 669', 'SPV 824' and 'SPV 710' among high-yielding varieties. Accumulation of higher amount of photosynthates in the stem and late senescence (stay green) prevent or reduce charcoal-rot incidence and hence evolving genotypes with non-senescence (stay green) beyond physiological maturity was suggested for improving post-flowering drought tolerance.

Following are the physiological limitations in increasing yield potential.

(i) Poor seedling emergence, crusting of soil in Alfisols and water and N limitation
(ii) Occurrence of drought at various growth stages and low and high temperature
(iii) Negative correlations among yield components
(iv) Inadequate supply of currently produced photo-asimilates during GS 3 stage
(v) Substantial post-bloom loss of stomatal control and its influence on CO2 exchange
(vi) Combined effects of temperature, water and nutrient stress on productivity under terminal drought in rabi ecosystem

(vii) Lack of precise information on agroclimatic characteristics of sorghum production test sites.

Strategies for enhancing yield potential in sorghum, are:
(i) Matching phenology of genotypes to expected water supply in the target region
(ii) Continuous increase in overall biomass production rather than merely partitioning
(iii) Stability in yield components, ie heads/m2, grains/head
(iv) Pre- and post-anthesis stress screening of genotypes
(v) Evaluation for abiotic stress tolerance traits, viz stay green, osmotic adjustment, nitrogen-use efficiency and transpiration efficiency
(vi) Selection for photoperiod and temperature responses
(vii) Root studies such as depth, thickness, volume
(viii) Aspects on contribution of heterosis in adaptation to environmental stress
(ix) Molecular markers for traits related to adaptation to water and temperature stresses
(x) Molecular and biochemical aspects of chloroplast and leaf senescence
(xi) Modelling of crop growth, development and yield to overcome production constraints

(xii) Canopy-air temperature differential correlation with yield under stress

(xiii) Selection for physiological traits with direct effects on yield and better understanding of such physiological traits and their relationship to yield

CROP PROTECTION

Pest management

Current work on temperate x tropical crossing programme lays considerable emphasis on multiple resistance to insects and diseases. Now the challenge today is to improve competitiveness without sacrificing the environmental quality. Emphasis has been given on the harmonious integration of diverse management strategies, so as to maintain the pest population at levels below those causing economic injury.

A systematic screening of the world sorghum germplasm accessions for sources of resistance to shootfly was started with multilocation testing in the AICSP programme. Gradual improvement in techniques of screening for shootfly, stem-borer, midge and head bugs has increased the efficiency of this screening in recent years.

Changes in pest status and management practices:

Since the introduction of high-yielding hybrids and varieties, distinct changes have been witnessed in the composition of insect complex. Several species considered to be occasional pests in the past have attained a major status and given priority attention, viz shootfly, stem-borer, midge and head bug. These changes are due to the influence of one or a combination of high-yielding cultivars, agronomic practices, abiotic factors and impact on the use of pesticides on pests and their natural enemies. Shootfly and stem-borer have attained major status within a short period of the introduction in 1964–65 of an early-maturing (95–100 days) first sorghum hybrid, 'CSH 1'. Similarly, the sorghum midge, a minor pest till mid-sixties, has gradually attained a major status and caused grain damage up to 15.1 and 19.8% in 1966 and 1967 respectively. Staggered sowings and cultivation of varieties of differential flowering or maturity made continuous availability of flowering panicles, which in combination with favourable weather conditions resulted in rapid population build-up and spread of the midge. In this process, generally, the late-maturing locals became more vulnerable to midge due to flowering synchronizing with low temperatures and humidity, a situation experienced in Maharashtra in 1973.

The change in status of shootfly (Atherigona soccata) necessitated to adopt cultural practices (early planting, increased seed rate, removal and destroying infested seedlings) for reducing the damage. Phorate 10 g or disulfoton 5 g applied at the planting time showed profound efficacy. Subsequently seed-treatment trials were conducted, resulting in the identification of a systemic carbamate insecticide (Carbofuran) showing encouraging results. This finding had a significant impact on the ease and economy in reducing the dosage, depending on the delay in planting time by mixing the treated with untreated seed in different proportions, and increasing the productivity and thus reducing the cost of cultivation. Further, carbofuran 3 g as seed furrow application was also found to quite effective. Carbofuran 50 sp was compatible with other fungicides like agrosan, thiram and captan in effectively checking the incidence of not only shootfly but also other foliar diseases and grain smut.

Attempts to correlate the stem-borer (Chilo partellus) damage with grain yields gave contradictory results due to variation in the time of infestation and the variability in the evaluation of resistance parameters, viz deadhearts, foliar injury, and tunneling in stalk and peduncle.

Cultural practices are highly relevant and ploughing and destroying of crop residues is encouraged. Stem-borer incidence, which is usually not serious in most situations, can be checked by a need-based application with 1 or 2 applications of granules of endosulfan 4 g, carbaryl 4 g or lindane 4 g in the whorls based on the foliar injury symptoms. However, among them, endosulfan 4 g gave effective control of spotted stem-borer over sprays, besides increasing the yields. The number of applications and quantity of granules were reduced to 2 applications.

Non-insecticidal means were developed for sorghum midge (Contarinia sorghicola) management. Screening and breeding for resistance in grain sorghum has primarily been through field evaluation, followed by artificial infestation in head cage technique. Concurrently, a great deal of attention has been directed at elucidating the components of resistance as well as evaluating their effect on ETLs and pest-management strategies.

Midge is effectively controlled by spraying panicles at pre-bloom stage (50% panicle emergence) with endosulfan 35 EC 1 litre, carbaryl 50 WP 3 kg or lindane 20 EC 1–2 litres in 500 litres water/ha, followed by another application after 4 days. Dust formulations of endosulfan 4 g, carbaryl 10 g or HCH 10 g @ 20 kg/ha are also effective. Two sprays are necessary.

Midge cultural control measures like removal and destruction of alternate hosts, stray sorghum plants, regional planting across contiguous farm units at community level, using early flowering cultivars under delayed plantings so as to synchronize flowering with the early-planted genotypes could avoid infestation, population build-up and spread of midge. Burning of chaffy panicles and their residues also to a greater extent reduces the population carry-over to the subsequent crop.

A number of head bug species feed and damage developing grains of sorghum in southern India and among them, Calocoris angustatus is the predominant species causing considerable grain yield loss. Same chemical control methods as for midges, effectively check the incidence of head bugs.
Influence of abiotic factors on population dynamics:

Key-pest monitoring in diverse agro-ecosystems with light, yellow sticky, square pan metal, and plastic jar traps as well as studying their ecobiology enabled to relate the interaction with abiotic factors. Shoot-fly population shows considerable variation and normally associated with the pattern of rainfall. Favourable temperature and high relative humidity in the rainy season rapidly build up the shootfly population leading to severe stand loss. staggered planting, due to late or poor rainfall, also induces high shootfly damage. Normally, they are very low in April–June, and slowly increase in July and reach the peak in August and gradually decline from September onwards. The shootfly may have 2–3 overlapping generations during the cropping season. The spotted stem-borer has 5 or more successive generations annually. The seasonal incidence varies in different states, and it shows peak in August–September in Haryana. The newly released cultivars flower and mature before the end of kharif season. Adult-midge activity shows considerable variability in different states, but in general, shows peak in August–September. But when the rain stops at the end of September or beginning of October, grain ripening takes place under high humid conditions, a condition congenial for midge, head bugs and headworms to thrive well.

Influence of cropping systems: Intercropping of sorghum with grain legumes and edible oilseeds is now an established practice, and many states are promoting intercropping of hybrids. Infact, traditional sorghum-based cropping systems are most frequently characterized by crop diversity. Few intercrop combinations have a positive effect in reducing the pest populations.

Panicle characteristics like compactness in CSH 9 was found associated with ideal microclimatic conditions as these encourage their susceptibility to headworms. Non-uniform growth of sorghum cultivars is also a factor for their increased infestation. Breeding efforts changed the panicle morphology to semi-compact nature, so as to prevent the infestation and damage by panicle pests as well as fast drying of the panicle soon after the rains.

Crop loss: Yield losses caused by key pests are often substantial but have seldom been precisely quantified. Shootfly infestation usually ranges from 8 to 97% with a grain yield reduction of 56–85% in high-yielding cultivars. There is a proportionate reduction of grain yield of 16–57 kg/ha in relation to the increase in 1% deadhearts. Losses of grain and forage vary, depending on the stage and severity of infestation of stem-borer and early infestation can result in heavy losses. However, the stem-borer infestation in eighties ranged 54–100% causing around 5–10% grain yield loss due to foliar injury and deadhearts. Similarly, the grain yield losses due to midge also varied in different states, 15–30% in locals and 18–94% in high-yielding cultivars due to headbugs, but cumulative effect of panicle pests led to 5% grain yield loss.

Sporadic pests: Changing status of sporadic armyworm (Mythimna separata), a key pest in Karnataka, effective control would be achieved with a poisonous bait comprising monocrotophos (250 ml), wheat bran (50 kg), jaggery (4 kg) and water (6–8 litres). It is now being practised by the farming community.

Disease management

In the process of evolution and agriculture, the farmer learnt to grow a range of cultivars and land races. This gives a better defence against pests and diseases. However in kharif season, with the introduction of early-flowering hybrids and varieties in 1960, coinciding with heavy rainfall during flowering is a predisposing factor for grain moulds to attain a major status. During rabi season, the crop with high harvest index is grown under receding moisture and the temperatures are high proved to be more susceptible to charcoal rot.

The susceptibility to most of the foliar diseases is favoured by monocropping and at high plant densities. The changing pattern of cropping systems also plays an important role in the control of diseases. Intercropping is the most practical system followed in India. Diseases usually become intensified in the intensive cultivation of monocropping. Crop rotation also helps in control of soil-borne diseases, eg charcoal rot.

The yield is reduced because of biotic and abiotic stresses. Under biotic factors diseases also cause a major role in reducing the crop yields. Under major diseases grain moulds, charcoal rot, downy mildew, ergot and rust were more destructive. All the other foliar diseases like leaf blight, rough leaf spot, sooty stripe, zonate leaf spot, gray leaf spot, tar leaf spot, anthracnose are considered as minor diseases. Sorghum diseases by and large controlled to some extent through one or the other methods. The measures are mostly followed are host-plant resistance, cultural, chemical and integrated control.

Chemical control: In the absence of high degree of resistance to grain moulds, it is imperative to go for chemical control measures of seed treatment prior to sowing or protection of standing crop this practice was not adopted by the farmer due to low crop yields and is being practised as a high-input technology in seed-production blocks. However, few other important diseases were effectively controlled by a broader range of fungicides.

Smuts are more prevalent on land races. Seed treatments with vitavax, thiram, benlate, dithane M-45, dithane Z-78 and cerean are effective against rots, seedling blights and seed-borne diseases.

Metalaxyl, a seed-dresser, significantly reduced the incidence of downy mildew. Spray of metalaxyl or radomil 0.1 g ai/litre 40 days after germination was recommended for the control of downy mildew. Effective control of rust was achieved with 4 sprays of Dithane M-45 @ 0.3% at 10-day interval from 35 days after germination. Two sprays of bavistin 0.1% ai or thiram 0.3% starting at 50% flowering and another application after a fortnight was found effective in reducing the sugary disease. Bavistin 1 000 ppm was found
promising for effectively checking the incidence of zonate leaf spot; zineb for the effective control of sooty stripe and leaf blight; captan 0.2% for grey leaf spot, rust, anthracnose and zonate leaf spot.

Several workers studied the fungicidal control of head moulds by using captan, thiram, aureofungin, ziram spraying twice—first at the time of grain setting and second at the time of grain maturity. Evaluation of fungicides is of utmost importance in the seed-production programmes to produce healthy seeds. Ceresan followed by captan, dithane M-45 and bavistin were found to be the best to inhibit majority of the grain mould fungi. To reduce the fungal population seed treatment with captan 4 g/kg seed may be used. Treatment with carbendazim 0.2% improves germination.

Three sprays of aureofungin 200 ppm + captan 0.3% starting at 50% flowering and the subsequent sprays at 10-day intervals are recommended for large seed growers.

**Cultural control:** The removal of sorghum stalks for fodder after grain harvest minimizes the carryover of the inoculum. Deep ploughing is needed to bury the oospore and reduce the incidence of sorghum downy mildew. Tillage also reduces inoculum density. Adjustment of time of sowing escapes the disease pressure. High levels of nitrogen increased the susceptibility of sorghum to ergot disease, leaf diseases, stalk rot and grain moulds. Nutrient imbalances play an important role in the susceptibility of sorghum to different diseases.

Destruction of collateral hosts like grasses is an effective control method of rust. Similarly, destruction of collateral hosts like Johnson grass in the vicinity of sorghum crop may be destroyed to avoid the build up of sugary-disease inoculum.

Management of charcoal rot through periodical hoeings, so that the moisture is retained in the soil and reduced charcoal rot incidence. Mulching with wheat straw reduces charcoal rot (%) and marginally increases the grain and fodder yields.

**Biological control:** Biological control of charcoal rot disease through seed dressing with *Trichoderma viride* reduces the disease incidence.

**Crop-protection strategies**

Past approaches to biotic management have relied heavily upon insecticidal control measures. The multiple applications combined with marginal profits for realizing yields, has necessitated to find alternate control strategies. Hence thrust was given to incorporate high degree of resistance to grain moulds, leaf-spot diseases, shoot-fly and charcoal rot combining resistance for other pests and diseases, under high-yielding background. Incorporation of tan plant pigment and hard seed increased multiple tolerance to 8–10 diseases in *kharif* cultivars. Utilizing ‘M 35-1’ as a potential source of resistance to shoot-fly, for incorporating resistance resulted in the release of resistant cultivars (‘Swati’, ‘CSV 8R’ and ‘CSV 14R’) but with marginal yield increase over ‘M 35-1’.

Moisture-stressed soils and increased temperatures during flowering stage are suitable for the incidence of charcoal rot disease. ‘E 36-1’ as a donor for its resistance was utilized in the breeding programmes. Early planting at the beginning of the rainy season is being practised to avoid shoot-fly in *kharif* season and enables to grow 2 crops after the introduction of short-duration cultivars.

Development of differential maturity cultivars are flexible not only in cropping systems but also in avoiding other biotic and abiotic stresses. But at the same time encouraged the intensity of pressure to panicles pests like midge and head bugs, and grain mould due to cropping of late-maturing cultivars or local simultaneously along with the early-maturing cultivars. Initial population spread or build up starts from the early-maturing group to late-maturing cultivars or locals. Similar situation was observed during 1973 in Maharashtra, wherein the locals were severely damaged by the midge. Though pest incidence was successfully managed in *kharif* without insecticidal use, there is still a need for diversification of genetic base to identify potential donors with increased levels of resistance to multiple pests and diseases.

Parasites and predators of key pests including their ecobiology were studied. In sorghum grown as a single-seasonal crop, these usually destroy the pest habitat. A small proportion of the parasitoids survive on the meagre pest population continuing in off-season on alternate crops or hosts. The natural enemy population must build up afresh on the host during the crop season. Most parasitoids usually lag behind their host in their population build up. Their benefit of suppression invariably is too little or too late. A diverse ecosystem generally has a richer insect fauna than a monoculture. Mixed cropping systems thus encourage their survival and build up. Further, some of the resistance components and plant characteristics are useful which make the target pests more accessible to natural enemies such as tightness of leaf sheath, trichomes for shoot-fly, resistance to borer penetration, and semi-compact or loose panicle type of cultivars exposes the panicle pests to increased parasitism and predation.

The benefit of incorporating multiple resistance associated with pest avoidance through cultural practices in sole or mixed cropping systems has so far been a major reliance in sustainable sorghum production.

Productivity of winter-season (*rabi*) sorghum continues to be low due to lack of suitable hybrids and varieties to meet the severe biotic and abiotic stresses. In spite of its importance in food and fodder scarcity of moisture-scarc areas, it remains challenging problem and can be met by using additional scientific resources and investment commensurate to area covered under this crop. Similarly, susceptibility to grain moulds is of serious concern in short-duration rainy-season (*kharif*) cultivars which reduces grain quality for human consumption and alternate uses and ultimate profitability. Thus intensive research on grain mould resistance is required to
improve the quality of *kharif* sorghum for meeting domestic (household and industrial uses) and international demands thereby enhancing household economy of sorghum growers. Major strength of sorghum lies in its high fodder potential. To sustain animal health, development of multi-cut forage sorghum hybrids with resistance to leaf-spot diseases by incorporating tan-plant pigment is imminent. Adoption of dual-purpose types in Uttar Pradesh, Madhya Pradesh and Rajasthan such as ‘CSV 15’ and ‘CSH 13’ which can also be cultivated as fodder type can greatly cater the need of large single-cult forage sorghum belt. The research efforts can be directed to reduce per unit cost of production through realizing potential yields under low-cost input management to make sorghum production environment competitive.