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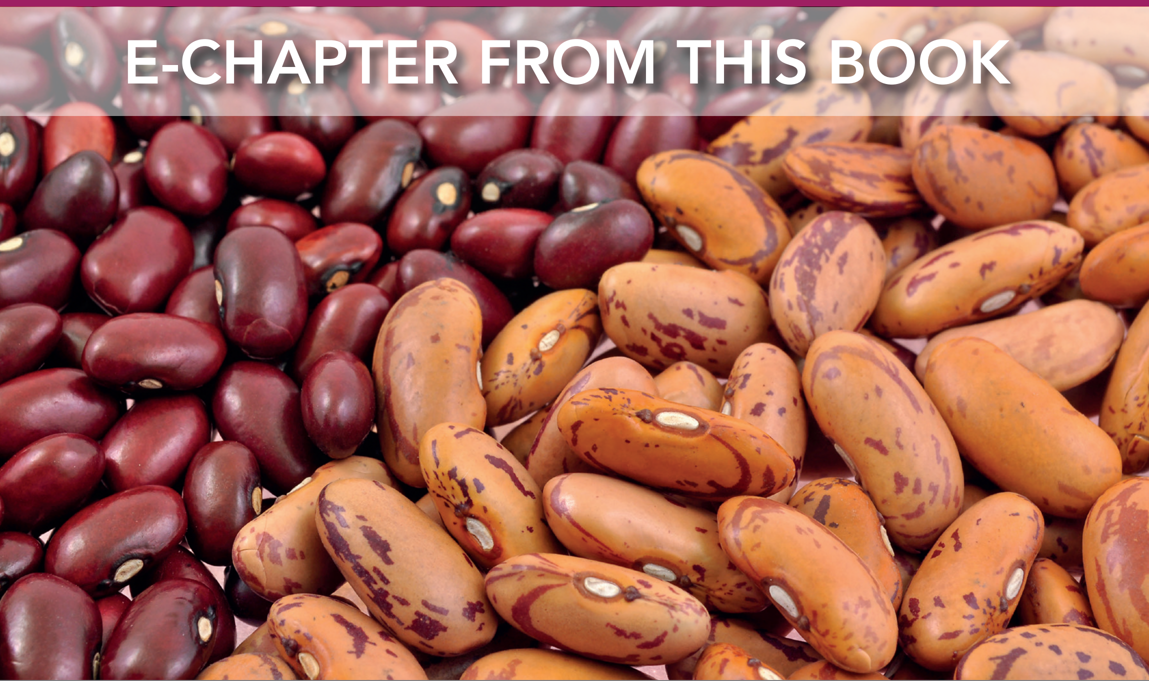

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Developing improved varieties of pigeonpea

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1 Introduction

By 2050 the world population is likely to reach nine billion, with most of the increase in the semi-arid tropics where many of the world's poor reside. It has been estimated that this will require a 70% increase in food production (Alexandratos and Bruinsma, 2012). Increasing food production to this extent in the face of looming climate changes, decreasing water resources, escalating production cost and limitation of arable land will be a Herculean task. In this context, a food legume, popularly called as pigeonpea (*Cajanus cajan* (L.) Millsp.), red gram (*tuar*) or yellow lentil, could play a significant role in providing food and nutritional security. This is possible because this crop has potential to grow well in warmer conditions with limited water and inputs.

Pigeonpea commands respect among farming communities due to its special traits and role in sustainable agriculture. The plants fix their own nitrogen, enhance the release of soil-bound phosphorus, require less fertilizers, withstand intermittent droughts and recover more quickly from the damage caused by various biotic and abiotic stresses (Saxena, 2008). It is, therefore, a favourite crop in low-input, rain-fed farming and, for these reasons,

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is an appropriate choice to meet the challenge of providing food security for the growing global population. This pulse not only suits the taste buds but also provides quality protein for building body tissues. It is one of the most popular pulses used in Indian and African cuisines. It is often said that no Indian vegetarian meal is complete without a bowl of pigeonpea *dal* (thick spicy soup).

According to the FAO (2013), the estimated global area for pigeonpea is over six million ha with a total production of 4.74 million tons and average yield of 762 kg/ha. The crop is well adapted to diverse soils and climatic conditions of semi-arid tropical regions of India (4.04 m ha), Myanmar, and eastern and southern Africa (with about 0.5 m ha each). India is the largest (3.02 m tons) producer of pigeonpea (DES, 2015), but to meet the domestic requirements, another 500,000 tons of pigeonpea is imported annually from Myanmar and Africa. In rural areas, pigeonpea is considered a multipurpose crop because it is used as food (fresh as vegetable and decorticated dry splits as *dal*), fodder, feed, fuel wood and even as construction material (Saxena, 2008). In this chapter, besides listing the factors influencing sustainability of production, the achievements of crop improvement efforts geared towards attaining the overall goal of sustainable legume production are reviewed.

2 Pigeonpea for nutritional security

2.1 Human nutrition

A sufficient quantity of protein in the diet is essential for normal growth and development. A lack of this vital growth component among people living under subsistence level is common, and it leads to severe malnutrition particularly among children and women. Animal protein is becoming less accessible day-by-day. The availability of home-grown vegetable protein is insufficient to meet the domestic needs of many farmers due to their limited smallholdings, low productivity and high input costs. This problem is now growing beyond dangerous proportions, especially in the underdeveloped and developing countries. For example, the per capita protein availability in India in the decade ending 2009 has seen a significant reduction from the recommended 46 g/head/day to <25 g (NIN, 2010). To overcome this shortage, there is a need to produce more protein per unit of land area. This is possible either by enhancing yield or by breeding high-protein cultivars. In this respect, pigeonpea stands ahead of most pulses due to its tolerance to various stresses and production of protein-rich (20–22%) grains. At ICRISAT, high-protein (28–30%) pigeonpea lines were bred with no loss of productivity and these lines yielded additional protein at 100,000 g/ha (Saxena and Sawargaonkar, 2015). Immature pigeonpea seeds also form a nutritive vegetable. Such types, mostly cultivated around cities and towns, have attractive pods with large sweet seeds and better nutrition than dry seeds (Saxena et al., 2010).

2.2 Livestock nutrition

Domestic animals are an integral part of sustainable agriculture. Farmers depend on draft animals for field operations and rural transportation, and mulch animals for generating additional income. Hence, animal health issues are also important for any sustainable agricultural system. Pigeonpea by-products such as fresh tops, pod shells and broken seeds offer a good fodder/feed supplement (Table 1) for domestic animals. During the

Table 1 Nutritional quality of pigeonpea fodder and feed

Nutrient (%)	Fresh fodder	Dried fodder	Silage	Seed	Seed coat
Moisture	70	11	67	10	–
Crude protein	7	15	15	18	5
Crude fibre	11	29	67	5	32
N-free extract	8	40	33	–	–
Fat	2	2	–	–	1
Ash	2	4	–	–	4

Source: various ICRISAT reports.

dry summer season, when fodder is scarce, farmers release their animals to graze in the harvested pigeonpea fields. The regenerated foliage on the pigeonpea stumps provides valuable fodder during the harsh summer. For stall-feeding, pigeonpea biomass also makes quality leguminous fodder. The nitrogen-deficient grasses are mixed with chopped pigeonpea fodder in the ratio of 3:1 for dairy animals. Whiteman and Norton (1981) recorded edible forage yields of 20–25 t/ha in Australia, while Yang et al. (2001) reported 30 t/ha fresh fodder yield in the Guangxi province of China. According to Embong and Ravoof (1978), pigeonpea leaves can provide a good substitute for alfalfa in animal feed formulations, particularly in areas that are not suitable for growing alfalfa. An important point in the forage usage of pigeonpea is that it is available at times of the year when there are shortages of energy and protein for the animals. Alongside this, the pigeonpea pod shells, left after threshing, also make good animal feed. The processes of de-hulling and splitting generate about 20–30% of by-products. These by-products, including husk, powder, and broken or under-sized seed, then form protein-rich concentrate for feeding both ruminant and non-ruminant livestock. These special components of pigeonpea make it a crucial component of sustainable agriculture in the tropics and subtropics.

3 Factors affecting stability of pigeonpea production

3.1 Physiological factors

Physiology is one of the least researched aspects of the pigeonpea crop (Sheldrake, 1984; Lawn et al., 1990). As large sections of the poor living in semi-arid tropics are increasingly dependent upon this crop for livelihoods and nutrition, it is imperative to reassess the physiology of pigeonpea to ensure tangible gains in yield, which currently are dismally low. Since the yield of this crop has remained low for decades, it appears that the key yield-forming factors have not been addressed adequately in the improvement programmes of the past.

3.1.1 Biomass

Grain yield in any crop is dependent on how efficiently it produces dry matter and converts it into yield. Unfortunately, neither dry matter production efficiency nor partitioning efficiency was appropriately assessed in pigeonpea to identify superior genotypes for these key physiological traits. The variety development, as in other legumes (Hay et al., 1995), has largely resulted in an indirect selection of genotypes that are superior only in biomass production (Chauhan et al., 1995). In the case of pigeonpea, breeders have unconsciously selected for higher biomass production capacity, the main determinant of yield. Most of this enhanced biomass production capacity among improved varieties results from longer growing duration or heterosis, and very little of its superiority arises from its better partitioning into yield.

Although genotypic differences in radiation use efficiency have been documented (Nam et al., 1998), there is little evidence of any increase in biomass having occurred due to improvement in radiation use efficiency *per se*. Often vigorous individual plants, arising from natural out-crossing in the preceding generation in farmer's fields, have attracted breeder's attention for exercising selection. However, such plants tended to lose this advantage due to inbreeding depression and competition for light and water when grown as a population. However, a number of pigeonpea varieties have been released from such individual plant selections (Singh et al., 2016). The biomass production among pigeonpea varieties varies considerably due to a number of agronomic and production factors. These include climatic conditions, cropping systems, duration and plant population, and this has resulted in a wide variety of yields being observed.

The enhanced capacity of biomass production in improved pigeonpea varieties and hybrids (Chauhan et al., 1995) ensured that such genotypes produced good yields when growing conditions were favourable, and ensured some yield even when growing conditions became slightly less favourable. However, in the event of being grown on marginal soils with low water-holding capacity, the extra rapid water utilization required to support greater growth tended to negate this advantage. If improved biomass production can be combined with better partitioning, it will lead to a greater potential and homeostasis in yield.

3.1.2 Harvest index

The dry matter production potential of pigeonpea is about 10 t/ha, and even a conservative harvest index of 20–30% suggests that up to 2–3 t/ha of yield should be harvested compared to the world average of only 746 kg/ha of this crop. The ideal route to realize higher yield in pigeonpea is to convert a greater amount of accumulated dry matter into yield. This approach to increasing yield has fascinated pigeonpea scientists, but little progress has been made in improving the harvest index on a consistent basis.

Low harvest index in pigeonpea is attributed to extensive flower drop (Sheldrake et al., 1979). Some of this flower drop could be due to indeterminate nature of flowering, where the earlier formed pods out-compete the later formed flowers for attracting assimilates. The focus on developing determinate cultivars in this crop has not paid desired dividends as these genotypes also behaved like indeterminate plants in terms of reproductive physiology (Sheldrake and Narayanan, 1979).

It appears that the key to increased partitioning could be to reduce indeterminateness through increased synchrony of flowering. Similar observations were also made in soybean, where the earlier formed flowers have greater chance of developing into pods, and more pods can be formed when flower synchrony is increased (Egli and Bruening, 2002). Hence, there is a need to develop varieties with greater synchrony in flower production in pigeonpea because it tends to equalize the competition among developing pods. Alternatively, cultivars in which seed development initially is very slow could defer serious intra-plant competition for assimilates to a later stage when most pod set has already occurred. The latter could also reduce insect pest pressure on the crop, as they will not be able to obtain much energy from slower growing grains until the pod walls become strong enough to resist their invasion. All those legumes, where pod wall constrictions (e.g. garden peas) are absent, have this trait. A wild relative of pigeonpea *Rhynchosia bracteata* also has this trait, which needs consideration in future breeding programmes.

3.1.3 Photoperiod sensitivity and flowering

Pigeonpea is a quantitative short-day plant and its flowering is delayed as days become longer than 13 h (Silim et al., 2007). The photoperiod sensitivity is also a source of indeterminateness and non-synchronous flowering in this crop. While warm weather combined with long photoperiods promotes longer vegetative phase, the short photoperiod and milder mean ambient temperatures (>18 and <25°C) promote flowering. Below the critical photoperiod, the temperature hastens or delays flowering. There are genetic differences in sensitivity to photoperiod which have been exploited to develop varieties which take less than 85 days to over 300 days. The traditional long-duration varieties are more photoperiod sensitive as compared to more recent extra-early varieties. Phenological plasticity achieved through genetic manipulation of photoperiod sensitivity has provided valuable means of developing varieties for various niches and has helped expanding its cultivation in a wider range of cropping systems and latitudes. There are also varietal differences on phenological effects of temperature. The optimum temperature for rapid flowering was 24.7°C for extra-early, 23.1°C for early, 22.2°C for medium and 18.3°C for long-duration varieties (Silim et al., 2007). A few studies also highlighted the carry-over effects of temperature and photoperiod on the period between flowering and maturity. Generally, optimum temperatures (~24°C) that hasten flowering also reduce the period between flowering and maturity. The cooler suboptimum period (<18°C) particularly tends to prolong this period.

Flowering in pigeonpea is more synchronous under inductive short days and optimum temperatures. In the post-rainy season, pigeonpea flowering is more synchronous. Harvest index of pigeonpea in this season is far greater than the crop planted in the regular season. This results in yield often being similar to that obtained in the main season even with half the dry matter production (Naryanan and Sheldrake, 1979). However, the strong negative relationship between dry matter production and yield in pigeonpea makes it difficult to increase the harvest index component of yield without reducing biomass production and vice versa (Chauhan et al., 1995). It is not clear if the negative relationship between dry matter and harvest index could be weakened through an appropriate selection strategy as has been achieved in wheat (Ding et al., 2016). To achieve this in pigeonpea, genotypes will need to be developed that are able to produce more biomass before flowering and partition more to grain after flowering, exhibiting a higher degree of determinateness.

Another approach to increase floral synchrony is to reduce photoperiod sensitivity. With the purpose of introducing greater photoperiod insensitivity in pigeonpea, the development of short-duration pigeonpea cultivars was taken up in the 1980s in Australia and India. Short-duration varieties not only take less time to flower and mature, but also have slightly higher harvest index. They are indeed less photoperiod sensitive too (Wallis et al., 1981; McPherson et al., 1985) and could be grown at higher plant population as a monocrop and fit into rotation with wheat (Dahiya et al., 2002). Breeding of such genotypes was undertaken in northern India as these genotypes were considered to be better adapted to wheat growing environments in terms of rainfall pattern and cropping windows. The evaluations done in tropical environments suggested that they could also grow well in central and southern India (Chauhan et al., 1987; Chauhan, 1990). Chauhan et al. (1987) Chauhan et al. (1987) compared early pigeonpea varieties grown at Hisar (29°N) in northern India, with those grown in tropical environments at Patancheru (17°N) near Hyderabad. Here, day length before flowering during the growing season was shorter. Varieties grown at Patancheru exhibited up to 42% harvest index and gave up to 2.7 t/ha in < 100 days. The yield obtained was also higher compared to those at Hisar where the yield was 2.35 t/ha and the biomass was 42% more due to almost one extra month of growing period.

3.2 Agronomic factors

3.2.1 Maturity and cropping systems

Major agronomic factors influencing yield of pigeonpea are appropriate maturity, sowing time, seed rates, row arrangements and nutrition. The short-duration types (<140 days) are cultivated as a sole crop and harvested before the sowing of post-rainy-season crops. Both the medium (170–180 days) and late-maturing (>250 days) types are sown after the longest day, and are harvested a few months after the shortest day. Because of their protracted growing periods, these types are cultivated in inter-crops with fast-growing cereals such as millets, sorghum and maize. Over the long growing period, they develop a deep root system (Chauhan, 1993) which helps the crop to exploit residual moisture left after harvesting of the companion crop. In pigeonpea-based inter-cropping systems, very little agronomic or genetic innovation, apart from hybrids, has been introduced in this century. Since the pigeonpea yields in such systems depend upon moisture that is present at the harvest of the companion crop, the 'decision support tools' based on crop simulation models could assist in maximizing and stabilizing the yield (Smith et al., 2016). These tools include vital parameters such as soil moisture holding capacity, utilization of light by cereal crops, and selection of appropriate pigeonpea genotypes. In pigeonpea, there are diverse plant types within each maturity type and therefore it would be ideal to further understand pigeonpea responses to plant population and row arrangements. This could help to enhance crop productivity and sustainability.

Rao and Wiley (1983) demonstrated the significant contribution of planting configuration and plant populations in the inter-crops. The plant population effect was, however, negative on companion crops leading to the recommendation of a conservative population of 50,000 plants/ha. However, in the shorter-duration genotypes the importance was higher and 300,000 plants/ha was recommended (Chauhan, 1990). This recommendation is based on the facts that such genotypes had less time to grow and were sown as a sole crop. The other benefits arising from higher plant population were greater production of stem biomass per unit area and leaf fall. Both these factors positively contributed to the sustainability of following crops (Chauhan et al., 2004).

3.2.2 Adaptation

Differences in sensitivity to day length experienced by short-duration genotypes in a given environment seems to play a crucial role in determining yield and to influences adaptation to different environments. Chauhan et al. (2002) evaluated pigeonpea genotypes that were selected under long day conditions of 45°N latitude (Minnesota, USA) and those selected under shorter day conditions in India at Patancheru (17°N). They observed that the genotypes selected in Minnesota were relatively less photoperiod-sensitive, and their harvest index was less affected by extended photoperiods. This study showed that changes in photoperiod influenced the dry matter partitioning in pigeonpea. They concluded that the selection environments representing different photoperiods had a profound influence on the level of partitioning in pigeonpea.

In this study, flowering and maturity durations were positively related to yield under natural days, but both were negatively related to yield under extended day length.These findings suggest a profound influence of photoperiod on pigeonpea physiology (Chauhan et al., 2002). The effect of photoperiod on harvest index does not appear unique to pigeonpea but seems a general response of other legumes as well (Wallace et al., 1993).

Studies by Chauhan et al. (2002) suggested that in pigeonpea photoperiod, controlls partitioning through the control of indeterminateness. In pigeonpea it has always been tempting to breed determinate cultivars, as these were expected to have higher partitioning in addition to facilitating mechanized management in terms of sprays and harvesting. However, Sheldrake and Naraynan (1979) showed that both cultivar types with respect to partitioning and the differences in flower and pod formation were morphological rather than physiological. In a later study, Chauhan et al. (1998) reported that the indeterminate pigeonpea types had a greater advantage over determinate varieties in the environments where growing period was longer, and less so in shorter growing period conditions.

Future physiological research could therefore focus more on the partitioning physiology of pigeonpea crops. An important area of research is the identification of genes related to photoperiod sensitivity, and the clarification of conditions affecting the expression of these genes. Conducting such experiments on medium- and long-duration pigeonpea will be a complicated task that must consider the confounding effect of different management factors. Hence, identification of the relevant genes/markers and their use in the selection of new genotypes will be a positive step forward.

4 Genetic factors influencing sustainability of pigeonpea production

4.1 Susceptibility to biotic and abiotic stresses

Under natural conditions, a number of biotic and abiotic factors adversely affect pigeonpea growth and development. The losses, however, vary from one environment to another. Among biotic constraints, insects (mainly pod borers and pod fly) and diseases (mainly wilt and sterility mosaic) are the common yield reducers in most pigeonpea areas. In general, breeding-tolerant cultivars tend to lack any effective genetic resistance against insects. However, the situation with respect to disease-resistance is more promising, with the availability of both cultivars and hybrids showing high levels of stable resistances to wilt and sterility mosaic.

4.2 Understanding the genetics of key traits

For successful plant breeding, it is important that genetic information regarding key traits is available to breeders. In pigeonpea, such information on yield and related traits is limited and inconclusive (Saxena and Sharma, 1990; Sawargaonkar, 2011). Lack of information on the aspects such as number of genes, their mode of action, heritability and genotype–environment interaction slows the process of genetic gain. Therefore, it is important to strengthen efforts in this direction using both traditional as well as genomic-based approaches.

4.3 Limited genetic variability

Genus *Cajanus* contains a tremendous amount of phenotypic variability within the primary gene pool for both quantitative as well as qualitative traits (Table 2). However, the studies conducted at molecular level to quantify the diversity in this group of materials showed contrasting results of limited genetic diversity (Yang et al., 2006; Odeny et al., 2007; Yadav et al., 2014). This limitation appears to be the main reason for the restricted genetic enhancement of yield and its stability in pigeonpea. Shiv Kumar et al. (2003) studied the diversity among the parents of released pigeonpea cultivars in India. They found that of the 86 cultivars released, 50% of them had ten parents in common. Further, Singh et al. (2016) reported that within the released cultivars, more than one-third originated directly from landraces. These include the present-day popular cultivars (Table 3) such as Maruti, BDN 2, LRG 30 and LRG 36 in the medium-duration group, and Gwalior-3, Bahar, MAL 13 and NA1 in the long-duration group. All these studies showed that the genetic diversity within the primary gene pool of pigeonpea is not large enough for the genetic enhancement of yield. The genetic diversity among crossable wild species, however, is relatively high (Yang et al., 2006; Yadav et al., 2014), and it could be used to diversify the genetic variation within the primary gene pool.

4.4 Limited use of genomics in breeding

In modern plant breeding, the genomics tools are helpful in achieving genetic gains with greater accuracy at a faster pace. In pigeonpea, research initiatives in this area gained momentum only after its draft genome was sequenced (Varshney et al., 2012). This provided necessary genomics resources in terms of molecular markers and information on genes controlling important traits in pigeonpea. Furthermore, this research also facilitated genetic mapping for the traits using advanced genotyping approaches such as whole-genome re-sequencing, genotyping by sequencing, high-density genotyping arrays and so on.

Table 2 Variability observed in *Cajanus cajan* germplasm

Trait	Variability	Trait	Variability
Days to flower	High	*Maruca* tolerance	Very low
Days to maturity	High	Wilt resistance	High
Plant type	Moderate	Sterility mosaic resistance	High
Plant height	High	*Alternaria* blight resistance	Very low
Seeds/pod	High	*Phytophthora* resistance	Very low
Seed colour	High	*Helicoverpa* resistance	Very low
Protein	Moderate	Pod fly resistance	Very low
Cooking time	Very low	Waterlogging resistance	Moderate

Table 3 Some popular pigeonpea cultivars developed by different breeding methods in three maturity groups in India

Maturity	Total releases	Introduction	Hybridization and selection	Mutation	Popular cvs	Year of release
Early	33	6	24	3	UPAS 120	1976
					AL 15	1981
					Manak	1983
					Pusa 992	2002
					ICPL 88039	2011
Medium	37	17	19	1	BDN 2	1979
					LRG 30	1980
					Maruti	1985
					Asha	1993
					BSMR 853	2001
Late	16	9	7	0	Gwalior 3	1980
					Bahar	1980
					NA 1	1997
					MAL 13	2004
					IPA 203	2012
Total	86	32	50	4	–	–

Source: Singh et al. (2016).

This knowledge can facilitate breeding of the traits of interest including (i) incorporation of resistance to various biotic and biotic stresses, (ii) molecular tagging of male fertility restoring (*Rf*) genes, (iii) transfer of targeted genes from wild species and (iv) genomics-based seed quality control. Tagging of the targeted genes can help breeders in identifying genotypes carrying the particular gene of interest within segregating populations or new germplasm. With this technology, the selection of individuals carrying the desired genes is possible without testing their progeny. The processes are accurate, economic and rapid. This technology is also useful for pigeonpea breeders to determine the seed quality of hybrids and their parents, to help maintain the valuable genetic stocks. Since the processes of genomics research in pigeonpea started recently, this technology in the past could not be exploited to breed cultivars with greater yield and stability.

4.5 Genetic contamination of seed

To reap the benefits of released cultivars, it is essential that their genetic purity is maintained year after year. Overall, it is not a serious issue in pulses, but in pigeonpea, where a considerable extent of natural out-crossing occurs, the maintenance of genetic purity is a significant issue. In a recent review, Saxena et al. (2016) reported that in pigeonpea the out-crossing occurs in most places, and it ranged from 0 to 48% in India, 0 to 60% in China, 14 to 19.64% in Sri Lanka, 13 to 70% in Kenya, 8 to 22% in Uganda, 15 to 39% in

Cameroon and 2 to 40% in Australia. In cases where the breeders/seed producers failed to maintain the purity of released cultivars, their performance with respect to disease resistance and productivity deteriorated rapidly. This factor has a negative impact on the productivity and stability of the cultivars.

5 Enhancing pigeonpea sustainability through crop modelling

Traditional pigeonpeas are cultivated as intercrop with short-aged cereals. Their long growing duration complements the resource use with companion crops, both in terms of time and space (Natarajan and Wiley, 1980). The sole crop cultivation in pigeonpea–wheat rotation is also popular with substantial residual benefit to wheat (Chauhan et al., 2004). A key question arises as to whether the advantages these systems could be further increased. In this context, conducting field experiments at the same scale to answer this question may not be feasible. In fact, a plethora of cropping systems and combinations exists which involves pigeonpea for rotations. This makes it difficult, if not impossible, to practically investigate them individually. Further, it would also be important to quantify the influence of other crops used in the systems. Moreover, such experiments, even on a limited scale, could only be done over a limited number of locations and seasons and may not generate useful information.

Given that all factors that contribute to sustainability of cropping systems are highly variable, results from such experiments will need to be examined for their applicability to other situations and seasons. These assessments need to be beyond the consideration of trade-offs in economic terms, as has been done in the past. In this context, accurate crop simulation models (Moller et al., 2007) which have already been demonstrated with wheat, could prove useful (Moller et al., 2014). The development of a pigeonpea model (Robertson et al., 2001a) has created the possibility of investigating the productivity/sustainability parameters in a more objective way.

5.1 The pigeonpea model

Robertson et al. (2001a) for the first time described a pigeonpea model that was capable of simulating its development, growth, nitrogen accumulation and yield in response to weather, agronomy and soil conditions. This model can simulate a range of maturity types and is based on extensive summarization of data collected at ICRISAT (Robertson et al., 2001b; Carberry et al., 2001). The model, when applied to a number of experiments covering a range of factors including sowing times, population densities, soil types and seasons effects on pigeonpea, could simulate yield of extra-short to medium-duration pigeonpea with a notable accuracy of 92–96%. However, for long-duration pigeonpea, simulation for smallholding farming systems was not possible due to limited data availability (Smith et al., 2016).

5.2 Crop modelling for developing sustainable cropping systems

One of the most common applications of models is to add value to experimentation and demonstration. Models, once properly parameterized and tested, will allow extrapolation of crop performance to other seasons (Whitbread et al., 2010). This could be helpful in explaining why farmers persist with certain practices. For example, farmers might be more inclined to grow long-duration pigeonpea intercropped with sorghum or maize, rather than pigeonpea followed by wheat or a single cereal crop. Such assessments based on the results of one or two seasons might help to understand the factors behind one crop being more favorable. However, under long-term rainfall conditions, a different cropping system might appear more stable. The relative profitability of different farming systems such as those which are contingent on prevailing climate conditions must be considered. Also, the availability of resources supported by modeling outcomes, and those outcomes which are more rigidly based on farmer's long-standing experience could be compared (Rodriguez et al., 2011).

The other application of pigeonpea models could be in assisting breeding efforts. The modelling thus far has been used in benchmarking yield, and assessing risk to production of a particular practice. Its use in facilitating breeding is just beginning to occur. Currently, the pigeonpea adaptation zones are largely based on agro-ecological regions that were defined by experts (Sameer Kumar et al., 2014). The frequencies with which droughts or thermal regimes are experienced in these target environments are not well defined.

Models could also be used to characterize pigeonpea growing environments which breeders can take into consideration to develop different genotypes. For example, the ideal production niches for the newly developed super-early pigeonpea types could be defined. The model could also assist in defining agro-ecological regions that are characterized by different frequencies of drought and temperature regimes as has been done in mung bean in Australia (Chauhan and Rachaputi, 2014). This could be followed by developing landscapes to identify superior genotype × environment × management interactions as done in sorghum by Hammer et al. (2014). It could be further used to identify appropriate maturity types for each environment. Following this, best local management practices with a broadly adapted genotype, or genotypes with specific adaptation to local agronomy could be determined.

6 Enhancing sustainability through an efficient seed system

Seed is a basic unit in agriculture because it contains all vital factors (genes) necessary to achieve productivity and sustainability during farming. Hence, it becomes imperative to produce and distribute quality seeds year after year. To achieve this goal on a sustainable basis, an efficient seed chain for different grades of seed with strict quality control needs to be established (Saxena, 2006). Unlike most pulses, the maintenance of seed quality in pigeonpea is rather difficult and resource-intensive. This is primarily due to a considerable extent (20–50%) of natural out-crossing. The maintenance of cultivars for the key traits that are under the control of recessive gene(s) is very critical, because the natural out-crossing can destroy them rapidly. There are examples where, in the absence of a good seed system, some previously disease-resistant pigeonpea cultivars have become highly susceptible over a period of a few years. At the time of its release, a late-maturing variety 'Bahar' was high yielding, widely adapted and highly resistant to sterility mosaic virus. After a few years, it became a mixture of resistant and susceptible plants and consequently, lost yield potentional and wide adaptation abilities. Similarly, there are other causalities (e.g.

cv. 'C11' and 'BDN 1'), which became highly susceptible under poor seed management. Therefore, for sustaining the high productivity of pigeonpea cultivars across locations and years, it is necessary to invest sufficient resources into the maintenance of quality seeds.

7 Enhancing sustainability through plant breeding

7.1 Breeding early maturing cultivars for high yield and adaptation

For expanding pigeonpea cultivation and ensuring sustainability, the diversification of cropping systems involving pigeonpea is essential. The traditional pigeonpea cultivars and landraces do not fit the bill due to their strong photosensitive nature. These types have a strict short-day requirement for the induction of flowering (also see Section 3), and it has restricted the adoption of traditional pigeonpea cultivars between 30°N and 30°S latitudes. This adaptation scenario started changing with the development of early maturing cultivars such as Prabhat, Pusa Ageti, UPAS 120 and a series of pigeonpea genotypes developed in India at Punjab, Haryana, Delhi, Pantnagar, Kanpur and ICRISAT. Wallis et al. (1981) suggested that earliness of pigeonpea genotypes was closely related to its photo-insensitivity reaction. After conducting a series of experiments at ICRISAT and in Australia, a number of relatively photo-insensitive cultivars were identified. To test their adaptation, these were tested at nine locations representing a wide range (7–46°N) of latitudes in an international nursery. Some of the genotypes such as ICPL 83015, 85030 and 85010 produced over 2 t/ha of grain even at 46°N (Table 4). Vales et al. (2012) reported breeding of some super-early pigeonpea genotypes, which mature in < 90 days. They also demonstrated that these types were adapted to higher altitudes and latitudes. In cases where grain yield and crop duration are considered together (yield per unit of time consumed), the super-early pigeonpea could be an attractive option. Besides yield, these types also have synchronous flowering and maturity to facilitate better insect management

Table 4 Seed yield (t ha^{-1}) of extra-short-duration pigeonpea lines at different latitudes, 1988–89

	Latitude (°N)								
ICPL	7	9	17	23	29	31	32	34	46
83015	2.32	1.48	2.35	1.75	1.06	1.74	3.73	1.86	2.06
83019	2.21	1.39	1.46	1.43	1.00	1.36	3.58	1.67	1.76
84023	2.34	1.14	1.42	1.83	1.37	1.87	2.99	2.49	1.59
85010	2.79	1.55	1.59	1.88	1.17	1.25	3.16	2.33	2.15
85030	1.52	1.11	1.21	1.29	0.98	1.16	2.52	0.83	2.46
Mean	2.17	1.27	1.65	1.59	1.16	1.67	3.19	1.70	1.77
CV%	22.8	23.3	14.5	29.2	12.9	4.70	17.1	NA	NA

Source: Saxena (2002).

Table 5 Summary of generation turnover in four early maturing pigeonpea genotypes

		Date of			Days			
ICPL No.	Generation number	Sowing	Flowering	Harvesting	Flowering	Pod age	Cumulative	Germ. (%)
85024	1	15 June	4 Aug	1 Sept	50	28	78	83.3
	2	9 Sept	24 Oct	17 Nov	43	25	146	81.5
	3	17 Nov	15 Jan	10 Feb	59	26	231	86.7
	4	16 Feb	14 Apr	9 May	57	25	313	72.7
	Mean				**52.3**	**26.0**	–	**81.05**
87093	1	15 June	4 Aug	1 Sept	55	28	78	100.0
	2	9 Sept	1 Nov	26 Nov	53	25	161	95.0
	3	26 Nov	29 Jan	24 Feb	64	26	251	80.0
	4	26 Feb	27 Apr	24 May	60	27	338	100.0
	Mean				**56.8**	**26.5**	–	**93.7**
00004	1	15 June	15 Aug	10 Sep	61	26	87	90.0
	2	16 Sept	11 Nov	11 Dec	56	30	173	96.0
	3	15 Dec	17 Feb	15 Mar	64	28	265	80.0
	4	20 Mar	15 May	11 June	57	27	349	100.0
	Mean				**59.5**	**27.8**	–	**91.5**
00151	1	15 June	12 Aug	16 Sep	58	35	93	96.0
	2	16 Sept	15 Nov	14 Dec	60	29	182	85.0
	3	15 Dec	20 Feb	20 Mar	67	28	277	86.2
	4	20 Mar	20 May	17 June	52	28	367	100.0
	Mean				**61.8**	**30.0**	–	**98.80**

Source: Saxena et al. (unpublished).

and mechanized culture. This material would allow farmers to introduce pigeonpea in new niches for enhancing sustainability and nutritional security.

The early maturing inbred cultivars can be bred quickly using a rapid generation turnover schedule as proposed by Saxena et al. (in press). This approach is an extension of the popular 'single seed descent' method. For generation advancement, instead of single seeds this approach uses single pods from each plant, and germination of immature seeds. This scheme ensures conservation of genetic variability for desirable traits in subsequent generations. Adoption of this technology will considerably reduce the breeding time, as pigeonpea breeders can easily produce four generations within a year (Table 5).

7.2 Breeding cultivars for fragile ecosystems

7.2.1 Wheat-based cropping systems

A key development in pigeonpea agronomy occurred when it was realized that pigeonpea could be grown in rotation with wheat in northern India. This rotation became even more popular with the development of extra-short-duration varieties such as ICPL 88039, which took less time to harvest than the ruling varieties UPAS 120 and Manak. This provided greater turnaround time for wheat sowings (Dahiya et al., 2002). This concept was further extended to diversify the cropping system in Indo-Gangetic plains, where rice–wheat crop rotation is extensively practised. The heavy use of chemical fertilizers and liberal use of irrigation have made this traditional rotation unsustainable, primarily due to increases in soil salinity and poor response to added fertilizers (Dahiya et al., 2002). ICPL 88039, the extra early pigeonpea variety, has allowed farmers in Indo-Gangetic plains, Punjab and Haryana, to replace the water-demanding rice crops. Unlike rice, pigeonpea only required two irrigations for crop establishment in these regions. Alongside this, it was also observed that in the pigeonpea–wheat cropping sequence yields of wheat were increased by a margin of about 1,000 kg/ha. These increases were due to the increased residual benefits of returning organic materials rich in nitrogen and other nutrients to the soil, as well as permitting the timely sowing of wheat crops.

7.2.2 Rain-fed low and mid-hills

In general, the slopping agriculture lands in hillside regions suffer from repeated heavy erosion of top soils. This makes the soils deficit in organic matter and important macro- and micro-nutrients. Agriculture in such areas entirely depends on rainwater, and it often suffers from post-rainy season drought. Hence, the productivity of traditionally grown cereals and pulses is very low (300–400 kg/ha). This has contributed to overall poverty and protein malnutrition among those living below the poverty line. To overcome this problem pigeonpea cultivar ICPL 88039 was introduced into the low to mid-hills of Uttarakhand. The on-farm trials conducted in the state demonstrated that pigeonpea could be grown successfully under rain-fed conditions up to elevations of 1,580 m (Table 6). This variety was found useful for both grain production (up to 1,878 kg/ha) as well as soil conservation (Saxena et al., 2011). The cultivation of pigeonpea has now been extended to all the districts of low and mid-lands. Variety ICPL 88039 is also growing successfully even in the rocky terrains, where no crop can produce economic yield. The adoption of this technology is easy and profitable, and it could pave the way for overall sustainability of agriculture and

Table 6 Yield recorded in different districts of Uttarakhand

District	Altitude (m)	Yield (kg/ha)
Champawat	1580	1400
Almora	1480	1275
Uttarkashi	1310	1266
Rudraprayag	1280	1250
Chamoli	1270	1878
Tehri Garhwal	1200	1266
Range	1200–1580	1250–1878

prosperity of hilly areas. Pigeonpea is a good source of home-grown high-protein food and the direct beneficiaries from this initiative are smallholder Himalayan farmers.

7.2.3 Arid environments

Frequent droughts and land degradation are common features of arid areas in Rajasthan, India. Here, a lack of soil-enhancing legume crops has led to further soil degradation. However, the introduction of the pigeonpea variety ICPL 88039 has paved the way for long-term sustainability in this region. At present, over 12,000 farmers are cultivating pigeonpea on about 10,000 ha of land, with an average production of 719 kg/ha over 120–130 days. The ICPL 88039 variety yielded a net average income of Rs. 60,000/ha under rain-fed conditions. Farmers recognized that this variety is ideal for their light soils, in a region where the annual rainfall only reaches about 300 mm. ICPL 88309 has become well-established among farmers in the region who value the variety's role in developing long-term sustainable agricultural solutions. Its appeal is not only due to its adaptation and yield, but also its provision of protein and other important nutrients. The dry stems can also be used as a fuel source, with 10 t/ha of stems providing 3,000 calories/kg in energy. The cultivation of ICPL 88039 has now restricted deforestation for domestic fuel purposes, and thus directly contributed towards environmental conservation, as well as the benefits already outlined above.

7.2.4 Wastelands

Successful attempts were made to introduce pigeonpea cultivars for rehabilitating the hilly wastelands of southern China by exploiting the cultivar's soil amelioration and perennial properties (Saxena, 2008). The long-duration pigeonpea varieties can survive under rain-fed, low-fertility conditions, whilst producing the significant amount of biomass needed to protect the soil. In these sloping terrains, the recovery of ecology is not easy due to heavy-intensity rains, long-term deforestation, and the fragile nature of soils. Traditionally, in the absence of any fast-growing forest tree species, shrubs such as *Phyllanthus emblica* and *Dodonaea viscosa* were transplanted to reduce soil erosion. However these have no economic value, and so two long-duration pigeonpea cultivars ICPL 87119 and ICP 7035 were introduced. These cultivars adapted well to the harsh conditions, produced a significant amount of biomass and grains, and covered the barren land within a few months. Due to these qualities, pigeonpea has been identified as a key species to help restore areas damaged by deforestation.

7.3 Breeding pigeonpea for resistance

7.3.1 Disease resistance

Since in medium- and late-maturing pigeonpea both *Fusarium wilt* and sterility mosaic diseases are two of the challenges faced by both medium- and late-maturing pigeonpea crops. ICRISAT's strategy aimed to breed both pure-line and hybrid cultivars with genetic resistance to both these diseases. Therefore, to breed such varieties and to attain the target sustainability, ICRISAT launched a strong breeding programme in which several cultivars and hybrid parents were bred. This was possible because of an effective field screening technology invented at ICRISAT by Nene et al. (1981). To achieve the target of resistance breeding, pedigree selection within the landraces has been very effective, both in India and Africa. In India for example, variety Maruti, a selection from ICP 8863 collected from Maharashtra, has been proven to be of benefit to the farmers of wilt-prone areas. In some districts, its adoption is as high as 60% (Bantilan and Joshi, 1996). Similarly, in eastern and southern Africa, the most popular pigeonpea variety is Nandolo wa nswana, which is also a selected from a Tanzanian landrace (ICP 9145). In Malawi, it occupies a considerable area (Simtowe et al., 2016). These genotypes have been used extensively as donor parents in resistance breeding programmes.

In 1992, ICRISAT used a bulk-pedigree method to develop a widely adapted, medium-maturing pigeonpea variety called ICPL 87119 (Asha). This variety, besides recording 20% high yield, had a high level of resistance to wilt and sterility mosaic diseases. The adoption of this variety is very popular in peninsular and central India. Similarly, both the released and unreleased hybrids have high levels of resistance to the two diseases (Table 7). Such cultivars will help to reduce yield losses and contribute significantly towards the sustainability of pigeonpea production in rain-fed agriculture.

7.3.2 Insect resistance

The most serious pigeonpea pests are the pod borers (*Helicoverpa armigera* and *Maruca vitrata*) and pod fly (*Melanagromyza obtusa*). Among these, *H. armigera* is prevalent throughout the tropics and subtropics, costing an estimated pigeonpeas loss of over $310 million annually (Ranga Rao et al., 2013). In most countries, the present-day plant protection systems are embedded with chemicals. In the past five decades, the use of chemical pesticides has increased by 170-fold, from 2.2 g/ha of active ingredient in 1950 (Vasantharaj,

Table 7 Some promising medium-duration pigeonpea hybrids

Hybrid (ICPH)	Yield (kg/ha)	Standard heterosis (%)	100-seed weight (g)	Wilt (%)	Sterility mosaic (%)
3371	3013	62**	11.50	0	0
2740	2900	57**	12.30	0	0
3762	3000	62**	11.90	0	0
Check	1864	–	11.10	0	0
CV (%)	11.9	–	3.98	–	–

Disease data recorded in sick nursery. Source: ICRISAT.
** Significant at 1% probability.

1995) to 381 g/ha in 2007 (Anonymous, 2009). To control this pest, pigeonpea farmers usually apply 5–8 chemical sprays. The repeated use of some insecticides may lead to the development of inherent resistance in the target insects. Alongside this, potential dangers of excessive dependence on pesticides can include outbreaks of secondary pests, chemical residues contaminating the food chain, and problems relating to loss of biodiversity.

The insect-control programmes should include both the recently developed high-yielding pure-line/hybrid cultivars (which offer a certain level of genetic tolerance), as well as an effective IPM package. Based on the mechanisms involved, Painter (1958) classified plant resistance to insects into three categories. These include (i) non-preference for oviposition, food or shelter, (ii) antibiosis – adverse effect of plants on the biology of insects, and (iii) tolerance – repair, recovery or ability to withstand infestation. In pigeonpea, so far there are no reliable genetic solutions for pod borers, and in spite of diverting huge resources to develop an effective host plant resistance, success up to this point has proved elusive. Field screening of over 10,000 germplasm for tolerance to pod borers at ICRISAT did not yield any genotype with a significant level of genetic resistance. A few accessions, however, with relatively less pod damage were identified, and one such selection (ICPL 332), was released as variety 'Abhaya' in India. This variety, in spite of good yield and tolerance to pod borers (Table 8), could not make any impact due to its high susceptibility to *Fusarium* wilt disease. Recently, this weakness of ICPL 332 was eliminated and it was renamed as ICPL 332WR (Sharma, 2016). This improved variety is likely to contribute significantly towards the sustainable production of pigeonpea.

M. vitrata (Geyer) is another serious insect pest of tropical legumes. It causes substantial losses to early maturing genotypes under humid conditions. Some pigeonpea genotypes with moderate levels of resistance (Table 9) were identified in Sri Lanka (Saxena et al., 2002), but no targeted resistance breeding programme followed. Long-duration genotypes PDA 88-2E, PDA 89-2E, PDA 92-2E and PDA 93-2E have been identified as resistant to pod fly, a serious insect pest of northern India (Lal et al., 1999).

7.3.3 Resistance to waterlogging

In soils characterized by high water-holding capacity, temporary waterlogging poses a worrying threat to pigeonpea productivity. According to Choudhary et al. (2011), about 1.1 m ha of land is waterlogged annually, inflicting losses of about 25–30% onto the productivity.

Table 8 Pod damage and yield of *Helicoverpa*-tolerant cv. Abhaya and control

	Selection		Control	
Year	Damage (%)	Yield (t/ha)	Damage (%)	Yield (t/ha)
1984	49.0	2.27	76.0	1.83
1985	11.6	1.84	33.4	1.44
1986	22.5	1.05	71.4	0.58
1987	70.6	2.73	94.2	1.54
1988	19.0	1.48	48.1	0.89
Mean	34.54	1.87	64.62	1.25

Source: Compiled from various ICRISAT reports.

Table 9 Yield (t/ha) of three lines selected for resistance to *Maruca vitrata* in Sri Lanka

Selection	Sprayed	Unsprayed	Loss (%)
MPG 664-M1-2-M2	2.41	1.99	17.4
MPG 664-M1-2-M13	2.64	2.19	17.1
MPG 664-M1-2-M27	2.22	1.92	13.5
UPAS 120 (control)	2.32	0.67	68.9
SE (spray)	2.41		

Source: Saxena (2002).

Under waterlogged conditions, the useful aerobic bacteria become inactive while their anaerobic counterparts (facultative/obligate bacteria) are able to thrive. This results in a shortage of oxygen in the soil which has a negative effect on general plant health. Chauhan et al. (1997) developed a laboratory technique to screen pigeonpea genotypes for their waterlogging tolerance. Recently, Sultana et al. (2013) identified a number of tolerant genotypes. As well as waterlogged soils, drought, soil salinity, aluminium toxicity and low temperature are other abiotic stresses affecting pigeopea, but very little information is available to understand various relevant aspects of these stresses.

7.4 Breeding cultivars with high-protein content

The protein malnutrition among poverty-stricken populations is usually high, especially in underdeveloped and developing countries. Pigeonpea seeds, besides providing valuable protein, also contain certain amounts of anti-nutritional compounds such as oligosaccharides, enzyme inhibitors, phenols and tannins. Pigeonpea seeds, whilst providing valuable protein, also contain compounds such as oligosaccharides, enzyme inhibitors, phenols and tannins which do not offer nutritional benefits. Where arable lands are limited, the only option available is to overcome this problem is to produce more protein per unit of land area. This means breeding new high-protein varieties for cultivation. Pal (1939) reported that in comparison to other pulses, pigeonpea has the best combination of nutrition-related traits with high biological value.

A considerable variety of for protein content among pigeonpea genotypes has been reported by various researchers, but it was not large enough for direct use in breeding programmes (see review by Saxena and Sawargaonkar, 2015). Therefore, wild relatives of pigeonpea were selected as alternative donors for breeding high-protein pigeonpea genotypes. These included *C. albicans* (30.5%), *C. sericeous* (29.4%) and *C. scarabaeoides* (28.4%). Dahiya et al. (1977) reported that 3-4 genes controlled the protein content in pigeonpea. Durga (1989) and Saxena and Sharma (1990) observed that protein content was under additive and complementary gene effects, and that low-protein genes were dominant or partially dominant over high protein genes.

The breeding for high-protein pigeonpea cultivars was undertaken at ICRISAT using a pedigree breeding method. A large population of approximately 3,000 plants was raised to form the F_2 generation, and as expected, the populations segregated for various other morphological traits. The primary selection criteria was for protein content. Therefore, seed samples from each F_2 plant were analysed to determine their protein content, with the desirable plants remaining in the field. The high-protein (>25%) segregants were selected for further breeding. Within each progeny a mild selection for plant type was exercised and the individuals carrying wild species traits such as creeping and abnormal growth were rouged. Interestingly, in the F_5 generation, some segregants with 28% protein were recovered. In the next four generations (F_6 to F_9) a few selections with protein ranging from 28 to 32% were also recovered. During this period, selection for seed shape and size was exercised. In the F_{10} generation, the yield trials of high-protein (> 28%) lines were conducted and the results were very encouraging (Table 10). Among the non-determinate selections, yield of the top two lines (HPL 40-5 and HPL 40-17) was similar to that of the control BDN 1 (2.02 t/ha), but the selections were significantly higher than the control (23.2%) in their protein content. The advantage of the high-protein lines was reflected in the 'total protein' harvest from unit land. Similar results were recorded from the evaluation of determinate high-protein lines. These results demonstrated that in pigeonpea, seed yield and protein content can be enhanced simultaneously.

Studies conducted to understand the effect of diverse environmental factors on the protein content of high-protein lines yielded very useful results. The evaluation of the lines across wide Indian locations in the south (Andhra Pradesh, Karnataka); centre (Gujarat, Maharashtra, Madhya Pradesh); and north (Haryana), showed that although minor (2–3 protein units) differences were observed, the differences between the high and low protein cultivars were maintained (Table 11). HPL 24 appeared to be the best with >30% protein recorded at each place. Similarly, evaluation of high-protein lines over a six year period showed that the protein content of each high-protein selection was higher in each year, and the values were much higher than the control. These observations indicated that high-protein traits derived from the wild relatives of pigeonpea were stable, and will not pose any difficulty in breeding high-yielding, high-protein pigeonpea cultivars in future.

Biological assessment of the protein-rich selections was conducted to determine if the additional protein can be utilized in growth and development of the individuals. The data (Table 12) showed that the high-protein lines were significantly superior to the control cultivar in terms of available protein. It was also reported that the high-protein lines were nutritionally superior to normal cultivars because of their greater amount of sulphur-rich amino acids.

Table 10 Seed yield and protein harvest from high-protein F_{10} lines

Genotype	Maturity (days)	100-seed wt (g)	Yield (t/ha)	Protein (%)	Protein yield (kg/ha)
HPL 40-5	169	9.6	2.10	26.9	452
HPL 40-17	169	8.5	2.07	26.5	440
BDN 1 (c)	168	9.6	2.02	23.2	373
SE	±0.9	±0.18	±0.16	±0.46	±37.3
CV (%)	0.9	3.4	17.3	3.0	17.0
HPL 8-10	163	10.5	1.66	26.5	353
HPL 8-16	162	10.5	1.57	27.4	344
ICPL 211(C)	162	14.3	1.46	21.6	251
SE	±1.1	±0.15	±0.19	±0.21	±38.5
CV (%)	13	2.5	27.0	1.7	25.8

Source: Singh et al. (1990).

Table 11 Stability of four high-protein selections at six diverse locations in India

Location	State	HPL 24	HPL 25	HPL 26	HPL 28	Control	SE
Patancheru	Andhra Pradesh	31.3	28.6	29.7	27.8	23.3	±0.26
Jalna	Maharashtra	32.2	28.9	29.7	30.4	23.1	±0.69
SK Nagar	Gujarat	30.9	28.4	29.0	27.3	21.4	±0.36
Gulbarga	Karnataka	32.1	29.9	–	27.6	23.0	±0.49
Gwalior	Madhya Pradesh	32.3	30.4	28.2	27.3	22.0	±0.71
Hisar	Haryana	31.1	29.6	31.7	29.2	24.5	±0.51

Saxena et al. (2002).

Table 12 Comparison of high-protein pigeonpea line and control for protein and its biological parameters

Item	High-protein line HPL 8	High-protein line HPL 40	Control line (ICPL 211)	SE
Constituents				
Starch (%)	54.3	55.6	59.3	±0.30
Protein (%)	28.7	31.1	23.1	±0.09
Albumin (%)	9.1	8.0	8.6	±0.34
Globulin (%)	63.5	66.2	60.3	±1.08
Glutelin (%)	20.2	19.7	22.8	±0.75
Prolamin (%)	2.9	3.2	2.1	±0.06
Cysteine	0.8	0.8.	0.7	±0.01
Biological parameters				
Total protein digestibility	83.7	82.9	85.7	±2.14
Biological value	67.0	65.3	62.9	±1.68
Net protein utilization	56.1	54.1	53.9	±1.06
Utilization protein	15.5	16.7	12.3	±0.25

Source: Singh et al. (1990).

8 Pigeonpea hybrids for greater productivity and sustainability

8.1 Evolution of hybrid technology

The discovery of cytoplasmic nuclear male sterility (Saxena et al., 2005) encouraged pigeonpea breeders to explore the possibility of developing commercial hybrids by using pigeonpea's inherent partial out-crossing and break the decades-old productivity barrier. Soon a multi-institutional research and development programme was launched

Table 13 Performance (yield kg/ha) of hybrid ICPH 2671 in the on-farm trials

State	Farmers (no.)	Hybrid yield	Control yield	Standard heterosis (%)
Maharashtra	782	969	717	35
Andhra Pradesh	399	1411	907	55
Jharkhand	288	1460	864	69
Madhya Pradesh	360	1940	1326	46
Total/mean	1829	1445	954	51

Source: Saxena et al. (2013).

by ICRISAT and ICAR. A breakthrough in this endeavour was achieved in 2010, when the world's first commercial pigeonpea hybrid ICPH 2671 was released in Madhya Pradesh (Saxena et al., 2013). Prior to its release, the hybrid was extensively evaluated in farmer's field. A total of 1829 on-farm trials were conducted (Table 13) in the states of Maharashtra (782 trials), Andhra Pradesh (399 trials), Madhya Pradesh (360 trials) and Jharkhand (288 trials). In this extended exercise, the hybrid ICPH 2671 recorded 30–60% superiority over the best local cultivar. Overall, the superiority of the hybrid ICPH 2671 over the control was 51%.

The release of hybrid ICPH 2671 was followed by the release of ICPH 2740 and ICPH 3762. A yet-to-be-released white-seeded hybrid named ICPH 4104 has also been identified, (and this will be released by a private seed company in Gujarat). These hybrids recorded 30–50% more yields in farmer's fields. To cater to the needs of different agronomic niches and cropping systems, a number of new hybrids in early and medium groups are in the advance stages of testing. These include ICPH 2433, ICPH 2438 and ICPH 2363 in the early-group category, which showed a yield advantage of 54%, 42% and 36%, respectively. Similarly, in the most popular medium maturity category, hybrids ICPH 3371 (3013 kg/ha) and ICPH 3491 (2919 kg/ha) were found to be highly promising with, respectively, 62% and 57% superiority over the national control variety Asha. All the medium-duration hybrids are free from both wilt and sterility mosaic diseases. This performance data showed that by cultivating these pigeonpea hybrids, a significantly higher productivity levels can be achieved by farmers.

Saxena (2015) have extensively reviewed this subject. They concluded that besides high yields, the pigeonpea hybrids also have the following advantages over the inbred cultivars, and can play a great role in enhancing both the productivity and sustainability of the crop.

- Hybrid seeds germinate faster and have rapid seedling growth
- Hybrid plants have >30% greater biomass both above and below ground
- Hybrids need 30% less seeding rate than varieties
- Hybrids maintain superiority under both high- and low-input situations
- Hybrids have extra resilience to encounter various stresses
- Hybrids compete well with inbred cultivars for various nutritional and marketing traits

8.2 Adoption of hybrids

For the adoption of hybrids, there are three primary prerequisites. These include (i) high and stable yields, (ii) economically viable seed technology, and (iii) a good promotion and marketing network. A brief overview follows.

8.2.1 High yields

The high yield potential of hybrids has been well documented across a range of field environments, including under rain-fed and high-input conditions (Saxena, 2015). In rain-fed situations, hybrid yields are around 1,500–2,500 kg/ha. Interestingly, under high-input conditions, the hybrid's productivity levels approached 4,000–5,000 kg/ha (Table 14). Such commercial productivity levels are encouraging, and more farmers are adopting this technology to reap high profits from this crop.

8.2.2 Seed production

The production of hybrid seed is the most important component of the breeding programme. The hybrid seed technology in pigeonpea has now been perfected (Saxena, 2015) and its on-farm validation has produced encouraging results. This programme was organized at 94 locations and, on average, 1,019 kg/ha hybrid seeds were harvested (Table 15). This productivity level is attractive and economical (MK Saxena et al., 2011). Furthermore, a number of key areas in Telangana and Madhya Pradesh, India, have been identified with hybrid yields of over 1,500 kg/ha. These results demonstrated that if the site selection is appropriate, and the crop management is effective, then reasonably high hybrid yields are possible. Also, a seed-to-seed ratio of 1:200 to 1:300 makes the seed production and marketing appealing to both the growers and seed companies. This

Table 14 Demonstration of exceptionally high yields (kg/ha) of ICPH 2740 by some farmers in Maharashtra

Location	Area (m^2)	Hybrid yield	Control yield	Standard heterosis (%)
Salod	450	3956	2044	94
Nimgaon	1012	3951	2469	60
Kothoda	450	4667	3556	31
Tamoli	450	3889	2278	71
Mean	–	4116	2587	59

Table 15 Hybrid seed production (kg/ha) recorded in six states

State	Locations	Mean yield	Highest yield
Andhra Pradesh	34 (6)	998	1750
Madhya Pradesh	9 (3)	1674	3040
Gujarat	4 (2)	1179	1669
Maharashtra	5 (2)	603	1017
Odisha	40 (1)	523	1040
Karnataka	2 (2)	1138	1900
Total/Mean	94	1019	3040

( )number of years. Source: ICRISAT.

information confirmed that (i) a perfect hybrid seed technology is now available and (ii) it is ready for large-scale adoption.

8.2.3 Promotion and marketing

Farmers in Maharashtra and Telangana, India, have realized the importance of hybrid technology in enhancing pigeonpea yields, and that its demand is on increase. Therefore, the attention has now been shifted to expand the area under hybrid cultivation. In this endeavour, the release of hybrid ICPH 2740 in Telangana has been an important development. This technology has also made a strong impact in the neighbouring state of Maharashtra. The hybrid has met the farmer's requirements in both the peninsular and central areas of India. By offering a yield advantage of approximately 700–1,000 kg/ha, with a market value of Rs. 50/kg, one hectare of hybrid cultivation can generate an additional Rs. 40,000–50,000 for farmers. In 2016, ICRISAT and the Agriculture Research Station (Palem, Telangana,) estimated that over 700,000 kg of hybrid pigeonpea seed was available. This quantity could replace more than 140,000 ha of the traditional pigeonpea cultivars. This will benefit farmers by providing an additional 70,000 tons of grain. This level of profitability from the pigeonpea hybrids is comparable with many high value field crops. Its commercial cultivation will be fundamental in improving pigeonpea sustainability.

8.3 Two-parent hybrid breeding technology

In pigeonpea, both temperature and photoperiod were understood to influence the initiation and appearance of floral buds. However, their role in determining male fertility/sterility still needed to be established. In studies conducted by Saxena (2014), temperature

Table 16 Number of male fertile and sterile plants recorded under July-sown field conditions in September, November and February (representing different temperature regimes) in four temperature-sensitive selections

Year	Selection/ type of plants	September		November		February	
		Sterile	Fertile	Sterile plants	Fertile plants	Sterile	Fertile
2008	Envs S-1	22	0	1	21	22	0
	Envs S-2	8	0	1	7	8	0
	Envs S-3	10	0	0	10	7	0
	Envs S-5	18	0	3	15	16	0
	Total	58	0 (0.0 %)	5	53 (91.4%)	53	0 (0.0 %)
2009	Envs S-1	37	0	0	37	37	0
	Envs S-2	32	0	0	32	32	0
	Envs S-3	27	0	0	27	25	0
	Envs S-5	23	0	0	22	21	0
	Total	119	0 (0.0 %)	0	118 (100.0%)	115	0 (0.0 %)

( ) per cent fertile plants.
Source: Saxena (2014).

was found to influence the fertility status of pigeonpea plants. Under the temperature regime of ≥25°C the plants were completely male sterile. In contrast, when daily mean temperatures dropped down to <24°C, the male-sterile plants turned fully fertile and produced self-pollinated pods (Table 16). In early generations of breeding this material, Saxena et al. (2004) observed that some male-sterile pigeonpea plants converted to male fertility much earlier than the rest, and these male-sterile plants were classified as 'early' and 'late' converters. This suggested the presence of more than one gene with different temperature thresholds to produce fertile plants. All the 'converted male fertile' plants reverted back to male sterility when these plants encountered high temperatures (Table 16).

9 Future trends and conclusion

According to the FAO (1983), the definition of 'food security' is that everyone has both physical and economic access to the basic food that they need. By this definition, most of the developing countries are 'nutritionally insecure'. The scenario of nutritional security in India is quite interesting, as it is self-sufficient in calorie production but is lacking in protein and other vital nutrients. The per capita protein availability in India has witnessed a sharp decline from 27.3 kg/year in 1950 to 10 kg/year in 2000 (www.commodityonline.com, 2009). The escalating prices of pulses and other nutrient-filled vegetables, fruits and dairy products have further added to this difficult situation. A large proportion of rural and urban populations, in particular women and children, are suffering from malnutrition and nutrient deficiencies. Therefore, a dramatic improvement in breeding techniques and sustainability of nutrient-rich crops is urgently needed. In this context, pigeonpea can play an important role as it can grow easily with minimal inputs, rejuvenate soils and produce high-protein grains. Therefore, its production needs to be increased 2-3-fold, and this can be achieved by increasing its area and/or productivity per unit of land.

In this context, the promotion of an early maturing cultivar ICPL 88039 (= VLA 1) in the non-traditional niches is an interesting development. Firstly, to attain sustainability and self-sufficiency, concerted efforts will be needed in the near future. Secondly, the recent breakthrough achieved in hybrid pigeonpea technology has shown a great promise with 30–50% yield increase experienced by farmers. The extensive on-farm testing of the hybrids in six states, has generated awareness among farmers as to the benefits provided by pigeonpea hybrids which include increased yields and improved profits. The seed technology relating to pigeonpea hybrids is now well developed, and with an attractive seed-to-seed ration of between 1:200 to 1:300, confidence in the technology continues to grow.

With a yield advantage of 1,000–1,500 kg/ha and a value of Rs. 50/kg, pigeonpea farmers can fetch additional profit of about Rs. 50,000 from one hectare of hybrid crop. The magnitude of realized heterosis for yield and its economics in pigeonpea is similar to those of other crops (Singhal, 2013) and therefore, pigeonpea hybrids are attracting scores of farmers in Maharashtra and Telangana states. The cultivation of hybrid ICPH 2740 is now receiving greater attention by the agriculture departments of these states. According to the estimates of ICRISAT, National Seeds Corporation, State Seed Development Corporations, State Agricultural Universities and private seed companies, in 2016 at least 700,000 kg of hybrid seed was available on the market to replace over 140,000 ha of traditional pigeonpea cultivars.

Development of a sustainable quality seed chain is the key for success, particularly in crops like pigeonpea which is prone to genetic contamination through a variety of nectarivore insects. The efforts of both public and private seed sectors along with appropriate agronomy are necessary to achieve the target of a healthy crop production.

The promotion of early maturing pigeonpea in new niches and hybrid technology in the traditional areas will not only raise the national pigeonpea production but also provide easily digestible quality protein. Pigeonpea is capable of fulfilling various social, nutritional, economic and environmental needs of the smallholder farming communities, and therefore, will pave the way for food security and long-term agricultural sustainability.

10 Where to look for further information

The first research paper on pigeonpea breeding was published by Howard et al. (1919) from Indian Agricultural Research Institute, Pusa (Bihar), in Botanical Series. The authors wrote that genetic improvement of yield in pigeonpea inbred cultivars will be a Herculean task. Unfortunately, the predictions of the authors proved right as, in spite of extensive national breeding programmes, there has been very little geniune yield enhancement in this crop in the last 100 years. These observations were based on the atypical breeding behaviour and long generation turnover time of pigeonpea germplasm. Besides these, this paper also highlighted other key breeding constraints which still persist even after a century. I believe that the present generation of pigeonpea breeders may not be aware of this quality research, and therefore, the authors would like to recommend a thorough reading of this valuable piece of work.

The celebrations of International Year of Pulses in 2016 provided an excellent opportunity to summarise the breeding accomplishments, challenges and opportunities of different aspects of genetic enhancement of the crop (Saxena et al., 2016). As discussed in the present paper, a breakthrough in pigeonpea productivity was achieved by developing a hybrid breeding technology, the first in any pulse crop. The entire scenario of the evolution of hybrid pigeonpea technology including its adoption and impact has recently been reviewed by Saxena et al. (2018), and soon it will appear in volume 41 of Plant Breeding Reviews.

The question of narrow genetic diversity in pigeonpea has often been related to the issues of yield plateauing. To overcome this constraint, utilization of the wild relatives of the crop has been recommended and a considerable progress has been made in this direction. For those researchers who are interested in this area, the review published by Mallikarjuna et al. (2011) will be an ideal publication.

The genomics scientists have also made significant progress in recent times and the technologies are being used by breeders to enhance the precision and pace of breeding new cultivars and hybrids. Varshney et al. (2017) have elegantly summarized these aspects and achievements, and the present-day pigeonpea scientists are advised to read this paper to help them in planning their high-profile research programmes.

11 References

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