

## Review

# Breeding pigeonpea cultivars for intercropping: synthesis and strategies

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Pigeonpea [*Cajanus cajan* (L.) Millsp.] is an ideal pulse crop of rainfed tropics and sub-tropics due to its high nutritive value and ability to survive various biotic and abiotic stresses. Thus it has continued to be cultivated on marginal land mostly under rainfed situation where the risk of crop failure is very high. To have insurance against crop failures and harvest more food in time and space, most farmers grow pigeonpea as an intercrop with short-aged cereals and other crops. Presently, intercropping system accounts for over 70% of the pigeonpea area. However, yield of pigeonpea in this system is very low (400–500 kg/ha). The non-availability of improved cultivars adapted specifically to the intercropping environments is perhaps the major constraint that accounts for low yield. Considering the food and nutritional needs of the ever increasing population, productivity enhancement of this high-protein pulse is highly indispensable. In this review, the authors critically examine the technical difficulties encountered by breeders in developing high yielding cultivars for intercropping systems and discuss the strategies to overcome these constraints.

**Key Words:** breeding cultivars, pigeonpea, intercrop, productivity enhancement, hybrid.

## Introduction

Protein mal-nutrition among the under-privileged masses is an age-old issue and unfortunately, it is on increase due to many factors such as population growth, limited arable lands, expensive inputs, and reduced purchasing power for protein-rich food (Prasad 2003, 2013). This situation has resulted in a significant reduction in the average protein intake from 66 g in 1965 to 33 g/person/day in 2005 (Tomar and Talukdar 2016). Legumes are the major source of digestible protein; but their productivity levels are low due to lack of inputs and frequent incidences of drought and pests. Also, in the backdrop of climate changes and degradation of soils, the enhancement of productivity appears to be a difficult task. At farmers' level, the cultivation of cereals always gets priority due to basic energy requirements of the family. This relegates the cultivation of pulses to the risk-prone marginal lands with little or no inputs, making them the major component of low input agriculture (Choudhary *et al.* 2013b). In this scenario, pigeonpea [*Cajanus cajan* (L.) Millsp.], a popular pulse crop of semi-arid tropics, has potential to play a significant role. This pulse commands a high place among rainfed farming communities due to its

abilities to fix atmospheric nitrogen, release of soil-bound phosphorus, and recovery from drought and other stresses (Saxena 2008). According to FAO (2017) statistics, the estimated globally-sown pigeonpea area now stands at over 7.03 m ha, with a production of 4.89 m t and average yield of 695 kg/ha. The crop is well adapted to rainfed areas of India (5.60 m ha), Myanmar (0.6 m ha), Kenya (0.28 m ha), and Tanzania (0.25 m ha). In all these countries, pigeonpea is intercropped either with cereals such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*) and maize (*Zea mays*) or legumes like soybean (*Glycine max*), mungbean (*Vigna radiata*) and urdbean (*Vigna mungo*) (Table 1).

The traditional pigeonpea cultivars are of long duration and mature in 170–275 days under different eco-systems (Saxena 2008). As the component of low input rainfed agriculture, traditional farmers invariably cultivate it as an intercrop with a range of above-mentioned short-aged cereals and legumes. This practice provides them additional income, diversity of diet and some sort of insurance against possible crop failures (Francis 1985). Many researchers have advocated growing pigeonpea as an intercrop even in high input agriculture to enhance total pulse production besides increasing system productivity and profitability (Praharaj and Blaise 2016, Singh 2016). The choice of intercrop combination and selection of cultivar primarily depends on soil type, rainfall pattern, evapo-transpiration, and family/market needs. Substantial advancements have been achieved in addressing various agronomical issues such as intercrop

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**Table 1.** Area, production and grain yield of the main pigeonpea growing countries

Country	Area (000 ha)	Production (000 t)	Yield (kg ha <sup>-1</sup> )	Intercrop system
Asia				
India	5602	3290	587	PP + Cereal/Leg
Myanmar	611	575	940	PP + Maize/Leg
Nepal	17	16	965	PP + Maize/Leg
Africa				
Kenya	276	274	994	PP + Maize
Malawi	81	335	4099	PP + Maize
Tanzania	250	248	990	PP + Naize
Uganda	33	13	406	PP + Maize
Global	7033	4890	695	

FAO STATS (2017); PP: Pigeonpea; Leg: Legume.

combinations, plant geometry and spacing in pigeonpea-based intercropping systems (Jat *et al.* 2016, Praharaaj and Blaise 2016). However, so far in pigeonpea no cultivar has been bred specifically for intercropping, and perhaps for this reason, the productivity of pigeonpea in the intercropping is still low (400–500 kg/ha). The development of high yielding pigeonpea cultivars for intensive intercropping is justified to increase productivity *per se*. This paper briefly describes the key intercrop systems involving pigeonpea, and the major constraints encountered in developing high yielding cultivars. Besides this, it also discusses the possible approaches to breed new pigeonpea cultivars for intercropping.

### Key pigeonpea intercropping systems

The culture of intercropping not only facilitates efficient use of resources, but also often leads to more productivity per unit of land area. Besides these, the practice of intercropping has other benefits. For example, sorghum as an intercrop has been found to reduce wilt (*Fusarium udum*) incidence in pigeonpea by about 30 per cent (Natarajan *et al.* 1985). Similarly, the losses due to pod borer (*Helicoverpa armigera*) in pigeonpea are reported to be significantly reduced when it is intercropped with sorghum (Bhatnagar and Davies 1978). The long maturity, genotypic plasticity, deep roots and perennial growth of pigeonpea make it compatible with a number of other field crops. In most intercrop combinations, pigeonpea remains a primary crop; while in a few such as cotton and groundnut, it serves as a companion crop. Based on the intercrop component, this cropping system has been classified into the following broad groups.

#### Pigeonpea-cereal

Intercropping of pigeonpea with cereals such as sorghum, pearl millet or maize is quite common (Praharaaj and Blaise 2016). In this system the cereal crops, maturing in about 100–120 days, are used, and the choice of crop/variety depends on local adaptation and farmers' choice. Traditionally, two rows of the cereal and one row of pigeonpea are grown together. In this combination, pigeonpea plants suffer from intense competition right from the early growth stage for light, moisture, space and nutrients. The number of

branches on the pigeonpea plants, the main yield contributing trait, reduces significantly, which results in heavy loss of productivity. Besides the major crops, some other cereals like *Setaria*, finger millet and rainfed rice are also intercropped with pigeonpea. However, the area under such combinations is limited.

#### Pigeonpea-legume

Pigeonpea is also intercropped with early maturing legumes such as groundnut, cowpea, green gram, black gram and soybean. Green gram, black gram and field bean have been reported to be suitable for intercropping with pigeonpea in Central and South Zones of India. However, intercropping of pigeonpea with soybean in the ratio of 2:4 resulted in 27.7% more grain yield than sole crop with 40.5% higher net return in the front line demonstrations (35 ha) conducted by ICAR (AICRPP 2015). Pigeonpea-soybean is thus the most profitable crop combination in high input agriculture. In this system, both the crops experience relatively less competition and give good yields. Pigeonpea-groundnut is another popular intercrop combination. This cropping system is practiced in rainfed areas having light soils, suitable for groundnut cultivation. Usually 6–8 groundnut rows are planted between the two rows of spreading type pigeonpea. Pigeonpea is used to fetch its green pods (for vegetable purpose)/dry pods (grain purpose) and stems for the much-needed domestic fuel.

#### Pigeonpea-long duration annual crops

In this category, pigeonpea-cotton is the most popular intercrop combination for rainfed vertisols of Vidarbha region of India (Blaise *et al.* 2005); and it is sown in row ratios of 4/6 cotton: 1 pigeonpea. Cotton, being a cash crop, occupies about 75% of the land area and receives the maximum attention. In this combination, pigeonpea plants also serve as a trap for pod borer (*Helicoverpa armigera*). Intercropping of pigeonpea with other long duration annuals such as castor, sugarcane and cassava is also practiced by farmers, albeit only in small pockets.

#### Pigeonpea-miscellaneous crop species

In addition to the above intercrop combinations, pigeonpea is empirically observed to be grown in farmers' fields with various other annual/perennial, plantation and arbor crops. These include young and aged tall coconuts, banana, young mango and young eucalyptus. In these cases, pigeonpea is used as a cover crop with no standard cultivation practices. Besides these, oil seed crops like sunflower, safflower and horticultural crops such as cucumber, ginger and turmeric are also intercropped with pigeonpea.

### Performance of 'sole-crop-bred' pigeonpea in intercropping systems

In literature one can find a few examples where the selections (improved varieties) carried out under pure stands

(monoculture) have been good performers as the intercrops compared to traditional genotypes or land races (Francis 1985). The fact, however, remains that the diversity within the two constituent crop species, their sowing patterns, cultural practices and micro environments are so large that the interactions among various agronomic and environmental factors cannot be expected to be consistent over seasons/years. Consequently, breeding gains under these circumstances are likely to be unpredictable and unrepeatable. The limited research towards understanding various intercropping systems and their varietal requirements has also not been understood so far (Green *et al.* 1981). Therefore, pigeonpea breeders have usually bred cultivars under pure stands for cultivation as sole as well as intercrops.

To generate information on this aspect, Green *et al.* (1981) tested a number of pigeonpea genotypes for four years in monoculture and intercropping with sorghum (Table 2). They selected top 20% of the tested lines from pure as well as intercrop experiments, and looked for the entries which appeared in both lists of selections. They reported that in different years the per cent of common entries ranged from 0 to 83% with a mean of 41%. This showed that even at a single location the performance of genotypes was highly variable over the years. Similarly, when the selection intensity was reduced from 20 to 33%, the mean selection efficiency increased to 55% with large year to year variation. For instance, selection 185-9 had high pure crop yield over 4 years; and in 3 of 4 years, it was in the top 20% in pure crop, while under intercrop, it occupied a place in the top 20% in only 1 out of 4 years. More or less similar results were also obtained when pigeonpea genotypes were evaluated in intercropping with maize. These observations suggested that the lines selected under pure stands cannot be considered well adapted for intercrop environments. One such attempt was also made at the Indian Institute of Pulses Research (IIPR), Kanpur. Although three test entries out-yielded the best check 'Bahar' (918 kg/ha) by over 30% under pigeonpea-maize intercropping system; but the overall pigeonpea equivalent yield was too low to be acceptable (IIPR 2007).

**Table 2.** Results of pigeonpea selections at 20% and 33% levels in sole crop and cereal intercrop at ICRISAT

Year	Inter crop	Entries tested	20% selected	Common entries	33% selected	Common entries
1976–77	Sorghum	36	7	2	12	5
1977–78	Sorghum	17	3	2	6	5
1978–79	Sorghum	19	4	3	6	5
1979–80	Sorghum	14	3	0	6	1
Total		86	17	7 (41%)	29	16 (55%)
1977–78	Maize	11	2	1	4	1
1978–79	Maize	19	4	1	6	3
1979–80	Maize	20	4	1	7	5
Total		50	10	3 (30%)	17	09 (53%)

Source: Modified from Green *et al.* (1981).

## Major breeding constraints

### Limited understanding of pigeonpea crop physiology

Low on-farm productivity of pigeonpea could partly be attributed to little understanding of growth and development under different cropping systems and major/micro environments and stresses. Pigeonpea plant is known to be a slow starter, especially during the first 6–8 weeks. This puts pigeonpea plants at disadvantage when it comes to intercropping with fast-growing cereals, leading to severe competition, and the situation continues until the cereal crop is harvested. During this period pigeonpea plants fail to put on sufficient biomass necessary for productivity. The number of primary and secondary branches, the main yield contributing traits, is drastically reduced (Saxena and Sharma 1990).

### Biotic and abiotic stresses

Under natural conditions, a number of biotic (Choudhary *et al.* 2013a, 2013b) and abiotic (Choudhary *et al.* 2011, Sultana *et al.* 2014) stresses adversely affect plant growth and stability. The genetic resistance to insects in cultivated pigeonpea is either lacking or too weak to be utilized in breeding program. However, some morphological features related to pods (thick pod wall, prominent pod constrictions and presence of "C" trichomes on pod surface) have been reported to provide tolerance to pod fly and pod borer in pigeonpea (Choudhary *et al.* 2013a). The situation with respect to diseases is quite good; and cultivars with stable resistances to both wilt and sterility mosaic are now available (Choudhary and Nadarajan 2011). As far as abiotic stresses are concerned, low heritability, high genotype × environment interaction, scarce sources of resistance/tolerance, limited genomic resources and poorly understood physiological processes and mechanisms have retarded the breeders from moving towards logical end.

### Abundance and complexity of interactions

The diversity in cropping systems is one of the main reasons that discourage pigeonpea breeders to undertake any targeted program. The selection of crop, cultivar, their maturity, planting ratios, time of sowing, and growing environments are among a few variables that produce a range of interactions (Allard 1999), adding to inefficiencies in breeding. Further, even the outcomes achieved despite the above constraints could be specific to the location, soil type and prevailing climate in each season (Francis 1985).

## Breeding strategies to develop pigeonpea cultivars for intercropping

As discussed in the preceding sections, breeding cultivars for intercropping will be a very challenging task. Prior to launching a program, breeder needs to take a firm decision related to two key issues; these are (i) the required breeding product (i.e., inbred or hybrid cultivar, or composite

populations), and (ii) the targeted production system and agronomy.

**Aggregation of intercropping systems**

For breeding cultivars suitable for intercropping, it is impossible to breed for each and every system. Therefore, based on the competition the pigeonpea plants encounter, we have tried to aggregate different intercropping production systems into two groups. This exercise will facilitate the decision making while breeding cultivars adapted to different intercropping systems.

1. Less-competitive intercrops: There are certain intercropping situations where pigeonpea plants encounter less competition with the companion crops. It can best be exemplified by intercropping of pigeonpea with cotton or groundnut, where a larger proportion of land is occupied by cotton/groundnut, and pigeonpea represents only about 25% area (Table 3). In these systems pigeonpea plants encounter less competition with cotton/groundnut due to their thin representation. Similarly, when pigeonpea is intercropped with fodder sorghum or soybean, the competition is not of high order because the forage sorghum is harvested within 50 days, and the medium or long duration pigeonpea gets enough time to recover from the stress of early growth competition and produces fairly good amounts of biomass and seed yield. In pigeonpea-soybean intercropping system, the differences in the canopy of the two crops are large, and soybean poses too little competition to cause serious reduction in seed yield of pigeonpea. Precisely for this reason, intercropping of pigeonpea with soybean has resulted in more grain yield than sole crop and higher net return in many front-line demonstrations (AICRPP 2015). The same holds true for pigeonpea-mungbean/urdbean intercropping systems as well.

2. Intense-competitive intercrops: In the intercrop combinations involving medium (150–200 days) and long duration (>200 days) pigeonpea and cereals like grain sorghum/pearl millet/maize, the competition between the two crops is intense; and therefore, breeding of high-yielding pigeonpea cultivars is difficult. In such systems both the crops are sown at the same time with two rows of cereal and one row of pigeonpea. The cereal crop is sown with normal plant population, and due to its rapid canopy development during the rainy season, the growth of pigeonpea plants is suppressed. Until the cereal crop is harvested, the pigeonpea crop

remains under severe competition for light, space, nutrients, and the like. The ultimate impact of this competition on pigeonpea is that its primary/secondary/tertiary branching is severely suppressed. Consequently, the individual pigeonpea plants produce a few pod bearing points within the top 30–50 cm of the plants, and the productivity losses due to intercropping often exceed 50%. Breeding pigeonpea cultivars for such situation is a real challenge; and in case it is taken up, then a careful planning is necessary. Some of the critical points are discussed in the following text.

**Defining the cropping system protocol**

Since the intercropping systems are quite diverse, no single crop combination could be recommended to carry out breeding activities; and for a long time it has remained a subject of speculation. Some breeders favor the selection and evaluation under sole cropping. In contrast, others recommend breeding under the cropping system for which the cultivar is targeted. This issue perhaps invited discussions for a long time, and therefore, no attempt has been made to review this subject. Byth *et al.* (1981) discussed the issues related to selection environments in length and argued that the selection should be made in the environment for which the end product is targeted. Their argument was based on the facts that (i) the estimation of key genetic parameters vary with the growing environment, (ii) pigeonpea is primarily a long duration crop, and during its life cycle it encounters various stresses, which vary year to year, (iii) heritability of yield is low and genetic advance is not easy to achieve, and (iv) the efficiency of pedigree selection is low due to high inter-plant competition (Green *et al.* 1981).

**Identifying the breeding product**

Data presented in Table 4 showed that yield losses due to intercropping were large in both long and medium duration “pure” line cultivars; whereas in the heterozygous/heterogeneous populations, such yield reductions were far less. This suggested that under intercrop situations, the populations with heterozygous/heterogeneous genetic base faced the intercrop competitions in a much better way than that of pure line cultivars. This is a consequence of greater levels of homeostasis in the former. Hence for intercrops situations, the breeding materials such as hybrids (heterozygotes) or recurrent populations (heterozygous and heterogeneous) are better options than inbred cultivars. In pigeonpea, Howard

**Table 3.** Some popular intercropping systems involving pigeonpea

Intercrop	Pigeonpea maturity (d)	Intercrop maturity (d)	Row ratio	Competition level	Remarks
Pigeonpea-fodder millets	>275	<90	Mixed	low	Pearl millet used for fodder
Pigeonpea-fodder sorghum	>275	<90	Mixed	low	Sorghum used for fodder
Pigeonpea-groundnut	180	120	1:8	low	Groundnut is main crop
Pigeonpea-cotton	180	120	1:6	low	Cotton is main crop
Pigeonpea-soybean	180	100	1:2	low	Pigeonpea is main crop
Pigeonpea-grain sorghum	180	140	1:2	severe	Sorghum is main crop
Pigeonpea-grain millet	180	140	1:2	severe	Millet is main crop
Pigeonpea-maize	180	140	1:2	severe	Maize is main crop

**Table 4.** Comparative yield (kg/ha) losses due to intercropping with grain sorghum in inbreds and F<sub>3</sub> populations of pigeonpea

Genotype	Maturity	Yield pure crop	Yield intercrop	Yield loss (%)
<i>Inbred cultivars</i>				
NP(WR) 15	Late	1353	525	46
Gw-3	Late	1222	878	28
C 11	Medium	986	659	33
JA 5	Medium	766	504	34
No. 148	Medium	753	273	64
<i>F<sub>3</sub> populations</i>				
Gw 3 × P 334	Late	1020	935	8
JA 275 × Sharda	Medium	538	297	8

Source: Modified from Singh *et al.* (1978)

*et al.* (1919) recommended the cultivation of a mixture of genotypes to enhance yield. Subsequently, Khan (1973), Byth *et al.* (1981) and Green *et al.* (1981) also recommended breeding of populations for better yields under intercropping. Onim (1981) demonstrated 2% yield gains in each cycle of recurrent selection. The ground reality of population breeding, however, is that it is a difficult approach for crops like pigeonpea because of its huge canopy that grows over six feet in height and makes the selection of individual plants with favorable alleles very difficult. In addition to this, there are other constraints (already discussed in preceding sections). However, some of these constraints of population breeding may be overcome by utilizing male-sterility systems (Saxena *et al.* 2010a) and recently developed genomic tools (Varshney *et al.* 2013) in pigeonpea. At present, hybrid cultivars appears to be good option for intercropping (details in following section).

### Selection parameters

In pigeonpea, the genetic enhancement of productivity under sole cropping is already a serious breeding issue with yield plateauing at around 700 kg/ha (Saxena 2015). There are many reasons for the display of poor productivity of the crop; but lack of suitable cultivars, specifically adapted to the intercrop conditions pops ahead of all. The biotic stresses have been taken care of to the best of scientists' abilities and resources (Choudhary and Nadarajan 2011). Among abiotic stresses, the issue of drought is the most threatening and perhaps breeding for specific root traits may help in overcoming this problem to some extent (Choudhary *et al.* 2011). Further, limitations imposed by high genotype × environment interaction and low heritability of certain key traits under rainfed intercropping system may be addressed by testing the materials in multi-environments.

The major yield components that would require breeders' attention, while selecting individual plants or progenies suitable for different intercropping systems are listed in **Table 5**. For the sake of brevity and based on their potential role and inheritance patterns, the traits have been aggregat-

**Table 5.** A list of traits to be considered while selecting genotypes suitable for intercropping with cereals

Trait	Selection criteria	Genetics	Remarks
Branching	Terminal, long	Polygene	Key trait
Pods/bunch	4–6	Polygene	Key trait
Seeds/pod	6–8	Oligo-genes	Key trait
100-seed wt. (g)	16–18	Oligo-genes	Key trait
Wilt disease	Resistance	1–2 genes	Key trait
Sterility mosaic	Resistance	2–3 genes	Key trait
Plant maturity (d)	170–190	Oligo-genes	Based on soil type
Growth habit	Non-determinate	1–2 genes	All combinations
Plant spread	Compact	1–2 genes	or semi spreading
Plant height	250–300 cm	Poly-genes	–
Seedling vigor	Rapid biomass	Poly-genes	–
Phytophthora	Tolerance	1 gene	–
Water-logging	Tolerant	1 gene	–
Insects	Tolerant	–	–

ed together. The importance of the key traits are briefly described herewith.

### Rapid initial growth rate

This is a very important trait for all the intercropping systems. However, available literature regarding early vigor and initial growth rate and their genetic variation and inheritance pattern is scanty. Empirical evidence suggests that 'IPA 203' (a variety of long-duration pigeonpea for north east plain of India) carries this desirable trait, and may be used as donor in breeding program for intercropping system. Alternatively, hybrid cultivars, which display rapid initial growth rate due to heterosis, may be used in intercropping system.

### Growth habit and plant type

These are most important parameters for realizing high yields and stability under intercropping systems. The characteristically adapted pigeonpea cultivars for intercropping are those with non-determinate growth, spreading or semi-spreading plant type with more number of primary/secondary/tertiary branches and long fruit-bearing lengths. The compact genotypes do not perform well in intercrops due to their poor plasticity and biomass production. The present day medium maturing semi-spreading cultivars such as 'Asha', 'AS 71-37', 'BDN 2' and 'Maruti' are being grown successfully under both pure as well as intercropping.

### Pod and seed size

These are very important yield contributing traits and their breeding is rather easy due to high heritability and easy identification of desirable segregants. In pigeonpea germplasm, there is a vast range of variability for both pod size (2–9 seeds/pod) and seed size (4–26 g/100 seeds). In general, pod and seed size are positively correlated with each other, but their relationship with yield is not linear; and this needs a compromise among seed size, pod size and yield. Farmers need high yield, while the millers require round bold seeds to achieve high (>70%) dhal recovery during

commercial de-hulling. Therefore, pigeonpea breeders, over a period of time, have worked out a combination of 4–6 seeds/pod plus seed size of 12–14 g/100 seeds for breeding high yielding cultivars with market-preferred traits. To achieve this, screening of parental lines carrying these two traits will help breeders because the segregating populations will have a desirable range, and then breeders can concentrate on other key traits including yield.

#### **Breeding for waterlogging tolerant cultivars**

Temporary waterlogging (WL) poses a serious threat to pigeonpea productivity, especially in high water-holding capacity soils. The annual productivity losses in India are estimated at 25–30% on 1.1 m ha waterlogged pigeonpea area (Choudhary *et al.* 2011). Under waterlogged situations, the shortage of oxygen in the soil adversely affects growth and development of the plants. Recently, Sultana *et al.* (2014) identified a number of WL tolerant pigeonpea genotypes which can be used as donor parents. The tolerant genotypes develop lenticels which help in oxygen intake. The tolerant reaction is known to be controlled by a single dominant gene. The availability of tolerant genotypes, good screening technology and favorable genetic system will make it easy to breed high yielding WL tolerant cultivars suitable for intercropping.

#### **Breeding for disease resistant cultivars**

In pigeonpea, two diseases namely Fusarium wilt (FW) and sterility mosaic (SM) are considered very important. These diseases cause heavy losses in almost all the pigeonpea growing areas. However, availability of resistant sources (donors) and reliable screening technology have resulted in a number of cultivars having joint FW and SM resistance. The pigeonpea cultivar ‘Maruti’ (FW resistant) and ‘Asha’ (FW and SM resistant) have proved to be a boon to farmers of the disease-prone areas both for sole and intercrop cultivation.

#### **Breeding ideal plant type for pigeonpea-cereal intercropping system**

In most rainfed areas, predominantly pigeonpea is intercropped with relatively earlier maturing and fast growing cereal crops. Till date, there is no well-directed research to define conclusively about the constituent components of an ideal pigeonpea plant type that would perform efficiently under different growing conditions. However, by putting the published pieces together, it can be inferred that for pigeonpea-cereal intercrop a pigeonpea cultivar should have rapid seedling growth, non-determinate growth, spreading or semi-spreading branches, more number of secondary and tertiary branches, long fruiting branches, more bunches of flowers, 5–6 pods/bunch, 4–6 seeds/pod, 12–14 g/100 seed weight, resistance to FW, SM and Phytophthora stem blight, deep root system/drought tolerance and ability to mitigate other abiotic stresses including waterlogging.

## **Breeding methods**

#### **Pure line breeding**

Breeding pure line cultivars for those intercrops which do not exert severe competition on pigeonpea plants does not require any special consideration. Therefore, the breeding program can be undertaken under sole cropping, and the end products should be tested under both pure as well as intercrops.

Breeding high-yielding pigeonpea cultivars for the intercrops where pigeonpea plants face severe competition is a real challenge. The severe most effect of the competition on pigeonpea is that its branching is suppressed. Consequently, the individual plants produce only a few pod bearing points within the top 30–50 cm of the plants at the top of the canopy. The use of classical pedigree breeding may be difficult due to various interactions as discussed earlier. Instead, using a bulk pedigree method of breeding may be more productive. In case the breeder is interested in a short cut approach, then a collection of germplasm with desirable plant type, maturity, and disease resistance should be assembled. This collection should be evaluated for their performance first under pure stands. Simultaneously, samples of these genotypes should be screened for wilt and sterility mosaic virus diseases in sick nurseries. Based on the yield and disease reaction, the selected accession bulks should be evaluated under both pure and sole crop situations. This should be followed by further selection and multi-location tests and seed maintenance. With this approach, some high yielding cultivars, namely ‘Maruti’, ‘LRG 30’ and ‘LRG 36’ have been successfully bred in the past.

#### **Hybrid breeding**

Recently, a breakthrough has been achieved in breeding hybrids in pigeonpea, and the three released commercial hybrids give about 30% more yields than traditional varieties (Saxena 2015, Saxena *et al.* 2017a). The hybrids produce vigorous plants and impart stability to the production. The heterotic effects are visible as early as seed germination (Mudaraddi and Saxena 2012) and seedling stages (Saxena *et al.* 1992). These traits of hybrid plants help them compete with cereal crop for critical inputs such as sunlight, water, and nutrients more efficiently than inbreds. Lopez *et al.* (1996) reported that the hybrids have greater root mass and maintain high water content in the plants under adverse conditions, which contribute to their capacity to encounter short spells of drought.

Under sole cropping the hybrid exhibited 23% superiority over the control cultivar (Table 6). The pigeonpea-maize intercrop system, where two rows of maize are sown in between single pigeonpea rows, provides tough competition to pigeonpea plants. In 87 on-farm trials, the pure line variety produced 598 kg/ha yield under intercrop, while the hybrid in this system yielded 829 kg/ha yield with an advantage of 231 kg/ha, amounting to 39% superiority. In another set of trials involving intercropping of pigeonpea (1 row)

**Table 6.** Productivity and advantage (kg/ha) of hybrids over inbred cultivar under two intercrop situations in farmers' fields

Cropping system	Farmers (no.)	Variety yield	Hybrid yield	% advantage of hybrid	Remarks
Pigeonpea pure crop	1120	913	1120	23	Rainfed
Pigeonpea + maize	87	598	829	39	Irrigated
Pigeonpea + soybean	29	648	1250	93	Irrigated

and soybean (3 rows), the control cultivar produced 648 kg/ha grains, while the hybrid under this system yielded 1250 kg/ha with 93% superiority over the inbred. The performance data suggested that the hybrid cultivars are better adapted to intercropping system as compared to inbred cultivars.

### Application of genomics in selection

The efforts to breed pigeonpea cultivars for intercropping can be enriched through genomics interventions. Such efforts have been proven very effective in a number of crop species (Varshney *et al.* 2006). In pigeonpea, the genomics research is rather recent. To kick-off this program, various tools such as BAC clone libraries and PCR-based simple sequence repeat (SSR) markers have been developed (Saxena *et al.* 2010b). The other type of markers such as diversity arrays technology (DArT) (Yang *et al.* 2011), millions of single nucleotide polymorphism (SNP) and indel markers have been developed (Kumar *et al.* 2016, Singh *et al.* 2017, Varshney *et al.* 2017). In the year 2012 pigeonpea genome sequence was decoded (Varshney *et al.* 2012), which further enriched the genomics resources with millions of markers. Further draft genome has led the foundation of re-sequencing of pigeonpea reference set (Varshney *et al.* 2017). Very recently, Axiom® *Cajanus* SNP Array with 56K SNPs has been developed for pigeonpea (unpublished). These markers are being used to construct a number of inter-specific and intra-specific genetic maps and for quantitative trait loci (QTL) analysis (Saxena *et al.* 2017b, 2017c). Presently, this genomics information is being used to identify the markers associated with the traits of importance and deploy them in genomics assisted breeding and maintenance of genetic purity (Pazhamala *et al.* 2015, Saxena *et al.* 2015). However in pigeonpea, besides developing ample genomics resources including draft genome sequence (Pazhamala *et al.* 2015), only a limited work has so far been done. These include identification of markers for genetic purity and some studies on marker trait associations. Now there is further challenge to effectively utilize the key traits (Table 5) in pigeonpea breeding programs. In this context, priority for genomics assistance should be given to the traits such as plant height, seedling vigor, number of branches and number of pods/bunch, which are known to be controlled

quantitatively or by oligo genes. In order to breed pigeonpea for inter-cropping, early vigor seems to be a critical trait for genomics interventions because it helps in seedling establishment, biomass production, and eventually the crop productivity. To achieve this, systematic genomics studies are necessary to dissect the early vigor into its component traits and then identify associated genes/genomic segments/QTLs for them. Once the markers/QTLs based associations are established, selection and transfer of the desired traits will be a possibility.

### Summary and way forward

Invariably, the farmers who earn their livelihoods from subsistence agriculture adopt intercropping systems to protect themselves from frequent crop failures. According to Willey *et al.* (1981), the sole pigeonpea fails once in five years and sole sorghum once in eight years; but intercropping fails only once in 35 years. However, to increase the productivity and stability, the farmers need adopt improved technologies that could sustain the vagaries of growing conditions. The practice of intercropping is traditionally for subsistence agriculture where the crop growing conditions are not favorable.

At present only a few agronomic recommendations are available for intercropping; therefore, most farmers use their own judgement in choosing the crop combinations and their geometry. Among legumes, pigeonpea is the most favorite intercrop component due to its ability to survive under stressed conditions and accommodate a range of species and plant types as its companion crop. Ideally, to achieve high and stable performance of intercrops the target production environments will need to be re-defined for identifying key eco-regions. These regions will also need to be further characterized for yield potential and risk factors to production using a model-based approach. Such initiatives will give the likely idea of adaptation area, variety and cultural practices for optimizing productivity of the unit area.

Some of the issues of pigeonpea-cereal intercropping may be addressed through agronomic practices. Although challenging and resources-consuming, the breeding program aimed at developing cultivars for pigeonpea-cereal intercropping needs to be undertaken due to its significant impact on sustaining productivity in rainfed/subsistence agriculture and increasing system productivity and profitability even in high-input agriculture. The limitation of unpredictable G × E interaction in rainfed agriculture (intercropping) may be overcome by the application of modern genomics tools. Presently, the introduction of hybrid cultivars of pigeonpea is the best option to address the issues of rapid growth rate, high competitive ability and higher yields in pigeonpea-cereal intercropping.

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