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ICPH 2671 – the world's first commercial food legume hybrid

Kul Bhushan Saxena[1,4], Ravikoti Vijaya Kumar[1], Ashok Narayanrao Tikle[2], Mukesh Kumar Saxena[2], Virendra Singh Gautam[2], Surapaneni Koteshwar Rao[3], Dhirendra Kumar Khare[3], Yashvir Singh Chauhan[1], Rachit Kumar Saxena[1], Belum Venkata Subba Reddy[1], Devendra Sharma[1], Linga Janardhan Reddy[1], John Melvin Green[1], Donald George Faris[1], Yashwant Laxman Nene[1], Myer Mula[1], Rafat Sultana[1], Rakesh Kumar Srivastava[1], Cholenahalli Lakkegowda Laxmipathi Gowda[1], Shrikant Laxmikantrao Sawargaonkar[1] and Rajeev Kumar Varshney[1,4]

[1]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru - 502324, Andhra Pradesh, India; [2]Rajmata Vijaya Raje Scindia Krishi Vishwa Vidyalaya, Gwalior - 466 001, Madhya Pradesh, India; [3]Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur - 482 004, Madhya Pradesh, India; [4]Corresponding authors, E-mails: k.saxena@cgiar.org; r.k.varshney@cgiar.org

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Abstract

ICRISAT scientists, working with Indian programme counterparts, developed the world's first cytoplasmic-nuclear male sterility (CMS)-based commercial hybrid in a food legume, the pigeonpea [*Cajanus cajan* (L.) Millsp.]. The CMS, in combination with natural outcrossing of the crop, was used to develop viable hybrid breeding technology. Hybrid ICPH 2671 recorded 47% superiority for grain yield over the control variety 'Maruti' in multilocation on-station testing for 4 years. In the on-farm trials conducted in five Indian states, mean yield of this hybrid (1396 kg/ha) was 46.5% greater than that of the popular cv. 'Maruti' (953 kg/ha). Hybrid ICPH 2671 also exhibited high levels of resistance to *Fusarium* wilt and sterility mosaic diseases. The outstanding performance of this hybrid has led to its release for cultivation in India by both a private seed company (as 'Pushkal') and a public sector university (as 'RV ICPH 2671'). Recent developments in hybrid breeding technology and high yield advantages realized in farmers' fields have given hope for a breakthrough in pigeonpea productivity.

Key words: pigeonpea — *Cajanus cajan* — cytoplasmic-nuclear male sterility — natural outcrossing — hybrid seed production

The word 'hybrid' cultivar excites farmers in the expectations of high yields and greater returns. The hybrid breeding technology has demonstrated quantum yield jumps in various cereal (Alexandratos 2001), vegetable (Rai and Rai 2006) and fruit (Kuznecov 1966) crops. The commercial exploitation of hybrids is known to be directly linked to the ease with which their hybrid seeds could be produced and delivered economically to farmers. The efficiency of mass pollen transfer from male to female parent through air or insects to affect cross-fertilization plays an important role in commercializing the hybrids in different crops. In most food legumes, the absence of natural cross-fertilization is the major bottleneck in exploiting hybrid vigour at commercial scale because their flower structure forces high level of self-pollination (Saxena et al. 1992).

Legumes are the major source of protein for the vegetarian population in South Asia. The legume crops are generally grown under low inputs and risk-prone marginal environments, especially in semi-arid tropics. At present, the availability of proteins among poor in the developing world is less than one-third of its normal requirements (Paul et al. 2011), and with growing population (expected to be 9 billion by 2050) and continuing low productivity of legumes, the protein availability to the masses is under threat of further decline. As the food production efforts in past in most developing countries favoured cereals, the issue of protein availability assumes even greater significance from nutrition point of view.

Globally, pigeonpea [*Cajanus cajan* (L.) Millsp.] is cultivated on 4.79 million ha in 22 countries. Besides India, Myanmar and Nepal are important pigeonpea-growing Asian countries; in the African continent Kenya, Malawi, Uganda, Mozambique and Tanzania produce considerable amounts of pigeonpea (FAO 2010). In India, the pigeonpea area has recorded a significant rise from 2.3 million ha in 1950 to 3.53 million ha in 2010; but the crop productivity has remained stagnant at around 700 kg/ha (FAO 2010). There are a number of factors for low crop productivity, but the lack of high-yielding cultivars has been identified as one of the major constraints underlying the stagnant productivity (Zaveri and Pathak 1998). The issue of yield plateau in pigeonpea has been a major concern for a long time, and to date, it has remained a challenge. To achieve a breakthrough in pigeonpea productivity, research on breeding a cytoplasmic-nuclear male sterility (CMS) system was initiated at ICRISAT (Reddy and Faris 1981). In the last decade (2002–2011), significant progress has been made to address various issues related to hybrid breeding and large-scale hybrid seed production technologies. The hybrid technology in pigeonpea is on the verge of commercialization in India. This study, besides briefly describing the progress in breeding and release of the world's first commercial pigeonpea hybrid, also documents its salient features including productivity in diverse environments.

Evolution of Hybrid Breeding Technology in Pigeonpea

Shull (1908) for the first time demonstrated hybrid advantage in maize (*Zea mays*) and foresaw the potential of this phenomenon in enhancing crop yields. Subsequently, the breeders of cross-pollinated crops designed suitable mating and selection schemes to enhance yields by exploiting hybrid vigour. As dominant genes generally contribute towards hybrid vigour, it was considered useful for only cross-pollinated crops; but later its utility was also established in self-pollinating crops (Sharma and Dwivedi 1995). They reviewed the phenomenon of heterosis in food legumes and concluded that dominance, overdominance, additive and various interallelic interactions play a significant role in the expression of hybrid vigour. They further postulated that the likelihood of obtaining heterotic crosses in pigeonpea is high because this crop also has a fairly good inherent capacity to carry a considerable genetic load of recessive genes due to partial natural outcrossing in the crop. In a subsequent review, Saxena (2008) showed that in pigeonpea important economic traits such as seed yield, pods/plant, plant height, seed size and seeds/pod are predominantly controlled by both additive as well as non-additive genetic variances. The level of realized heterosis for seed yield in pigeonpea is comparable to other crops where commercial hybrids have already made a mark in global agriculture (Saxena 2009).

A search for male sterility in pigeonpea germplasm led to the selection of a genetic male-sterility (GMS) system that was controlled by a single recessive gene (Reddy et al. 1978). A breeding programme was launched to generate valuable data on the extent of hybrid vigour and various other issues related to large-scale hybrid seed production in pigeonpea. The GMS hybrids showed 25–30% heterosis for seed yield in farmers' fields with wide adaptation, but various seed production difficulties and seed quality concerns did not permit commercialization of these hybrids (Saxena et al. 1992). The hybrid breeding programme at ICRISAT was then shifted towards developing a more efficient cytoplasmic-nuclear male-sterility (CMS) system.

Development of A_4 CMS System

Cytoplasmic-nuclear male sterility system is ideal for commercial hybrid seed production of field crops. The expression of CMS, in part, is controlled by genetic factors that are carried through both the male and female parents and retained over the generations. The male-sterile (A) line with 'sterile' cytoplasm and homozygous recessive (*frfr*) nuclear genes is maintained by its counterpart male-fertile maintainer (B) line that carries a normal (fertile) cytoplasm, and the same homozygous recessive (*frfr*) nuclear genes. To produce male-fertile hybrids, the A-line is crossed with a male-fertile restorer (R) line, which carries normal cytoplasm and dominant nuclear alleles (*FrFr*) for fertility restoration. To sum up, the CMS-based hybrid system consists of an A-line, its corresponding B-line, and R-line. As no CMS system was available in pigeonpea germplasm, efforts were made to breed for this trait by placing pigeonpea genome into the cytoplasm of its related wild species. The CMS system in pigeonpea was developed by crossing *Cajanus cajanifolius* as female parent with a pigeonpea cv. 'ICP 28' as a male parent.

Cajanus cajanifolius (Haines) Maesen (Fig. 1) is a wild relative of pigeonpea belonging to secondary gene pool. Based on various considerations, van der Maesen (1990) and De (1974) concluded that *C. cajanifolius* is the most closely related wild species to the cultivated pigeonpea and is a putative progenitor of the cultivated type. They also mentioned that these two species differ by a single gene. *Cajanus cajanifolius* has a chromosome complement (2n = 22) similar to that of cultivated pigeonpea. According to Ohri and Singh (2002) the karyotype of *C. cajanifolius* is almost similar to that of pigeonpea in morphology and number of satellite chromosomes. The close relationship between

Fig. 1: A snapshot of *Cajanus cajanifolious* – a wild relative of pigeonpea that has been used to develop cytoplasmic-nuclear male-sterility system (A_4)

C. cajan and *C. cajanifolius* was also established through various studies on plant morphology (van der Maesen 1990), isozyme analysis (Krishna and Reddy 1982), seed protein profiles (Ladinzinsky and Hamel 1980), trypsin and chymo-trypsin inhibitors (Kollipara et al. 1994), RAPD (Nadimpalli et al. 1993) and RFLP markers (Ratnarpakhe et al. 1995). Such a close relationship of the donor species generally reduces the problems of negative linkage drag, commonly observed in interspecific crosses. The CMS system derived from *C. cajanifolius* (accession ICPW 29) was designated as A_4 (Saxena et al. 2005); and it is an excellent male-sterility system because of its high stability across environments (Sawargaonkar 2011). In addition, this system has a number of good maintainers and fertility restorers in the cultivated *Cajanus* germplasm. The F_1 hybrid plants derived from this CMS produce excellent pollen load and pod set. At present, the A_4 CMS system is being used by pigeonpea breeders in India, Myanmar and China (Saxena 2009) for genetic diversification of A-lines and to produce commercial hybrids.

Development of Seed Production Technology

The benefits of hybrid technology cannot be realized unless sufficient quantities of genetically pure hybrid seed is commercially produced and sold at affordable prices. The experiments conducted at different locations have shown that extent of partial natural outcrossing (20–70%) in pigeonpea varies considerably (Saxena et al. 1990). The hybrid seed set on the male-sterile plants is chiefly determined by the availability of bee population in the vicinity. The known prime pollinating vectors in pigeonpea are *Megachile lanata*, *Apis florea* and *Apis mellifera* (Pathak 1970, Brar et al. 1992). Onim (1981) reported that each insect visit lasts for 15–55 s when they trip the unopen floral buds, thereby introducing foreign pollen on the stigmatic surface to affect the cross-fertilization. Williams (1977) counted 5500–107 333 pollen grains on the body of a single pollinating insect, of which pigeonpea pollen accounted for 98–100%.

As pigeonpea flowers are prone to natural cross-pollination by insects, a safe isolation distance (about 500 m) is essential to produce pure seed of hybrids and their parents. The commercial seed production of pigeonpea hybrids involves large-scale seed production of A-, B-, R-lines, and the hybrid combination (A × R). For seed production of A-line, breeder seed of both A- and B-lines are planted using a female : male row ratio of 4 : 1. In the production areas where greater bee activity is observed, a higher row ratio can be used for getting high yields. For hybrid seed production (A × R) also, the same ratio can be used. In general, roguing of off-type plants is carried out both at seedling as well as reproductive stages.

For effective hybrid seed production, it is important that flowering of the male and female parents synchronizes well to affect cross-pollination. The other issues related to productivity of seed parents have to be looked into by considering the interaction of genotype with biophysical factors such as spacing and irrigation. Mula et al. (2011) reported that growth and yield of female parent ICPA 2043 were significantly affected by row ratio, plant spacing and soil moisture availability. In Alfisols, the spacing of 75 cm × 30 cm with 3 : 1 row ratio and irrigation at every 14 days produced A-line seed yield of 1872 kg/ha. In vertisols, the seed yield of 2357 kg/ha was recorded at Patancheru at the spacing of 75 cm × 30 cm with 3 : 1 row ratio and irrigation at every 21 days.

To harvest good hybrid seed yield, it is imperative to select suitable seed production sites with good insect pollinator activity. To achieve this, a few small pilot seed production plots were sown at a number of locations in diverse environments, and the sites with abundance of bees (as indicated by pod set on male-sterile plants) were selected for hybrid seed production. Large-scale hybrid seed production in central India was successful with hybrid yields ranging between 1333 and 3040 kg/ha (Table 1). Similarly, a few high-yielding seed production sites were also identified in the Indian states of Andhra Pradesh, Maharashtra and Gujarat.

In most field crops, it may not be possible to produce large quantities of crossed seed with such a moderate level of outcrossing, but in the male-sterile populations of pigeonpea, good amounts of seed set are often recorded. In the present context, good hybrid yield is obtained even with 25–30% outcrossing. This is primarily attributed to prolonged flowering in pigeonpea as an evolutionary consequence. The pollinating insects may visit the male-sterile plants several times, and in each visit, a certain proportion of the flowers are pollinated to set the pods while the un-pollinated flowers should drop. This is followed by the emergence of new flowers on the same plant, and again a proportion of them set pods through open pollination. This cycle continues, and at the end of the season, plenty of crossed pods are observed (Fig. 2) on each male-sterile plant (Saxena et al. 2005). This phenomenon delays pod maturity on female parent by 3–4 weeks.

Table 1: Hybrid pigeonpea seed production in some selected areas in India, 2011

Location	Area (ha)	Production (kg)	Yield (kg/ha)
Madhya Pradesh			
Tikamgarh	5.0	15 200	3040
Seoni	1.0	2500	2500
Indore	0.15	340	2267
Rewa	1.0	1740	1740
Katni	3.0	4350	1450
Jabalpur	1.5	2000	1333
Andhra Pradesh			
Nizamabad	0.4	700	1750
Patancheru	0.4	500	1250
Medchal	1.4	1700	1214
Warangal	1.2	1275	1063
Nalgonda	2.0	2000	1000
Maharashtra			
Risod	0.6	600	1000
Gujarat			
Ahmedabad	0.8	850	1063
Mean	–	2597	1590

Economics of Hybrid Seed Production

The cost–benefit estimates are vital for every business enterprise. The hybrid seed cost should be such that the hybrid could be made available to small-holder farmers at affordable prices. Also, this endeavour should yield sufficient profits to the seed companies. According to Saxena et al. (2011), the cost of producing hybrid seed in one hectare was Rs. 26 395 (US$ 523). One kilogram of seed was sold at Rs. 60 (US$ 1.2)/kg and generated a total revenue of Rs. 86 400 (US$ 1728)/ha. Further, it was also estimated that the hybrid pigeonpea seed production can yield profits as high as Rs. 60 000 (US$ 1205)/ha as compared to Rs. 34 996 (US$ 693)/ha for pure line variety. In this study, the cost of producing 1 kg hybrid seed was estimated at Rs. 18.32 (US$ 0.37)/kg.

Development of Marker-Based Hybridity Test

For sustaining the productivity of hybrids, it is important to produce and supply genetically pure hybrid seed to farmers. In general, the purity of hybrid seed is assessed through standard 'grow-out test' using simply inherited morphological traits (Saxena 2006). In pigeonpea, such tests take more time due to the long duration of the crop and feasibility to raise a single crop in a year, particularly in medium and long duration of pigeonpea hybrids. Therefore, a simple, rapid and cost-effective hybrid seed quality testing approach in pigeonpea based on molecular markers assay is very much needed. Saxena et al. (2010) identified a set of simple sequence repeat (SSR) markers for testing the hybridity of ICPH 2671. They used 148 SSR markers for polymorphism survey on 159 parental lines of hybrids. Of these, a total of 41 markers were found polymorphic. Bohra et al. (2011) used a set of 18 149 SSR markers that could be used in multiplexes for assessing the hybridity of ICPH 2671. From this study a set of 42 SSR diagnostic markers were identified for hybrid ICPH 2671. This assay (Fig. 3) can now be used by both the public and private seed companies for reliable detection of seed

Fig. 2: A snapshot showing the pod set on hybrid seed production plot

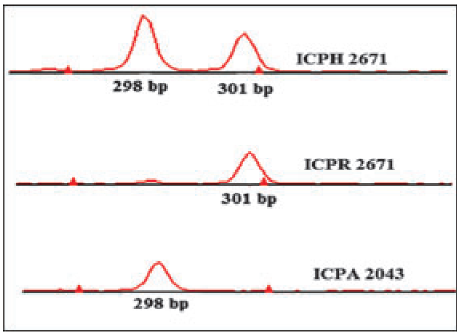

Fig. 3: A snapshot showing the hybrid purity assessment of hybrid ICPH 2671 with the CcM 0021 marker. The parental lines ICPA 2043 (A-line) and ICPR 2671 (R-line) show 298- and 301-bp alleles, respectively, on screening with a diagnostic simple sequence repeat (SSR) marker (CcM 0021), while ICPH 2671 seed showing the presence of both alleles (298 and 301 bp) represents true hybrid (Bohra et al. 2011)

purity within the commercial seed lots of hybrids ICPH 2671 to ensure the supply of high-quality seeds. For assessing the genetic purity of a large number of farmers' samples, alternative genomics technologies were explored and found that the single-nucleotide polymorphisms (SNPs)-based marker purity assay was the best. In this approach, 16 SNPs (R. K. Varshney, unpublished data) could be used for testing the genetic purity of the parents (ICPA 2043 and ICPR 2671) and the hybrid ICPH 2671. This is an easy, rapid and relatively cheap approach with a single data point costing 0.5 US$.

Features of the First Commercial Pigeonpea Hybrid ICPH 2671

Parentage and morphological traits

Hybrid ICPH 2671 (Fig. 4) was produced by crossing CMS line (ICPA 2043) with pedigree reading as (ICPA 2039 × ICPL 20176) × ICPL 20176 × ICPL 20176 × ICPL 20176 × ICPL 20176 × ICPL 20176 × ICPL 20176 with a restorer line (ICPR 2671) with pedigree of ICPX 78143 (C 11 × ICP 1-6)-WB-WB-WB-WB-W27–B. The plants of ICPH 2671 are semi-spreading and non-determinate in growth habit with profuse secondary and tertiary branches achieving a height of 210–226 cm at Patancheru (17°N). Inherently, the canopy of ICPH 2671 is sensitive to photoperiod and plastic in nature and responds to both spacing and planting time. The sowings around the longest day produce large canopy, and it reduces gradually as the sowings approach shorter days. Similarly, the size of canopy is big at wide spacing and small at close spacing. The deep roots of ICPH 2671 impart ability to tolerate drought and produce reasonably good yields under stress conditions (Saxena 2008). On average, ICPH 2671 flowers in 114–120 days and its 75% pod maturity is achieved in 164–184 days at Patancheru, India. The flowers of ICPH 2671 are yellow with dense red streaks on their petals. The pods of this hybrid are dark purple in colour and on average contain 3.7–4.0 seeds. The genetics of seed colour in this hybrid is interesting. The seed colour of both the parents and the F_1 hybrid (A × R) is brown, but the commercial seed produced on the F_1 plants are purple (colour code 183C of the Standard Identification Numbers of Royal Horticulture Society). However, the colour of cotyledon is yellow. Saxena et al. (2012) reported that the seed colour in this hybrid is controlled by three dominant genes; the female parent carries two such genes while the third gene is present in the male parent. The purple colour in the seed is produced when one or both the genes present in the female parent interact with the gene present in the male parent. The 100 seeds of ICPH 2671 weigh between 10.5 and 11.2 g. The fertility restoration in this hybrid is high (95–100% pollen fertility), stable across environments and controlled by two dominant genes (Dalvi et al. 2008, Sawargaonkar et al. 2012).

The plants of hybrid ICPH 2671 are more vigorous than pure line varieties, and it helps in quick establishment and competitiveness (Saxena et al. 1992). They also reported that 1-month-old seedlings of the hybrids produced 43.9% higher shoot and 42.8% higher root mass than that of traditional cultivars. Higher crop growth rate of the hybrid results in more biomass production, which helps in significant (50%) reduction in the seeding rate of the hybrid crop.

Fig. 4: The world's first commercial pigeonpea hybrid ICPH 2671 released in India has shown in the picture at pod maturity stage

Resistance of ICPH 2671 to biotic stresses

Fusarium wilt and sterility mosaic are major pigeonpea diseases, and together, they cause significant yield losses every year (Reddy et al. 1990). ICPH 2671 has demonstrated high levels of resistance to both the diseases over years in farmers' fields as well as at research stations. In general, the hybrids are known to express better environmental buffering compared with pure line cultivars (Saxena 2009). Therefore, the yield fluctuations brought about by various stresses could be reduced by cultivating pigeonpea hybrids based on genetically diverse parentage.

Resistance to abiotic stresses

As pigeonpea is grown as a rainfed rainy season crop, it is subjected to both drought (intermittent and terminal) and temporary waterlogging. It has been observed that in comparison with pure line cultivars, the hybrid ICPH 2671, by virtue of its greater root mass and depth, possesses greater ability to draw water from deep soil profiles (Sultana et al., 2012). Its fast root growth also helps plants to tide over early season drought conditions. Lopez et al. (1996) demonstrated that early maturing hybrids maintained relatively high water content under adverse conditions, which contributed to its capacity to enhanced drought tolerance.

Evaluation of pigeonpea hybrids and pure line varieties under 8 days of continuous waterlogging revealed that hybrid ICPH 2671 had survival rate (88%) as compared to a pure line variety (58%), irrespective of their stage of testing (seed, early seedling and late seedling stages). The high survival rate in the hybrid was attributed to its ability to utilize the stored assimilates through anaerobic metabolism during germination and early seedling growth (Choudhary et al. 2011). In another set of experiment, it was also observed that the genotypes with dark seed coat exhibited greater (64.5%) survival in comparison with the light-coloured (54.4%) genotypes. As seed coat colour of ICPH 2671 is dark, the presence of various phenolic and tannins reduced the rate of water uptake in the seeds. Khare et al. (2002) reported that the dark-seeded pigeonpea genotypes encountered waterlogged situations much better than those with light-coloured seeds. The greater waterlogging tolerance in the hybrid may also be related to relatively high initial vigour of the hybrid plants, which experienced less oxygen deprivation during submergence as compared to pure line cultivars.

Quality parameters and consumer preference

It is essential that any new food product matches well with those in common use with respect to various quality, organoleptic and market preferred traits. It is more important in the present case because one of the parents of the hybrid is derived from a wild species. Hence, the hybrid was compared to the local cultivar 'BSMR 736' for important food quality parameters (Table 2). The data showed that the hybrid ICPH 2671 compared well with respect to milling recovery, an important trait for traders and for dal mill industry. The protein content of hybrid (20.73%) was more or less similar to that of local cultivar (19.86%). The hybrid ICPH 2671 took about 5 min less to cook, a trait that is preferred by most consumers (Sawargaonkar 2011). In addition, we also conducted 357 organoleptic tests of dal (decorticated split peas) in Maharashtra, Andhra Pradesh and New Delhi. The survey reported that 79.2% consumers preferred hybrid dal over the market samples for its taste and flavour; 18.6% found it as good as the market sample, and 2.2% rated the hybrid dal inferior to market sample (unpublished data).

As the seed colour of commercial grains of hybrid ICPH 2671 is dark due to specific complementary gene action (Saxena et al. 2012), its marketing posed some problems in the states of Karnataka, Andhra Pradesh and Maharashtra where brown seeded pigeonpea is preferred. However, in the states of Madhya Pradesh and Jharkhand, the seed colour was not an issue, and hence, this hybrid was released in Madhya Pradesh.

Productivity of ICPH 2671

Performance in on-station multilocation trials

During 2005–2008, the hybrid ICPH 2671 was tested in 21 multilocation trials (Table 3) and its mean performance in different years ranged from 2117 to 3183 kg/ha. On average, the hybrid produced 2736 kg/ha yield, demonstrating 47% superiority over the control 'Maruti' (1862 kg/ha). The highest yield of 5375 kg/ha was recorded at Aurangabad. Further, to generate the performance data of the hybrid in central and south zone, it was tested in the All India Co-ordinated Research Project (AICRP) on pigeonpea under the aegis of Indian Council of Agricultural Research (ICAR) at six locations in 2007. In Warangal, it recorded the highest yield of 3583 kg/ha as against 2134 kg/ha for control 'Asha' and 1549 kg/ha for control 'Maruti'. Over all the six locations, the hybrid ICPH 2671 produced 2490 kg/ha yield, and it was, respectively, 35% and 29% superior to control cultivar 'Maruti' and 'Asha'.

Table 2: Important quality parameters of hybrid ICPH 2671 and control cultivar 'BSMR 736'

Quality parameters	ICPH 2671	'BSMR 736'
Dal recovery (%)	77.42	76.49
Processing losses (%)	6.83	5.96
Protein (%)	20.73	19.86
Cooking time (min)	32.44	38.25
Water absorption (g/g)	1.74	2.14
Taste	Excellent	Excellent
Flavour	Very good	Good
General acceptability	Excellent	Very good

Source: Sawargaonkar (2011).

Performance in farmers' fields

During 2009 and 2010, ICPH 2671 was evaluated in 2013 on-farm locations of five Indian states (Table 4). Each trial involving hybrid and local check was grown on one-acre land, and the farmers were allowed to use their own package of practices. A total of 782 trials were conducted in seven districts of Maharashtra, and on average, ICPH 2671 (969 kg/ha) produced 35% more yield over the control variety 'Maruti' (717 kg/ha). In Andhra Pradesh (399 trials), the hybrid exhibited 56% superiority over the control. Similarly in Karnataka (184 trials) and Madhya Pradesh (360 trials), the hybrid outyielded the control cultivar by the margin of 26% and 56%, respectively. In Jharkhand, ICPH 2671 was evaluated in 288 on-farm trials, and the hybrid ICPH 2671 demonstrated 69% superiority over the control cultivar 'Bahar'. Considering the overall performance in the five states, the hybrid ICPH 2671 produced 1396 kg/ha yield, and it was 46.5% more than the local check (953 kg/ha). The yield advantages recorded by ICPH 2671 are very encouraging, and it is expected that a large-scale adoption of the hybrid could enhance productivity of pigeonpea in India. In 2009, the hybrid ICPH 2671 was evaluated in 36 on-farm trials conducted in six provinces of Myanmar (Table 5), and, on average, the hybrid (1057 kg/ha) was 20% superior (Kyu et al. 2011) to local control (881 kg/ha).

Hybrid to resolve the pigeonpea yield plateau: general view

Even after centuries of cultivation and natural selection, pigeonpea still retains unique characteristics such as perennial and indeterminate growth habit, low harvest index, and photo – and thermosensitivity. Its ability to survive and produce high protein food even under stress conditions helps in providing food and nutrition security to subsistence farmers, and therefore, it may be considered as the ideal rainfed legume crop of small-holder farmers. As the demand for food legumes like pigeonpea is ever increasing and the scope for area expansion is limited, the attention is now focusing on increasing and stabilizing its economic yield. In order to enhance the productivity, more than 100 pure line varieties were released in India, but these could not bring any significant improvement in the crop productivity, and the yields have remained consistently low for the past six decades. In this context, ICRISAT and partners took an initiative to explore the possibility of enhancing yield by breeding high-yielding hybrids.

The successful developments of a stable CMS system and the existing natural cross-pollination have opened up an avenue for enhancing the yield potential of pigeonpea through hybrids. The yield superiority recorded in pigeonpea hybrids in different years and different locations has conclusively established the high yield potential of hybrids. The magnitude of realized standard

Table 3: Yield of hybrid ICPH 2671 and control cultivar 'Maruti' in multilocation trials conducted in India

Year	Location	Hybrid yield (kg/ha)	Control yield (kg/ha)	Standard heterosis (%)	SEM±	CV (%)
2005	Patancheru	2671	1677	59	207.7	13.7
	Medchal	2996	1041	188	331.1	21.1
	Bangalore	2571	1476	74	540.7	32.2
	Jalna	3416	2541	34	152.1	7.3
	Coimbatore	4262	2538	68	252.7	17.3
	Mean	3183	1855	72	–	–
2006	Patancheru	2660	1919	39	140.7	7.8
	Coimbatore	1823	1100	66	324.7	28
	Jalna	1948	1092	78	91.8	10.2
	Phaltan	3208	2243	43	270.1	19.1
	Mean	2410	1589	52	–	–
2007	Patancheru	2373	1931	23	191.8	12.1
	Aurangabad	5375	3893	38	267.8	7.6
	Jalna	2038	1713	19	206.8	17.8
	Medchal	2936	2350	25	604.0	26.4
	Pargi	2253	1328	70	493.5	28.2
	Akola	2489	1557	60	288.8	21.1
	Phaltan	3439	2694	28	281.1	12.1
	Mean	2986	2209	35	–	–
2008	Patancheru	2534	1790	42	194.8	15.4
	Jalna	2670	2083	28	43.7	3.1
	Parbhani	2006	1863	8	334.8	23.3
	Medchal	707	391	81	58.9	14.0
	Aurangabad	3085	1889	63	145.0	9.0
	Mean	2117	1603	45	–	–
	Grand mean	2736	1862	47.0	–	–

Table 4: Mean yield of hybrid ICPH 2671 and control 'Maruti' in on-farm trials conducted in five states of India during 2009 and 2010

State	Districts	Number of farmers	Hybrid yield (kg/ha)	Control yield (kg/ha)	Standard heterosis (%)
Maharashtra	7	782	969	717	35
Jharkhand	9	288	1460	864	69
Andhra Pradesh	8	399	1411	907	55
Karnataka	4	184	1201	951	26
Madhya Pradesh	10	360	1940	1326	46
Mean/total	38	2013	1396.2	953.0	46.5

Table 5: Performance of pigeonpea hybrid ICPH 2671 in farmers' fields in Myanmar, 2009

Division	Township	Number of trials	Yield (kg/ha) Hybrid	Yield (kg/ha) Local check	Standard heterosis (%)
Sagaing	Monywa	6	1830	1414	29.4
Sagaing	Depeyin	6	1051	1051	0.0
Sagaing	Myinmu	6	619	542	14.2
Mandalay	Myingyan	6	1300	1162	11.9
Mandalay	Nhahtoegyi	6	842	550	53.1
Mandalay	Taungtha	6	700	567	23.5
Mean		36	1057	881	20.0

Source: Kyu et al. (2011).

heterosis for yield over check varieties in pigeonpea is high, and under well-managed and high-input conditions, the productivity of the crop can approach about 4000 kg/ha or more (Table 6). We believe that the CMS-based hybrid pigeonpea technology is now ready for take-off with all its major components in place, and our major responsibility is to take this new product to both small- as well as large-scale farmers. To achieve this, it will be necessary to keep the hybrid seed costs within the reach of resource-poor farmers. In India, both public and private seed sectors are strong, and these are being harnessed to improve the accessibility of hybrid seed to farmers. As a grower-friendly hybrid seed production technology is now available, it can be concluded that hybrid vigour can be exploited commercially to increase the pigeonpea production and productivity. The scientific community firmly believes that in pigeonpea, the breakthrough in yield will come through the hybrids. In this endeavour, an excellent beginning has been made, and it is expected that the farmers of the tropics and subtropics will benefit from this technological breakthrough.

Table 6: High yields from pigeonpea hybrids recorded under irrigated conditions as a sole crop, in 2009 in Maharashtra (India)

Locations	Area (m^2)	Hybrid yield (kg/ha)	Control yield (kg/ha)	Standard heterosis (%)
Salod	450	3956	2044	94
Nimgaon	1012	3951	2469	60
Kothoda	450	4667	3556	31
Tamoli	450	3889	2278	71
Mean		4115.8	2586.8	59.1

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References

Alexandratos, N., 2001: World Agriculture Towards 2010 and FAO Study: Growth of Agricultural Production in Developing Countries, 151—204. Published by FAO UN and John Wiley and Sons, New York, ISBN: 92-5-10 3590-3.

Bohra, A., A. Dubey, R. K. Saxena, R. V. Penmetsa, K. N. Poornima, N. Kumar, A. D. Farmer, G. Srivani, H. D. Upadhyaya, S. R. Ramesh, D. Singh, K. B. Saxena, P. B. Kavi Kishor, N. K. Singh, C. D. Town, G. D. May, D. R. Cook, and R. K. Varshney, 2011: Analysis of BAC-end sequences (BESs) and development of BES-SSR markers for genetic mapping and hybrid purity assessment in pigeonpea (*Cajanus* spp.). BMC Plant Biol. **11**, 56—70.

Brar, H. S., H. S. Jhajj, and G. S. Gatoria, 1992: Abundance and activity of the bee visits to pigeonpea [*Cajanus cajan* (L.) Millsp.] and role of *Apis mellifera* (L.) in its pollination. Indian Bee J. **54**, 76—80.

Choudhary, A. K., R. Sultana, A. Pratap, N. Nadarajan, and U. Jha, 2011: Breeding for abiotic stresses in pigeonpea. J. Food Legum. **24**, 165—174.

Dalvi, V. A., K. B. Saxena, and I. A. Madrap, 2008: Fertility restoration in cytoplasmic-nuclear male sterile lines derived from three wild relatives of pigeonpea. J. Hered. **99**, 671—673.

De, D. N., 1974: Pigeonpea. In: J. Hutchinson (ed.), Evolutionary Studies in World Crops, 79—87. Cambridge University Press, London.

FAO, 2010: Available at: www.faostats.org (last accessed on October 30, 2011).

Khare, D., S. Rao, J. P. Lakhani, and R. G. Satpute, 2002: Tolerance for flooding during germination in pigeonpea. Seed Res. **30**, 82—87.

Kollipara, K. P., L. Singh, and T. Hymowitz, 1994: Genetic variation of trypsin and chymotrypsin inhibitors in pigeonpea [*Cajanus cajan* (L.) Millsp.] and its wild relative. Theor. Appl. Genet. **8**, 986—993.

Krishna, T. G., and L. J. Reddy, 1982: Species affinities between *Cajanus cajan* and some *Atylosia* species based on esterase isozymes. Euphytica **31**, 609—713.

Kuznecov, P. V., 1966: Heterosis in plant production. Record of the Proceedings of the Joint Session of the Lenin All-Union Academy of Agricultural Sciences, the Department of General Biology and the Department of Biochemist, 290—297.

Kyu, K. L., K. B. Saxena, R. V. Kumar, and A. Rathore, 2011: Prospects of hybrids in enhancing production and productivity of pigeonpea in Myanmar. J. Food Legum. **24**, 1—7.

Ladinzinsky, G., and H. Hamel, 1980: Seed protein profiles of pigeonpea (*Cajanus cajan*) and some *Atylosia* species. Euphytica **29**, 313—317.

Lopez, F. B., Y. S. Chauhan, and C. Johansen, 1996: Effects of timing of drought stress on phenology, yield and yield components of short-duration pigeonpea. J. Agron. Crop Sci. **177**, 311—320.

van der Maesen, L. J. G., 1990: Pigeonpea: origin, history, evolution, and taxonomy. In: Y. H. Nene, S. D. Hall, and V. K. Sheila (eds), The Pigeonpea, 15—46. C.A.B. International, Wallingford, UK.

Mula, M. G., K. B. Saxena, R. V. Kumar, and A. Rathore, 2011: Influence of spacing and irrigation on the seed yield of a CMS line 'ICPA 2043' of hybrid pigeonpea. J. Food Legum. **24**, 202—206.

Nadimpalli, R. J., R. L. Jarret, S. C. Pathak, and G. Kochert, 1993: Phylogenetic relationships of the Pigeonpea (*C. cajan*) based on nuclear restriction fragment length polymorphisms. Genome **36**, 216—223.

Ohri, D., and S. P. Singh, 2002: Karyotypic and genome size variation in *Cajanus cajan* (L.) Millsp. and some wild relative. Genet. Res. Crop Evol. **49**, 1—10.

Onim, J. F. M., 1981: Pigeonpea improvement research in Kenya. In: Y. L. Nene (ed.), Proc. International Workshop on Pigeonpeas, 15–19 Dec, 1980, Vol. 1, 427—436. ICRISAT Center, Patancheru, AP, India.

Pathak, G. N., 1970: Red gram. Pulse Crops of India, 14—53. Indian Council of Agricultural Research, New Delhi, India.

Paul, I., R. Don, K. McMahon, and M. Bernstein, 2011: Nutrition, 425. Jones and Bartlet Publishers, Sudbury, MA, ISBN 978-0-7637-7663-3.

Rai, N., and M. Rai, 2006: Heterosis Breeding in Vegetable Crops. G. Kalloo (ed.), 531. New India Publishing Agency, New Delhi, India, ISBN: 81-89422-03-0.

Ratnarpakhe, M. B., V. S. Gupta, M. R. Murthy, and P. K. Ranjekar, 1995: Genetic fingerprinting of pigeonpea [*Cajnus cajan* (L.) Millsp.] and its wild relatives using RAPD markers. Theor. Appl. Genet. **91**, 893—898.

Reddy, L. J., and D. G. Faris, 1981: A cytoplasmic-genetic male-sterile line in pigeonpea. Int. Pigeonpea Newsl. **1**, 16—17.

Reddy, B. V. S., J. M. Green, and S. S. Bisen, 1978: Genetic male-sterility in pigeonpea. Crop Sci. **18**, 362—364.

Reddy, M. V., S. B. Sharma, and Y. L. Nene, 1990: Pigeonpea: disease management. In: Y. L. Nene, S. D. Hall, and V. K. Shiela (eds), The Pigeonpea, 303—347. C.A.B. International, Wallingford, Oxon, UK.

Sawargaonkar, S. L., 2011: Study of Heterosis, Combining Ability, Stability and Quality Parameters in CGMS Based Pigeonpea [*Cajanus cajan* (*L.*) Millsp.] Hybrids, 151. PhD Thesis. Marathwada Agricultural University, Parbhani, Maharashtra.

Sawargaonkar, S. L., I. A. Madrap, and K. B. Saxena, 2012: Study of inheritance of fertility restoration in pigeonpea lines derived from *Cajanus cajanifolius*. Plant Breed. **131**, 312—314.

Saxena, K. B., 2006: Seed Production Systems in Pigeonpea, 76. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India, ISBN 92-9066-490-8.

Saxena, K. B., 2008: Genetic improvement of pigeonpea- a review. Trop. Plant Biol. **1**, 159—178.

Saxena, K. B., 2009: Evolution of hybrid breeding technology in pigeonpea. In: M. Ali, and S. Kumar (eds), Milestone in Food Legume Research, 82—114. Published in IIPR, Kanpur. Milestones in Food Legume Research Conference 2009.

Saxena, K. B., L. Singh, and M. D. Gupta, 1990: Variation for natural out-crossing in pigeonpea. Euphytica **39**, 143—148.

Saxena, K. B., Y. S. Chauhan, C. Johansen, and L. Singh, 1992: Recent developments in hybrid pigeonpea research. New Frontiers in Pulses Research and Development. Proceedings of National Symposium held during 10–12 November 1989, 58—69. Directorate of Pulses Research, Kanpur, India.

Saxena, K. B., R. V. Kumar, N. Srivastava, and B. Shiying, 2005: A cytoplasmic-genic male-sterility system derived from a cross between *Cajanus cajanifolius* and *Cajanus cajan*. Euphytica **145**, 291—296.

Saxena, R. K., K. B. Saxena, and R. K. Varshney, 2010: Application of SSR markers for molecular characterization of hybrid parents and purity assessment of ICPH 2438 hybrid of pigeonpea [*Cajanus cajan* (L.) Millsp.]. Mol. Breed. **26**, 371—380.

Saxena, M. K., U. Saxena, K. B. Saxena, V. S. Khandalkar, and R. Sultana, 2011: Profitability and production cost of hybrid pigeonpea seed. Electronic J. Plant Breed. **2**, 409—412.

Saxena, K. B., R. K. Saxena, R. V. Kumar, and R. K. Varshney, 2012a: Evidence of a unique inter-allelic epistatic interaction for seed coat color in pigeonpea [*Cajanus cajan* (L.) Millspaugh]. Euphytica **186**, 813—816.

Sharma, D., and S. Dwivedi, 1995: Heterosis in grain legume crops – scope and use. In: B. Sharma (ed.), Genetic Research and Education: Current Trends and the Next Fifty Years. B. Indian Society of Genetics and Plant Breeding, 960—979. Indian Agricultural Research Institute, New Delhi, India.

Shull, G. H., 1908: The composition of a field of a maize. Report Am. Breeders's Assoc. **4**, 296—301.

Sultana, R., M. I. Vales, K. B. Saxena, A. Rathore, S. Rao, S. K. Rao, M. Myer, and R. V. Kumar, 2012: Water-logging tolerances in pigeonpea [*Cajanus cajan* (L.) Millsp.]. Genotypic variability and identification of tolerant genotypes. Cambridge J. Agricult. Sci., 1—13.

Williams, I. H., 1977: Behaviour of insects foraging on pigeonpea (*Cajanus cajan* (L.) Millsp.) in India. Trop. Agric. **54**, 353—363.

Zaveri, P. P., and A. R. Pathak, 1998: Hybrid cultivar development. In: S. S. Banga, and S. K. Banga (eds), Pigeonpea, 439—449. Narosa Publishing House, New Delhi, India.