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Review Paper

50-Years of hybrid pigeonpea research and development: The gains and hiccups

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ABSTRACT

To smash the low-yield plateau in pigeonpea [*Cajanus cajan* (L.) Millsp.], a hybrid breeding programme was launched in 1974. Now 50 years of its research and development have been completed and this manuscript takes stock of its accomplishments, hiccups, present status, and future plans. This programme got wings when pigeonpea breeders successfully bred cytoplasmic nuclear male sterility (CMS) systems, and following this, six hybrids with 30-50% standard heterosis were released. To realize the true value of hybrids and commercialize them, a strong seed quality control system is necessary. Traditionally, the genetic truthfulness of hybrid seeds is assessed through a standard "Grow-out Test (GoT)". This involves sowing the freshly harvested hybrid seeds and assessing their progenies for a dominant quality determining phenotypic marker. Pigeonpea, being a short-day species, its plants flower only when the day length is around 10-11 h. Since the pigeonpea crop is harvested under increasing photo-periods, the sowing of hybrid seeds, soon after the harvest will not produce flowers under the prevailing long summer days and this will not allow the required assessment of their progenies. Due to this sole reason, the GoT could not be applied to the released photo-sensitive hybrids. This leaves breeders with no option except to look for some alternative seed quality control system. In this context, the application of molecular markers to discriminate between true hybrids and off-types appeared to be the right way. At present molecular marker-based quality testing kits are available to assist seed producers in controlling the purity of hybrid seeds. We believe that in future a follow-up hybrid promotional programme with new technologies would help in breaking the low-yield plateau and enhance the national pigeonpea production.

Key words: *Cajanus cajan*, Fertility restorer, Heterosis, Male sterile, Out-crossing, Technology transfer, Wild relatives

PIGEONPEA PROFILE AT A GLANCE

Pigeonpea [*Cajanus cajan* (L.) Millsp.], a high-protein drought tolerant pulse that originated about 3000 years ago, is known to play a significant role not only in the sustainability of rainfed agricultural systems, but also in the nutritional security of the inhabited masses of these eco-systems. Although pigeonpea was produced and consumed on large areas since ages, its informal genetic improvement programme was started only in 1931. In the initial years of breeding research, only pure line selections were orthodoxly made within available landraces. This exercise was confined to the selection for seed traits, plant type, disease (wilt) resistance, pod size, pod load, and grain yield. Gradually, similar research activities were also initiated in different parts of India and Africa. This informal breeding led to the selection of some inbred lines which produced reasonably good yields, and among these a few performed well in wilt-prone areas as well. Within this group of improved germplasm, the National Pulse Breeders selected and maintained a few inbreds which were liked and cultivated by farmers for a fairly long period. The pigeonpea breeding activities got momentum after establishment of 'All India Co-ordinated Pulses Improvement Project' by the Indian Council of Agricultural Research (ICAR) in 1967. Over the next few decades, under this research and development endeavour, dozens of inbred cultivars were released, mostly through the selections made within and among diverse landraces. Besides these, a few varieties were also bred from the populations derived from biparental matings and mutagenesis (Singh *et al*. 2015).

Globally, pigeonpea is cultivated in 22 countries at more than 5.38m ha of land area with an average productivity of 850 kg/ha (FAOSTAT 2023). Among these, India ranks first with 4.03 m ha cropped area with total production and mean productivity of 3.31 m t and 814 kg/ha, respectively (FAOSTAT 2023). The other major pigeonpea producing countries are Malawi (451,000 t), Myanmar (307,000 t), Tanzania (196,000 t), and Kenya (104,000 t). Besides these, Uganda, Mozambique, the Caribbean islands, and some South American countries also produce substantial amounts of pigeonpea (FAOSTAT 2023). In India, pigeonpea is cultivated under very diverse cropping and eco-systems, each with its specific maturity, plant type, and other canopy parameters. Asia is the largest contributor with 83.6% and 78.2% to the global pigeonpea area and production, respectively. According to Nigam *et al*. (2021), from 1961-63 pigeonpea production in Asia recorded an increase of 109%, largely due to an increase in the area of 78%. The gain in the mean yield during the same period was negligible (116 kg/ha). They further estimated that by 2030 the world's projected pigeonpea demand would stand at about 5.58 m t; and this trend would continue to grow to over 6.41 m t in another 10 years.

The decorticated splits (*dal*) and fresh immature grains (vegetable) of pigeonpea are used in the preparation of a number of popular and nutritive cuisines (Saxena *et al*. 2010). The demand of pigeonpea is on the rise, and each year it out-scores the production tonnage. To meet domestic needs, not only the entire (4.34 m t) produce consumed locally but each year its bulk quantities are imported. For example, in 2016/17, a total of 7,03,540 t of pigeonpea was imported from Myanmar and Africa (Reuters News Agency, August 5, 2017).

Among adaptation parameters, crop growing period is the most critical. The flowering is controlled by the amount of light absorbed by a plant system. Accordingly, the plant species are classified as qualitative or quantitative short/ long day type. Based on this criterion, pigeonpea is classified as a quantitative short-day plant with its critical light hour requirement being 11-13 h (Silim *et al*. 2007). In general, the pigeonpea plants are either determinate or non-determinate and the flowering is profuse, but only 10-20% of them produce pods (Saxena 2008). Pigeonpea flowers are unique because they allow both self- as well as cross-pollination on the same plant. They have 10 anthers which are placed in a di-adelphous (9+1) configuration. Cross-pollination in pigeonpea is brought about by a variety of flying insects (Saxena *et al*. 2016) which collect pollen while foraging the flowers for harvesting honey. The cross-pollination in pigeonpea varies considerably from location to location, but on an average, it is between 25 to 30%.

Pigeonpea exhibits a large variation for maturity, and based on their flowering at 17 °N, the germplasm has been classified into 11 groups (Table 1). However, for practical purposes it is broadly grouped (Table 1) into extra-early (91-120 d), early (121-150 d), medium (161-200 d), and late (>220 d) types (Saxena *et al*. 2019). This variation allows farmers to choose the most suited variety for cultivation. But in the entire country the medium maturing types are most popular, and they occupy the largest (≈ 65%) area, followed by late varieties (≈30%). The early maturing cultivars occupy only ≈5% of the area. Botanically, the entire *Cajanus* genus is perennial but traditionally all the cultivars are grown as annuals. Besides these, some large seeded genotypes are also grown as short (2-3 years) perennials on field bunds or as hedges. Among the major production constraints, some biotic (*Helicoverpa*, *Maruca*, wilt, sterility mosaic) and abiotic (water logging, salinity) stresses are considered the main yield reducers (Choudhary *et al*. 2011, Choudhary and Nadarajan 2011).

In comparison to cereals, pulses are known to produce less food per unit area; and there are scores of agronomic, physiological, and genetic factors for their low productivity. To overcome at least some key productivity constraints, well-knit plant breeding efforts have been pursued for the past 6-7 decades using new genetic materials and breeding methods. The perusal of these crop improvement endeavours reveal that significant progress has been

Table 1. Pigeonpea maturity groups based on days to maturity at Patancheru (17° N 30′)

Maturity group		Maturity (days)	Adaptation system
ICRISAT	**Popular**		
00	Super-early	< 90	Sole crop
0	Extra-early	91 – 100	
I	Extra-early	101 –120	
II	Early	121 – 130	
III	Early-medium	130 – 140	
IV	Early-late	141 – 150	
V	Medium-early	151 – 160	Inter or mixed crop
VI	Medium-I	161 – 180	
VII	Medium-II	181 – 200	
VIII	Mid-late	201 – 220	
IX	Late	>220	

Source: Saxena *et al*. (2019)

registered in developing cultivars which resist the menace of fusarium wilt and sterility mosaic virus, the two threatening diseases of pigeonpea. Also, a notable success has been recorded in the areas of breeding high yielding early maturing varieties by incorporating key market-preferred seed traits (Saxena *et al*. 2019).

With respect to enhancement of pigeonpea yield through breeding efforts, it is obvious that, in spite of huge investment of resources, the progress has been far from the satisfactory level (Figure 1). The varieties released for cultivation after nation-wide coordinated testing showed very low yield gains (Nigam *et al*. 2021). Besides this, the performances also lacked a high stability to encounter the threats of various biotic and abiotic stresses and changing environment.

Although the joint plant breeding efforts by ICAR and ICRISAT were encouraging with respect to some research areas, but these were not good enough to meet the increasing national demand of this pulse. This is evident from the mean yield data spreadsheet which shows that the national pigeonpea productivity is unacceptably low, and over the past 5-6 decades it has been hanging around 600-800 kg/ha. In view of nutritional security of under-privileged masses and demand and supply scenarios of pigeonpea, the Indian policymakers and scientists, particularly breeders are concerned about its low yield plateau. To overcome this production constraint, long-term strategic research and development programmes have been designed from time to time, and amongst them, breeding the commercial hybrids has been the most ambitious.

BREEDING HYBRIDS: A GIANT STEP IN BREEDING PIGEONPEA

As stated, in spite of decades of research efforts and huge investment of resources, productivity

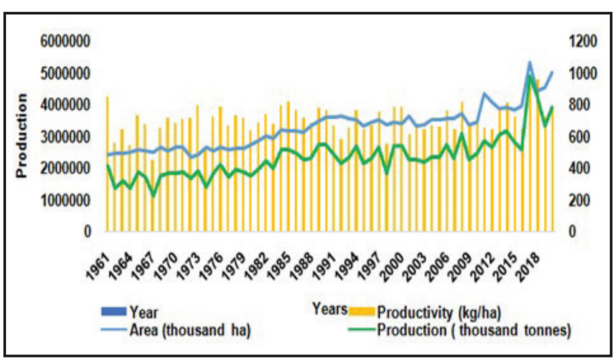

Fig. 1. Pigeonpea global area, production and productivity

Fig. 2. Advantage in seedling growth of hybrid (left) over inbred variety (right) at 60 days

increases did not meet the expectations. Limitation of arable land, increasing costs of inputs and population increases increased the pressure on crop scientists to enhance crop productivity on a sustainable basis.

Historically, exploitation of heterosis in enhancing yield has been globally recognized. This breeding technology had evolved initially for maize and later applied to other out-breeding crops. But it could not be implemented in legumes due to their predominantly self-pollinating nature. Pigeonpea, however, is a different legume with respect to its pollination behaviour. The large bright coloured flowers of pigeonpea produce nectar which invites a variety of foraging insects. In the process, a load of viable pollen grains get stuck to their abdomen, and when they visit other flowers, the pollen grains are scrubbed onto stigmatic surface to affect cross-pollination and fertilization. In literature, a number of out-crossing reports have appeared from different locations exhibiting 25-30% cross-pollination in pigeonpea (Saxena *et al*. 2016).

In 1973, a comprehensive pigeonpea improvement programme was launched at ICRISAT. As a follow up, the institute's breeding team thoroughly reviewed different international pigeonpea research and development programmes. The team concluded that the breeders in the past explored different breeding methods recommended for self-pollinated crops but with no positive results. Therefore, there was need to think out-of-the box to smash the low yield plateau of pigeonpea. Soon the breeders planned to breed hybrids in pigeonpea using its partial natural cross-pollination. It was, indeed, a Herculean plant breeding task since no hybrid was ever bred in any food legume. There are three important pre-requisites of successful hybrid breeding technology in any crop. These include (i) presence of significant levels of hybrid vigour for grain yield, (ii) an effective mass cross-pollination mechanism, and (iii) cost-effective methods of producing genetically pure hybrid seed. Hence, the hybrid pigeonpea breeding programme was launched at ICRISAT with research planned on all three critical areas. This endeavour was joined by a number of ICAR institutions and some private seed companies.

Solomon *et al*. (1957) were the first to report significant (24%) hybrid vigour over the better parent for yield in pigeonpea. The recent reviews on this aspect by Saxena *et al*. (2018) and Sawargaonkar and Saxena (2020) revealed that many hybrids carry exploitable hybrid vigour in early, medium, and late maturity groups. The mass-pollen transfer in pigeonpea takes place through a number of flying insects including *Megachile* and *Apis* species. For exploiting heterosis at commercial level, the production of hybrid seed in large quantities is essential. To facilitate this, availability of stable male sterility systems was essential; but unfortunately, such a system was not available in pigeonpea, and therefore, it became mandatory to breed a stable male sterility system.

In most cases, the male sterility in plants arises through spontaneous mutations. Besides this, such male-sterile genotypes can also be bred through the application of certain physical/ chemical mutagens and wide hybridizations. Both, Stephens (1937) and Jones and Emsweller (1937), simultaneously demonstrated that male sterility in plants can be used to produce hybrid seeds without manual emasculation. Later, the plant breeders also discovered the ways to exploit the hybrid vigour on a large scale for increasing the overall productivity of cross-pollinated crops. Pigeonpea is the first grain legume in which this technology has been successfully developed.

DEVELOPMENT OF GENETIC MALE STERILITY-BASED HYBRID BREEDING TECHNOLOGY

Breeding of genetic male-sterility system

In pigeonpea, the first spontaneous male sterile mutant was reported by Reddy *et al*. (1978). This source, identified within germplasm collection of 7,216 accessions, had fully developed translucent anthers but no pollen grains. Cytological studies showed that during microsporogenesis the tetrads failed to separate due to persistence of tapetum layer. A single recessive allelic pair controlled this genetic male sterile (GMS) trait. Soon some more sources of GMS were also reported through spontaneous mutagenesis (Saxena and Hingane 2015); however, only the translucent anther type of male sterility was used in breeding pigeonpea hybrids.

Releases of GMS-based hybrids

The first GMS-based pigeonpea hybrid 'ICPH 8' was bred at ICRISAT, and was tested in collaboration with various ICAR institutions. Evaluation of this hybrid in 100 yield trials under different agro-ecological conditions showed that 'ICPH 8' was superior to the control cultivar 'UPAS 120' by 35%. In the on-farm trials conducted in two states, this hybrid demonstrated 20-30% superiority over the national control. Since no commercial hybrid was ever bred before in food legumes, the release of the world's first pigeonpea hybrid 'ICPH 8' (Saxena *et al*. 1992) is considered a major technological breakthrough. Subsequently, five more GMS-based hybrids were also released by ICAR (Table 2). These included 'PPH 4' in Punjab with 32% standard heterosis, 'CoH 1' (32% heterosis) and 'CoH 2' (35% heterosis) in Coimbatore, and 'AKPH 4104' (35% heterosis) and 'AKPH 2022' (64% heterosis) in the state of Maharashtra (Table 2).

Table 2. Standard heterosis (%) in GMS-based pigeonpea hybrids

Name	Parents	Year	State	Standard heterosis*
ICPH 8	ms Prabhat × ICPL161	1991	Telangana	31
PPH 4	msPrabhat × ICPL 81	1994	Punjab	32
CoH 1	msT21 × ICPL 87109	1994	Tamil Nadu	32
CoH 2	msCo5 × ICPL 83027	1997	Tamil Nadu	35
AKPH 4101	AKms4 × AK 101	1997	Maharashtra	35
AKPH 2022	AKms2 × AK22	1998	Maharashtra	64

Source: IIPR, Kanpur, India; *over the best local check

SEED PRODUCTION OF GMS-BASED HYBRIDS

In field crops, where hybrid seed requirement is high, the GMS-based hybrid seed technology is difficult to adopt. The main issue is the maintenance of genetic purity of female parent and hybrid seeds. This is because the female parent population would always segregate for male fertility and sterility, and for seed production, uprooting of 50% fertile segregants from this population is mandatory. The manual rouging activity within the female rows is labour intensive, and it is not practical in the large production plots because this operation is time-bound. Therefore, in spite of high heterosis, these were not accepted by seed producers.

INITIAL EFFORTS TO BREED A CYTOPLASMIC NUCLEAR MALE STERILITY (CMS) SYSTEM IN PIGEONPEA

Since the screening of vast germplasm failed to yield any CMS genotype, the efforts were made to breed this system through mutagenesis and inter-specific hybridizations. The first attempt in this endeavour was made by Reddy and Faris (1981) by crossing a wild species *C. scarabaeoides* as female with a fertile F_1 hybrid of *C. cajan* × *C. scarabaeoides* as male parent. The resulting BC_1F_1 was male fertile; but in its BC_1F_2 generation, a few male-sterile segregants were identified. This observation gave a strong indication that in certain hybrid combinations, carrying the cytoplasm of *C. scarabaeoides*, the CMS genotypes could be bred. Subsequently, Ariyanayagam *et al*. (1995) attempted to breed CMS genotypes by integrating the nuclear genome of pigeonpea into the cytoplasm of *C. sericeus*. The hybrid plants derived from this cross were partially male-sterile, and their backcross populations segregated for male-sterility and fertility. This programme was adversely affected due to frequent reversal of male sterility to male fertility.

SUCCESSFUL BREEDING OF CMS SYSTEMS IN PIGEONPEA

Considering long-term sustainability of hybrid technology, it becomes important to infuse mitochondrial diversity in the breeding programme. This will shield future hybrids from the threats of various stresses associated with that particular cytoplasm. The efforts made in this direction in pigeonpea produced good results, leading to the identification of nine CMS-inducing cytoplasmic systems. This may help in developing a strong broad-based hybrid breeding programme. Of these, seven systems were from wild species; whereas the remaining two had the cytoplasm from different cultivars and their brief is presented here.

Breeding of A_2 CMS System with C. scarabaeoides cytoplasm

A male sterile line was derived from a natural hybrid identified within an open-pollinated bulk population of a wild species *C. scarabaeoides*. This natural hybrid plant was found to be partial male sterile. In the F_2 generation of this plant, several complete male sterile segregants were recovered. This male sterile selection was maintained by an inbred line 'ICPL 288' (Tikka *et al*. 1997). This study also reported the identification of some fertility restoring genotypes which produced fertile hybrids. This male sterile source exhibited high stability across diverse environments and was used in developing a hybrid 'GTH 1' for cultivation in the Gujarat state. Unfortunately, during its large-scale on-farm promotion its major weakness of unstable fertility restoration was exposed.

Breeding of A_4 CMS System with C. cajanifolius cytoplasm

Saxena *et al*. (2005) crossed 'ICPW 29', an accession of *C. cajanifolius* (a wild relative of pigeonpea), as the female parent with pigeonpea line 'ICPL 28'. The F_1 hybrid plants were found to be fully male-sterile, and their multi-environment testing revealed that this male sterility source was highly stable across environments and years with no morphological deformity ever observed. To develop diverse pigeonpea hybrids, this male-sterile source was transferred into a number of genetic backgrounds.

The cytological studies showed that the tetrad formation during microsporogenesis was normal in both the male sterile (ICPA 2039) and its maintainer (ICPB 2039) lines. The tapetal cells in the male-sterile anthers degenerated soon after the tetrad formation, and it resulted in shriveled and degenerated microspores. On the other hand, the maintainer line had normal tapetal cells and functional microspores. In A_4 CMS system, the disintegration of tapetum before the completion of the microsporogenesis was the major cause of male sterility. The perfect fertility restoration was achieved when two dominant genes were present in the hybrid.

Breeding of Other CMS Systems with diverse cytoplasm

Cytoplasmic or mitochondrial uniformity in hybrid breeding programmes of a crop always carry the entrenched threats of mass crop losses. This may happen due to the presence of susceptibility gene(s) for certain disease in mitochondria of a specific cytoplasm. This fear is based on the incidence of en masse out-break of leaf blight disease in the hybrids sown in the corn-belt of USA, which was ascribed to the susceptible genes located in their mitochondrial genome (Tatum 1971). Therefore, to protect pigeonpea hybrids from such potential catastrophes, the diversification of cytoplasm was taken up on priority, and nine CMS-inducing cytoplasms derived from different wild species representing secondary and tertiary gene pools (Table 3) were bred (Saxena and Hingane 2021). This will help in developing a strong broad-based hybrid breeding programme.

REALIZED HETEROSIS IN EXPERIMENTAL HYBRIDS

Soon after the successful breeding of two stable CMS systems (A_2 and A_4) in pigeonpea, the process of synthesizing and field testing of hybrid combinations began. At ICRISAT the hybrids were made using only A_4 CMS system, while at ICAR institute and SAU both A_4 and A_2 systems were explored. The experimental CMS hybrids with different A-lines were made in early and medium maturity groups and evaluated with the best available cultivars. The range of standard heterosis (superiority of hybrid over control cultivar), recorded among the hybrids of each maturity group of both A_4 and A_2 systems, was quite high. Hybrids recording above 40% standard heterosis in the station trials were considered for multi-location and advance level testing.

A_4 CMS-based hybrids

Heterosis in early maturing hybrids

Since the early maturity group (121-150 days) has limited adaptation, it received relatively less importance while breeding hybrids. The genetic variability in this maturity group is rather limited (Mudaraddi and Saxena 2015) and relatively less heterotic hybrids were bred. At ICRISAT, the first set of early maturing hybrids carrying A_4 cytoplasm, was evaluated in multi-location trials for four consecutive years (Table 4). Based on the mean performance, hybrids ICPH 2433, ICPH 2438, and ICPH 2383 were found promising with 54%, 42%, and 36% superiority, respectively, over the early maturity popular cultivar 'UPAS 120'. The highest mean yield of 2300 kg/ha was recorded by hybrid ICPH 2433. The estimates of unit productivity (yield/ha/day) also showed that the hybrids (17.1-22.2 kg/ha/day) were far superior to the control (12.52 kg/ha/day). This information suggested that the hybrids were more efficient in dry matter production and accumulation (partitioning) into the grains.

Heterosis in medium and late maturing hybrids

The largest area under pigeonpea cultivation is represented by medium maturity group (161-200 days). It received priority in breeding new hybrids, and at present this group has the largest number of A- and R- lines (Saxena *et al*. 2014). This allowed the development of over 3,000 hybrid combinations. As expected, the hybrids demonstrated a large variation for standard heterosis, but interestingly, about 10% of them exhibited in excess of 30% heterosis. It is believed that some of the hybrids such as ICPH 3491 (57% heterosis), ICPH 3497 (44% heterosis) and ICPH 3481 (41% heterosis), which performed consistently well in diverse environments (Table 4**)**, can benefit farming communities.

The traditional long duration (>200 days to maturity) pigeonpea types have strict short day photoperiod requirement for the induction of flowering. This restricts their adaptation to areas where the daylength is about 10 hrs. The adoption

Table 3. Different CMS systems derived from secondary and tertiary gene pools of genus Cajanus

CMS ID	Cytoplasm source	Gene pool	Male parent	Reference
A_1	*C. sericeus*	Secondary	*C. cajan*	Ariyanagam *et al*. (1995)
A_2	*C. scarabaeoides*	Secondary	*C. cajan*	Tikka *et al*. (1997)
A_3	*C. volubilis*	Tertiary	*C. cajan*	Wanjari *et al*. (1999)
A_4	*C. cajanifolius*	Secondary	*C. cajan*	Saxena *et al*. (2005)
A_5	*C. cajan*	Secondary	*C. acutifolius*	Mallikarjuna and Saxena (2005)
A_6	*C. lineatus*	Secondary	*C. cajan*	Saxena *et al*. (2013)
A_7	*C. platycarpus*	Tertiary	*C. cajan*	Mallikarjuna *et al*. (2011)
A_8	*C. acutifolius*	Secondary	*C. cajan*	Saxena (2013)
A_9	*C. cajan*	Secondary	*C. lanceolatus*	Shrikanth *et al*. (2015)

Table 4. Yield and Standard heterosis recorded in hybrids of three maturity groups

Maturity group	Hybrids	Locations	Mean yield (kg/ha)	Standard heterosis (%)
Early	ICPH 2433	25	2,306**	54
	ICPH 2438	25	2,127**	42
	ICPH 2363	25	2,048**	36
Medium	ICPH 3491	18	2,919**	57
	ICPH 3497	18	2,686**	44
	ICPH 3481	18	2,637**	41
Late	ICPH 2307	05	2,855**	53
	ICPH 2306	05	2,600**	39
	ICPH 2896	05	2,579**	38

Source: ICRISAT; ** : significantly different from the corresponding control variety at P<0.01

of this group is limited to deep soils with high moisture holding capacity. In this group, the potential of hybrids is also high; however, not much research has been carried out with respect to the exploitation of heterosis. Some hybrids such as ICPH 2307 (2900 kg/ha, 53% heterosis), ICPH 2306 (2600 kg/ha, 39% heterosis) and ICPH 2896 (2600 kg/ha, 38% heterosis) hold promise.

A_2 CMS-based hybrids

Heterosis in early maturing hybrids

After report of A_2 CMS system and identification of 'GTH 1' for release and notification, breeders at ICAR-IIPR, Kanpur began to diversify this male sterility source in various genetic backgrounds within early maturity group. After diversification, a number of experimental hybrids in short-duration pigeonpea were developed. The prominent among those were 'IPH 08-1' (2901 kg/ha), 'IPH 07-3' (2498 kg/ha) and 'IPH 08-2' (2335 kg/ha) which exhibited over 30% yield advantage over the check 'UPAS 120' (1754 kg/ha) (IIPR 2009). With the improvement in performance of CMS and restorer lines, many experimental hybrids, viz., 'IPH 09-5' and 'IPH 15-03', were developed, which after evaluation in the coordinated trials got released for cultivation in the north-west plains (PC Report 2024). In addition to this, breeders at IARI, New Delhi were also involved in developing early-maturing hybrids using A_2 cytoplasm. Their efforts also led to the development of a number of heterotic hybrids including 'PAH 5'.

Heterosis in medium and late maturing hybrids

The reports on experimental hybrids developed by crossing A_2 CMS lines with restorers in medium groups are scanty. This is partly because ICRISAT did not use A_2 cytoplasm in developing medium maturing hybrids for the reason of incomplete fertility restoration in the hybrids. Moreover, medium maturing genotypes get converted into long-duration ones due to severe winter months (Dec-Jan) in the north-east and north-west plains. However, there are but a few reports on exploitation of A_2 CMS source for developing experimental hybrids in the long maturity group. In one such study, Choudhary and Singh (2015) reported that experimental hybrids, developed by crossing A_2 CMS lines (Hy 4A and H 28A) with five long duration genotypes (Kudrat 3, MA 6, IPA 7-6, IPA 234 and IPA 203), did not show fertility restoration in F_1 generation. In another study, Saroj *et al.* (2015) also reported that none of the restorer lines restored fertility in A_2 CMS lines. Precisely for these reasons, definitive reports on heterosis in medium and late maturing hybrids developed by using A_2 CMS sources are almost unavailable.

RELEASES OF EARLY MATURING A_2 CMS-BASED HYBRIDS

Hybrid 'GTH 1'

GTH 1 was the first early maturing CMS hybrid with A_2 cytoplasm. This hybrid was bred at Gujarat Agricultural University, Sardar Krishinagar (Gujarat, India). This hybrid performed well both in the multi-location as well as on-farm trials. In multi-location trials, conducted from 2000 to 2003, 'GTH 1' recorded more than 50% yield advantage over the best control 'AKPH 4101' (1200 kg/ha). In the following year 'GTH 1' recorded 25.3% standard heterosis in the on-farm demonstrations and subsequently released for cultivation. During its promotional mini-kit trials, it was observed that in some environments the hybrid plants did not produce sufficient pollen grains. The investigations revealed that this disaster was caused by instability of fertility restoration. This resulted in huge losses to farmers and finally led to the withdrawal of the hybrid 'GTH 1' by the state government.

Hybrid 'IPH 09-5'

An early maturing high yielding pigeonpea hybrid 'IPH 09-5' (average yield of 1864 kg/ha) was developed from a cross between '*PA 163A*' (A line carrying A_2 cytoplasm) and '*AK 261322 R*' (restorer line) was identified for NEPZ in 2012. This hybrid possessed >33% yield advantage over the best existing check variety 'UPAS 120'. It is resistant to

Fusarium wilt and sterility mosaic diseases and has brownish red colour and round seeds with 9.3 g/100 seed weight. It matures 8-10 days earlier than the check variety (IIPR 2013). Somehow its notification got delayed until 2020 when it was notified for cultivation in the north-west plain zone. It matures in 145-150 days at Kanpur and has been reported to show over 30% standard heterosis for yield (PC Report 2024).

Hybrid 'IPH 15-03'

The hybrid 'IPH 15-03', the first CMS-based hybrid from ICAR-IIPR, Kanpur, was released and notified in 2019 for cultivation in the north-west plains. It is an early maturing (150-155 days) hybrid developed by utilizing A_2 CMS system. This hybrid (PA 163A × AK 250189R) showed the standard heterosis of 28-55% for yield. In coordinated trials, it recorded an average yield of around 1600 kg/ha. With maturity duration of 153 days, it showed resistance to Fusarium wilt and pod borer (PC Report 2024). The seeds of this hybrid can be produced in the rainy season at Kanpur itself; however, a winter GoT - crop cannot be grown due to prevailing low temperatures at Kanpur.

Pusa Arhar Hybrid 5

'Pusa Arhar Yamuna' (PAH 5) is an early maturing hybrid carrying A_2 cytoplasm that was developed by crossing the CMS line 'Pusa 2002A' with the known fertility restorer 'ICPR 261411' (PC Report 2024). This hybrid flowers and matures, respectively in 89-93 and 135-144 days, and has been reported to be moderately resistant to SMD, Phytophthora stem blight and Alternaria leaf spot. The yield potential of the hybrid is reported to be 2546 kg/ha. The multi-location testing of this hybrid revealed the standard heterosis of 25.39% over the control 'Pusa 992' (Raje and Singh 2023). It was released and notified in 2023 for cultivation in the NCR Delhi (PC Report 2024).

RELEASES OF A_4 CMS-BASED MEDIUM MATURING HYBRIDS

Hybrid 'ICPH 2671'

The first commercial A_4 CMS-based pigeonpea hybrid 'ICPH 2671' was produced by crossing a restorer line ICPL 87119, designated as 'ICPR 2671', with male sterile line 'ICPA 2043'. In the multi-location trials, the hybrid 'ICPH 2671' recorded 35% yield superiority over the check cultivar 'Maruti' (2000 kg/ha). In 1,829 pre-release on-farm trials, conducted in five provinces, the hybrid 'ICPH 2671' (1400 kg/ha) produced 52% more than the local check (954 kg/ha). In the state of Maharashtra, the largest number (782) of trials was conducted, and the hybrid produced 35% more yield (Table 5) over the control cultivar 'Maruti' (Saxena *et al*. 2013). Considering its overall performance, the hybrid ICPH 2671 was released for general cultivation in the state of Madhya Pradesh (India).

Hybrid 'ICPH 3762'

Hybrid 'ICPH 3762' was produced by crossing 'ICPA 2092' (A_4 cytoplasm) and 'ICPR 3762'. It belongs to mid-late (180-210 days) maturity duration. In multi-location trials, the hybrid recorded 112% standard heterosis over the control cultivar. The on-farm evaluations of this hybrid were conducted at 144 locations in five districts, and on average, the ICPH 3762 (1726 kg/ha) was 112% superior to the control in grain production (Saxena *et al*. 2021). This outstanding performance of the hybrid ICPH 3762 in the on-farm trials led to its release for general cultivation in the state of Odisha with the popular name 'Parbati' (Table 5).

Table 5. Demonstration of yield advantages recorded in three released pigeonpea hybrids over inbred cultivar in 1772 on-farm trials conducted under rainfed conditions in four states of India

Hybrid	State	Farmers (no.)	Hybrid yield (kg/ha)	Control yield (kg/ha)	Hybrid yield advantage (%)
ICPH 2671	Maharashtra	782	969	717	35
	Andhra Pradesh	399	1411	907	55
	Madhya Pradesh	360	1940	1326	46
	Total/mean	1541	1437	983.3	46.1
ICPH 2740	Andhra Pradesh	47	1999	1439	39
	Gujarat	40	1633	1209	35
	Total/mean	87	1816	1324	37.2
ICPH 3762	Odisha	144	1726	813	112
	Total/mean	-	-	-	-

Source: ICRISAT

Hybrid 'ICPH 2740'

Another medium duration hybrid 'ICPH 2740' was developed at ICRISAT and released in the state of Telangana as 'Mannem Konda Kandi' (Table 5). 'ICPH 2740', developed involving A_4 cytoplasm, was tested at 31 locations over five years; the data showed 40.7% superiority of the hybrid over the ruling control variety 'Asha'. In these on-farm trials, the hybrid recorded 36.2% advantage in four provinces (Saxena *et al*. 2016). This hybrid is highly resistant to wilt and sterility mosaic diseases.

HYBRID SEED PRODUCTION TECHNOLOGY

Sustained increase in agricultural production and productivity depend on the development of new improved cultivars and their specific management practices. The quality seed production is a specialized activity that paves the way for initial assurance towards realization of high output. DSR (2025) estimated that quality seed alone contributes 15-20% to the total production, and it can further be raised up to 40% with effective management practices. Breeding hybrids in pigeonpea is the first such endeavour among the pulses. This programme is based on a small window of natural cross-pollination that is mediated by a range of flying insects. The insects forage on large bright colored flowers, and in the process, they affect cross-pollination. The hybrid technology in pigeonpea is now established. In order to sustain this technology, it is imperative that hybrid seed production technology is grower-friendly and economical. However, the road ahead is not easy, and scientists have to work together with the seed sector to make this technology a reality. In pigeonpea the hybrid technology is new (Saxena *et al*. 2018), and information on seed quality control is still being worked out.

Hybrid seed production methodology

For hybrid seed production the recommended isolation is 500 m (Tikle *et al*. 2014). This isolation plot should preferably be located in the area surrounded by bushes and small water bodies. Such natural habitat helps in harboring pollinating insects. Main focus in designing the layout should be to make fresh pollen available as long as possible. To ensure this, the net seed production plot should be surrounded by a 1-2 m belt of pollen parent; hence, it should be sown about two weeks after the sowing of net plot. This technique has worked well and in most places. The seed lot should be planted in the ratio of 4 female (CMS) and 1 male (restorer) row.

On-farm validation of seed production technology

The two released hybrids 'ICPH 2671' and 'ICPH 2740' were chosen for on-farm validation of seed production technology. The yields recorded at Indore (2267 kg/ha), Seoni (2500 kg/ha) and Tikamgarh (3040 kg/ha) were very encouraging (Table 6). In Telangana, the yields recorded in hybrid plots were around 1000 kg/ ha.

Economics of hybrid seed production

Saxena et al. (2011) estimated that the cost of producing one hectare of pigeonpea hybrid 'ICPH 2671' seed was Rs 26,395. This plot produced a hybrid yield of 1440 kg/ha, providing a net profit of Rs 70, 000/ha. Using these estimates, the hybrid cost at farm gate was Rs. 18.85/kg. This seed production technology yielded a very healthy seed-to-seed ratio of 1:200-300.

Grow-out testing of hybrid seed

The on-farm assessment of pigeonpea hybrids demonstrated 30-50% on-farm yield gains over the inbred controls. These hybrids, however, failed to reach farmers due to a single factor, *i.e.*, inability of seed producers to maintain high seed standards. In general, the hybrid seed quality in field crops is determined by applying the standard "Grow-out tests" (GoT). Unfortunately, this approach could not be used due to their photo-period sensitivity and long generation turnover time. The advances in pigeonpea breeding and genomics research, however, have provided user-friendly solutions to overcome the limitation.

SOME KEY HYBRID BREEDING RESEARCH

Revealing stigma receptivity pattern in pigeonpea

In pigeonpea, the stigma becomes receptive a

Table 6. Record of hybrid seed produced (kg/ha) in six states

State	Locations	Highest yield (kg/ha)	Mean yield (kg/ha)
Andhra Pradesh	34	1750	998
Madhya Pradesh	9	2267	1674
Gujarat	4	1669	1179
Maharashtra	5	1017	603
Odisha	40	1040	523
Karnataka	2	1900	1138
Total / mean	94	--	--

Source: various reports and presentations by different institutions day prior to flower opening (Dalvi and Saxena 2009, Choudhary *et al*. 2012), and it peaks for the next three days, including the day of flower opening. After this period, the petals start unfolding with about 35% of the buds remaining un-pollinated but the stigma remained receptive to receive pollen grains. The flowers remained in this condition for the next two days. This critical period coincides with visits of nectarivore insects, and while collecting nectar, they also collect pollen grains and transfer them onto stigmatic surface of other flowers.

Formation of heterotic groups

Following the classic work on the relationship of genetic divergence and hybrid vigour, the popular concept of combining ability was developed by Sprague and Tatum (1942) to discriminate the parental lines for their ability to combine with other genotypes to produce more vigor. The value of genetically distinct parents in hybrid breeding was demonstrated by many researchers in different crops. In this context, various methods of selecting such elite parents were proposed from time to time, and these eventually matured into a concept of 'heterotic groups'. This approach involved clustering and selection of parents on the basis of their combining ability, origin, genetic diversity or application of statistical and genomics tools. This breeding technology, for the first time, was applied in pigeonpea by Saxena and Sawargaonkar (2014). They formulated seven heterotic groups based on multi-location specific combining ability (SCA) data and reported that heterosis for seed yield was much greater when the parental lines represented two diverse heterotic groups. This approach has since been refined using genomic tools. Most notably, Saxena *et al*. (2021) used genome-wide SNP markers to classify a global collection of pigeonpea lines into three heterotic groups and validated these with multi-location hybrid performance data. Their work provided a robust framework for heterotic grouping in pigeonpea and emphasized that the use of genomic markers can significantly enhance the accuracy of parental selection by eliminating the confounding effects of the environment on phenotypic traits.

Naked-eye polymorphic marker

In pigeonpea, there is a distinctive naked-eye polymorphic marker called 'obcordate' leaf. This marker, controlled by a single recessive gene, is stable across environments and expresses within 3 to 4 weeks from sowing (Saxena *et al*. 2011). This trait is a great tool to ensure purity of pigeonpea genotypes and to make its use in hybrid breeding it has been incorporated into A-/B- lines. Any out-crossed "off-type" plant with dominant normal (lanceolate) leaves can be easily identified and rogued out at seedling stage, and this will help in maintaining genetic purity of female parent. Likewise, when a restorer line (normal leaves) is crossed to an A-line carrying obcordate leaves, all the true hybrid plants will show *hybrid* leaves. Genetic purity of hybrid can be ensured at the seedling stage. Some A-/B- lines with obcordate leaves have recently been developed and used in developing hybrid combinations (Patil *et al*. 2014). However, this marker trait has been reported to be strongly associated with photoperiod sensitivity, late maturity, seed size and reduced reproductive fitness (Choudhary *et al.* 2015). Therefore, while incorporating this trait into A-/B- lines, these attributes need to be looked into.

Effect of different cytoplasms on hybrid yield

While advocating cytoplasmic diversity in hybrid breeding, it is also important to know if a particular cytoplasm has any adverse effect on seed yield or any other important trait. In pigeonpea, a study was conducted using the cytoplasms of *C. cajanifolius* and *C. cajan* (Saxena *et al*. 2015**).** The results showed that the hybrids carrying cultivated cytoplasm yielded marginally better than those with *C. cajanifolius* cytoplasm. The greatest yield penalty of 19% due to the wild species cytoplasm was recorded in a cross involving a restorer line 'R-2364'. For other traits, no definite trend in favor of any specific cytoplasm was recorded. This study also revealed that the cytoplasmic effects on the performance of hybrids were influenced by the genetic constitution of the restores.

Hybrid seed production under controlled environment

In order to explore the possibility of producing hybrid seed under controlled conditions, both A- and B-lines were grown under a net house with bee hives housed with active *Apis mellifera* placed inside the net, and the bees were allowed to forage freely. The results of this exercise showed that the pod set and seed yield of A-lines obtained inside the net house were significantly lower than the harvests obtained from open plots (Vales *et al*. 2018). This exercise showed a clear non-preference of *A. mellifera* in visiting the flowers devoid of pollen grains, exhibiting its pollen-eating character for tripping to flowers. Besides this, it could also be attributed to the short proboscis of this species due to which workers were not comfortable in harvesting nectar from the base of flowers and therefore avoided visiting the male sterile flowers.

Breeding of temperature-sensitive male-sterility

The effect of different environmental factors on the expression of male sterility or fertility is well documented (Kaul 1988). The utility of this natural phenomenon was demonstrated in hybrid rice breeding (Sun *et al*. 1989). Recent success in breeding a similar temperature-controlled male sterility system in pigeonpea (Saxena 2014) has opened up options to breed pigeonpea hybrids through this route. In this system, the genotype under high (>25°C) temperature regime produced no pollen grains and seed. On the contrary, the same line under low (<24°C) temperature produced self-pollinated seeds (Table 7). Thus, unlike the CMS system, A-line (temperature sensitive) would not require maintainer (B-) line for seed multiplication. Thus, this type of male sterile line can be used to produce hybrid seeds under high temperature regimes without rouging.

Table 7. Proportions of male fertile and sterile plants recorded in the progenies of selections under two temperature regimes

Genotype	Mean temperature (>25°C)		Mean temperature (<24°C)	
	Sterile	Fertile	Sterile	Fertile
Envs-Sel 1	37	0	0	37
Envs-Sel 2	32	0	0	32
Envs-Sel 3	27	0	0	27
Envs-Sel 5	23	0	0	23

Source: Saxena (2014)

ADVANTAGES OF HYBRIDS OVER INBRED CULTIVARS

Hybrid technology is known to boost biomass and yield by significant margins. In pigeonpea, such heterotic effects are visible right from seed germination to yield formation. Bharathi and Saxena (2012) reported that in comparison to inbred cultivars, the hybrid seeds germinated at a faster rate, recording 20-40% longer radicle and 7-14% greater seedling vigour index. Moreover, an experiment conducted at ICRISAT (Saxena *et al*. 1992) showed that in comparison to inbred cultivars, the 60-day old hybrid seedlings (Fig 2) produced 44% more shoot and 43% more root mass. These enhanced traits not only help hybrid plants to encounter brief drought spells and temporary water-logging effectively but also deliver the ability to compete well with various types of rainy season weeds. Also, due to their superior root traits, the hybrid plants maintain relatively high-water content even under adverse conditions; and this, adds directly to their ability to tolerate drought (Lopez *et al*. 1996). It was also observed that both the hybrid and inbred plants had more or less similar dry matter partitioning; since the former utilized critical inputs better than inbreds, they produced higher yields. In this context, Saxena *et al*. (2020) reported that the hybrid plants were more productive (22 kg/ha/day) than the inbred cultivars (12.5 kg/ha/day). Therefore, the hybrids demonstrate an extra degree of resilience to produce greater and stable yields, and have better environmental buffering.

GENOMICS ADVANCES IN HYBRID BREEDING

Thus far, the large-scale commercialization of pigeonpea hybrids has not been realized, primarily due to challenges in maintaining seed quality and genetic purity. However, recent advances in genomics have provided a practical solution to this long-standing issue. Molecular marker technologies, particularly those involving simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs), have emerged as powerful tools in hybrid seed quality assurance.

A collaborative initiative between ICRISAT and ICAR has led to the development of a robust, genomics-assisted protocol for hybrid seed purity testing in pigeonpea. This protocol is rapid, accurate, and suitable for deployment at the commercial level. The molecular identification of the A_4 cytoplasmic male sterility (CMS) system, including both its cytoplasmic (*Cajanus cajanifolius*-derived) and nuclear components, is essential for assessing the genetic identity of CMS lines. A gene-based mitochondrial marker (*nad7a*_del), derived from the *nad7* gene, has been developed for distinguishing A- and B-lines at the molecular level (Sinha *et al*. 2015).

Early research efforts focused on the use of low-throughput SSR markers to assess genetic purity and diversity (Saxena *et al*. 2010, Bohra *et al*. 2011). The release of the pigeonpea draft genome sequence (Varshney *et al*. 2012) and subsequent whole-genome re-sequencing of hundreds of pigeonpea accessions (Varshney *et al*. 2017, Saxena *et al*. 2021) facilitated a shift towards high-throughput SNP genotyping. These SNPs enabled the development of customized genotyping platforms for quality control in hybrid breeding.

Currently, a set of diagnostic SNP markers is available for identifying A_4-specific fertility restorers across 25 pigeonpea hybrid combinations from varying maturity groups (data unpublished). These SNPs have been converted into cost-effective and scalable Kompetitive Allele Specific PCR (KASP) assays, allowing flexible deployment across laboratories. Even in the absence of in-house genotyping facilities, breeders can send leaf samples of hybrids and parents to authorized genomics labs, with a typical turnaround time of approximately two weeks.

Cost assessments conducted at ICRISAT indicate that using KASP assays for 10 SNP markers across 384 samples would amount to about 2.5 USD per sample, making this a viable solution for routine seed quality monitoring (Data unpublished). These genomics-based seed purity kits are currently being used in commercial seed production systems. However, ensuring high seed quality requires a holistic integration of both field-based and genomics-driven protocols. This includes adherence to recommended practices in seed production such as isolation distance, pest control and rigorous rouging along with standardized laboratory testing using mature seed samples. Seeds passing visual quality inspections should be submitted for molecular testing to ensure genetic fidelity before release for cultivation.

FAILURES IN TAKING PIGEONPEA HYBRIDS TO THE DOORSTEP OF FARMERS

Technology transfer in the agriculture sector is a process which involves the adaptation studies, and further adoption of new selected technologies within or across the systems. This is a critical element in agriculture development, as it seeks to modify the existing production system or addition of value. In case of pigeonpea, productivity stagnation is a long-standing constraint, and the breeders have been struggling to break this barrier.

Numerous attempts were made in the past to enhance the productivity levels in pigeonpea through breeding pure line cultivars but with no success. Therefore, pigeonpea breeders started thinking out of the box and settled to launch a hybrid breeding programme. It was a big challenge as no such attempt was ever made in any pulse crop due to their pre-dominant self-pollinating nature. To develop a hybrid technology in pigeonpea, it was decided to exploit its partial cross-pollinating and breed the cytoplasmic nuclear male sterility system. This research reached a milestone when high-yielding hybrids were developed and later released for cultivation.

Although this technology has demonstrated high yield and adaptation, unfortunately, the farmers are still unable to reap the benefits of this technology. In fact, both ICRISAT and ICAR conducted thousands of on-farm demonstrations of the hybrid yields and their seed production technology. From these technology efforts it appeared that both the farmers and seed growers were convinced with their performances. However, their expected adoption did not take place because the seed growers could not ensure the genetic purity of hybrid seeds. This was due to the inability to conduct viable grow-out quality seed tests. The main reason relates to the inherent photo-sensitivity of parents and hybrids. This was a big upsetting to the ambitious hybrid breeding programme and the breeders are on the lookout for some amicable alternatives.

OVERCOMING THE HYBRID SEED QUALITY CONTROL ISSUES

The hybrid seed quality in field crops is determined by applying the standard "Grow-out tests" (GoT). Unfortunately, in the released medium duration pigeonpea hybrids this test could not be applied due to their photo-period sensitivity and long generation turnover time. This bottleneck has blocked the movement of hybrid technology from seed companies to farmers.

The recent research advances targeted to solve the hybrid seed quality constraint have provided a couple of user-friendly valuable options (Saxena *et al*. 2021). Based on these openings, it is suggested that future investments in hybrid project should be made in: (i) breeding early maturing hybrids where GoT can be applied with ease due to photo-insensitivity of the hybrids and their parents (Tables 7 and 8), and (ii) encouraging the application of seed quality control genomics tools. These can easily bring pigeonpea hybrid programmes back on rails. For this to happen, coordinated efforts of different disciplines would be a requisite.

SUMMARY AND CONCLUSIONS

Pigeonpea is an important pulse crop that produces high-protein grains. Unfortunately, the productivity of the crop is low, and considerably

Table 8. Grow-out testing protocol for pigeonpea hybrids of different maturity groups

Seed production of target hybrids					Grow-out test of the hybrids			
Maturity groups	Sowing	Flowering (days)	Maturity (days)	Harvesting	Sowing	Flowering	Data recording	Month of sale
Super early	July	<50	<90	Sep	Oct	Dec	Jan -Feb	May
Extra early	July	50- 65	110-120	Oct	Nov	Jan	Jan -Feb	May
Early	July	70- 85	121-150	Nov	Dec	Feb	Jan -Feb	May
Mid-early	July	90-105	151-160	Dec	Jan	Mar	Mar/Apr	May
Mid-late	July	120-125	180-190	Feb	GoT not possible			

lags behind the main cereals. Although a number of agronomic and management factors may be responsible for their poor productivity, it is also true that the efforts made towards the genetic enhancement for yield witnessed only a limited success in the past. To overcome this bottleneck, the pigeonpea breeders made plans to exploit its window of partial out-crossing to breed hybrids. A hybrid breeding programme in pigeonpea was launched with the breeding of a cytoplasmic nuclear male sterility system. These efforts yielded fruits when two CMS systems (A_2 and A_4) were bred successfully using the cytoplasm of wild species. Subsequent hybrid breeding efforts resulted in the release of hybrids in early and medium maturity groups. These hybrids exhibited economically viable standard heterosis, ranging around 30-50% or more. As a follow-up, their seed production technology was also developed with a healthy seed-to-seed ratio of 1:200/350. This seed production statistics was economically viable. But, in spite of this productivity level, the hybrid pigeonpea technology could not be adopted by seed companies. This was due to the inability of breeders to conduct a proper grow-out-test to ensure genetic purity of the hybrid seeds; and it was due to photo-sensitivity of the hybrids which did not allow raising a follow-up generation to determine the degree of genetic purity of a given hybrid a seed lot before marketing. This was a big setback particularly, in the backdrop of plateauing yield of pigeonpea.

The major constraint of seed quality control, which haunted the breeders for a long time, has now been ably overcome through reliable tools of genomics. It can be assumed safely that this issue can now be addressed amicably if the genomics approach can be utilized and promoted in hybrid seed production programmes. The low seeding rates and high levels of standard heterosis make the hybrids quite attractive from farmers' points of view. In spite of various positives, the up-scaling of pigeonpea hybrids are still a challenge to breeders and those who are involved in technology transfer. To achieve the objective, it is necessary that an efficient seed chain is established to cater the needs of breeder, foundation, and certified seeds and timely supply of seed to the distributors and farmers. To achieve the goal, coordination of different public and private seed organizations dealing with production, marketing, distribution, and extension would be required to give a boost to the adoption of hybrid pigeonpea.

The authors hereby visualize that in spite of this inherent limitation; the farmers can still reap the benefits of hybrid technology if the breeders opt for early maturity hybrids and/or utilize the latest molecular tools. In the early group hybrids also significant hybrid vigour is available and quality determination through GoT is possible. For the longer version of hybrids, the quality assessment can be done using specific molecular markers for which effective protocols are now ready for use. To implement this, it should be noted that (i) for generating the targeted markers the inbred seed should be obtained from a highly reliable source, (ii) the markers should be polymorphic between A- and R- lines, and (iii) only the cross-specific proven genetic markers should be used.

Hybrid breeding technology has opened up a positive avenue to address the issue of stagnating productivity. The efforts done in the past 50 years have been encouraging and carry several advantages. However, some hiccups still remain to be addressed for large-scale commercial adoption. The latest moves involving genomics and other approaches can surely take pigeonpea hybrids to the doorsteps of the farmers inhabiting in the semi-arid tropics.

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