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Sybrid Population: A New Breeding Method for Often Cross-Pollinated Legumes (*Leguminocea*)

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ABSTRACT

To enhance the productivity of often-cross-pollinated legumes, the authors hereby propose a new breeding concept to augment their crop improvement programmes. This method, christened as 'sybrid population breeding', is designed for those crops where a considerable hybrid vigour is present, but its exploitation is mired either by nonavailability of a stable male-sterility system or inadequate natural cross-pollination. Its breeding is done by growing two high-yielding genetically diverse but phenotypically uniform inbred lines in an isolation and exposing them to natural cross-pollination. Their bulk harvest, which include both the crossed (hybrid) and self-pollinated (inbred) seeds, is the 'sybrid population'. This population partially reaps the benefits of pure line as well as hybrid breeding technologies, thereby capitalizing on both additive and nonadditive genetic variances. Unlike popular hybrids, the sybrid seeds are produced without using any male-sterile line, and this not only simplifies its seed production but also reduces the cost considerably. To mitigate inbreeding depression, the sybrid seeds are intended only for a single-time use, and this ensures the population to maintain its hybrid vigour and avoids negative influences of inbreeding. The sybrid seed production also yields a high seed-to-seed ratio, and this would make it an affordable new product for the farmers. In view of these benefits of sybrids, the plant breeders are encouraged to explore this innovative breeding avenue for enhancing the productivity of some often-cross-pollinated legumes.

1 | Introduction

Cross-pollination plays a significant role in the genesis of genetic variability and new recombinants. In nature, there are different biological mechanisms that lead to out-breeding across plant species. These include dichogamy (differences in the timing of anther dehiscence and stigma receptivity), herkogamy (spatial separation of anthers and stigma), dieliny (unisexual flowers on different branches or plants), self-incompatibility (inhibition of pollen germination on stigma) or male sterility (nonfunctional or absence of male reproductive parts). In some crops, both self- and cross-pollinations also take place, but their relative proportions vary quantitatively from low to high due to variation in the frequencies of insect visitations.

Legumes play significant roles both in the sustainability of rainfed production systems and nutritional security of masses, but unfortunately, this group of crops is often identified as low yielders (Figure 1) and less profitable (Saxena, Dalvi, et al. 2021). In contrast to the common belief, all the legume crops are not self-pollinated, and in some of them, a certain level of insect-aided out-crossing occurs. These include pigeonpea (*Cajanus cajan*), common bean (*Phaseolus vulgaris*), mung bean (*Vigna radiata*), cowpea (*Vigna unguiculata*), faba bean (*Vicia faba*) and grasspea (*Lathyrus sativus*) with, respectively, around 40%, 10%, 13%, 15%, 50% and 30% natural cross-pollination (Table 1). Also, the reviews published by Bond et al. (1966), Sharma and Dwivedi (1995), Bishnoi et al. (2012), Saxena, Patel, et al. (2018) and Saxena, Tikle, et al. (2021) revealed that in this group of crops some of the single crosses exhibited better-parent heterosis in the range of 100% or more. Because the out-crossing in legumes is abetted by insects, its levels are often inadequate to sustain a hybrid breeding programme. Therefore, to enhance their productivity and stability, the legume breeders, dealing with the self- or often-cross-pollinated crops, invariably breed pure line cultivars.

In view of productivity stagnation and to fulfil the ever-rising demand of legumes, it was thought worthwhile to script a new breeding scheme that is hassle-free, and besides, exploiting a portion of hybrid vigour also retains the benefits of inbred cultivars. In this context, a unique population breeding method was initially conceptualized by Saxena et al. (2020) for pigeonpea, and now, an effort is being made to extend this same to other legumes with technical elaborations on the aspects of its breeding procedure, seed production and utilization.

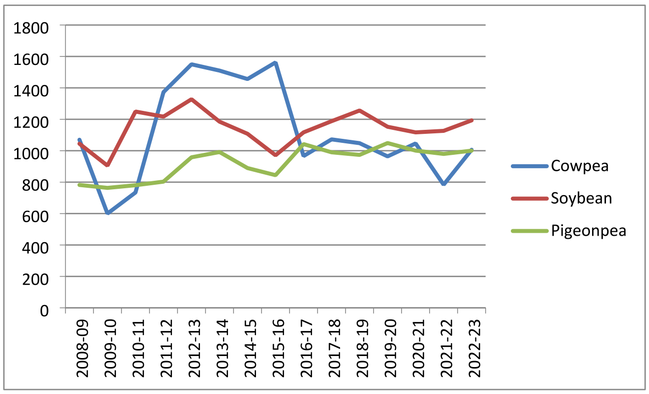

FIGURE 1 | Productivity (kg/ha) of cowpea, soybean and pigeonpea in India (2008–2023).

TABLE 1 | Mean natural out-crossing in some often-cross-pollinated legume crops.

Common name	Scientific name	% Out-crossing
Faba bean	*Vicia faba*	50
Pigeonpea	*Cajanus cajan*	40
Grasspea	*Lathyrus sativus*	30
Cowpea	*Vigna unguiculata*	15
Mung bean	*Vigna radiata*	13
Bean	*Phaseolus vulgaris*	10
Soybean	*Glycine max*	07

Note: For references, see Saxena and Gangashetty (2021).

2 | Mechanisms of Natural Pollen Transfers

In nature, there are five established channels that are known to facilitate pollen transfers across the plants. These, in diminishing order, are insects, birds, wind, mammals and water. However, worldwide, the flying insects representing a range of species, are the most common players in the business of pollen transfers. This is because their bright flower colours of and emission of volatile compounds attract a variety of pollenivore (pollen-eating) and/or nectarivore (nectar-hunting) insects for foraging. The cross-pollination by wind is prevalent in grasses and certain dryland species. Their lightweight desiccated pollen grains are easily blown away to various distances through air currents. When such air-borne pollen grains land on physiologically receptive stigmatic surfaces, the uncontrolled cross-pollinations take place.

2.1 | Factors Influencing Cross-Pollination in Legumes

The extents of insect-aided cross-pollination in crop plants vary a lot. For example, in pigeonpea, it varied considerably across locations and seasons (Table 2). Some of the factors that directly or indirectly affect the levels of out-crossing are summarized below.

2.1.1 | Type and Density of Pollinating Insects

The type and density of pollinating insects present at a particular location are important factors in determining the extent of natural out-crossing. Insects representing *Hymenoptera*, *Diptera*, *Lepidoptera* or *Coleoptera* spp. often visit flowers to collect pollen/honey and in the process affect cross-pollinations. Often, a specificity between particular insect and plant species is also observed. Therefore, on a particular

TABLE 2 | Mean natural out-crossing reported in pigeonpea from different countries.

Country	% Out-crossing	Country	% Out-crossing
Australia	40	Kenya	46
Cameroon	39	Myanmar	40
China	40	Nepal	25
India (North)	21	Sri Lanka	20
India (East)	41	Trinidad	40
India (West)	32	Uganda	22
India (Centre)	21	USA	30

Note: For references, see Saxena et al. (2016).

crop, some types of pollinating insects are more frequent than others. For example, in pigeonpea, *Apis florea* spend about 22.79 s per visit, whereas *Megachile* and *Xylocopa* species take only 2 s per visit to the flowers. Also, on average, *A. florea* visits 2.11 flowers per plant, whereas the corresponding value for the *Megachile* bees was only 1.08. It has also been reported that some physical factors such as temperature, humidity, wind velocity, specific fruits/grasses species and water bodies also help in harbouring the pollinating insects to enhance cross-pollination (details in Saxena et al. 2016).

2.1.2 | Stigma Receptivity

The physiological maturity of stigma and pollen germination determines fertilization and subsequent seed development. Under natural conditions, the duration of stigma receptivity varies across species from hours to a few days. The extended duration of stigma receptivity provides ample opportunities for the foreign pollen to land on their surface through some vectors and affect cross-fertilization. At present, the information on stigma receptivity and fertilization of different crops is inadequate to develop any central dogma on this aspect. To understand the stigma receptivity pattern in pigeonpea, Dalvi and Saxena (2009) demonstrated that stigma of the pigeonpea plants become receptive a couple of days prior to flower opening, and during this period, self-pollination takes place. The stigma of the unfertilized flowers remains receptive for the next 4–5 days also. During this period, the petals start unfolding to attract insects for foraging and affected cross-pollination. Because the biology of such flowers allows both self- and cross-pollination, this crop is classified as 'often-cross-pollinated'.

2.1.3 | Nectar Production

To attract different insect species, certain plant species produce nectar from their floral nectaries. The amount and duration of nectar production, however, determine the insect activities such as number and duration of insect visitations, their foraging period and speed, and ultimately the extent of cross-pollination. Radhika et al. (2010) reported that nectar production in *Brassica napus* starts with the opening of flowers; it peaks when the corolla is fully expanded and continues until the corolla wither. They further reported that nectar production in the plants is regulated by an endogenously produced phytohormone called 'Jasmonic acid'.

2.1.4 | Fragrance Producing Volatile Compounds

The pollen grains in some of the plant species are known to emit a variety of fragrances associated with volatile organic compounds. These help in attracting various insect species, and some of them help in cross-pollination. In pigeonpea, for example, Layek et al. (2023) found a total of 26 volatile organic compounds, emanating from pigeonpea flowers, and their retention time varied considerably from 4.3 to 33.86 min. Cunningham et al. (2006) reported that a blend of floral volatiles (benzoid and monoterpenoid linalool) attracts specific foragers like *Hymenoptera* spp.

2.2 | Methodology of Estimating the Extent of Natural Out-Crossing

Determination of the extent of natural out-crossing in crops is important to decide on their maintenance breeding strategies. A perusal of published studies on natural cross-pollination in different field crops showed that for conducting such studies, two genotypes with simply inherited contrasting traits are used. These include a dominant marker (e.g., purple stem) as contaminator and the pollen recipient carrying its alternate recessive phenotype (green stem). Such a pair of genotypes is sown in a predetermined layout and isolation distance. The crop is allowed to grow and cross-pollinate under natural environment. At maturity, the open-pollinated single plants of the recipient genotype are harvested randomly, and their progenies are grown and assessed for the number of plants carrying the dominant marker. The results are reported as per cent natural out-crossing at particular location or at a distance from the contaminator.

The authors visualize that the out-crossing values obtained in such studies do not represent a true picture about the efforts made by insects in cross-pollinating the flowers. The reason for this belief is that the pollinating insects move and forage randomly across the field from one plant to the other and affect cross-pollinations. Under this scenario, the cross-pollinations take place in both the directions, that is, recessive (female) x dominant (male) and dominant (female) x recessive (male). The natural hybrids, thus produced from the later type of matings, are not detected in their progenies. This means that the literature reported only one-way of cross-pollinations (recessive x dominant). From these arguments, it can be deduced that the actual level of natural cross-pollination is roughly double of the reported values. Such studies, however, could be refined further in the near future through the use of molecular markers to get the accurate information about natural out-crossing. From the available information, it is inferred that the levels of natural cross-pollination in some of the often-cross-pollinated legumes such as pigeonpea and faba bean are high enough to undertake the breeding of sybrid populations.

3 | Sybrid Breeding: A Novel Method for Exploiting Both Hybrid and Pure Line Advantages in the Often-Cross-Pollinated Legumes

3.1 | Popular Methods for Breeding Often-Cross-Pollinated Crops

In the past, a number of inbred cultivars and populations were bred in different often-cross-pollinated legumes, but these could not help in increasing their on-farm productivity, which continued to remain unacceptably low (Figure 1). The primary methods used in the breeding of the often-cross-pollinated crops are briefly referred here.

3.1.1 | Mass Selection

This is the oldest method of improving the available cultivars. A number of individual plants are chosen from landraces or breeding populations on the basis of their appearance or performance. The next generation of crop is sown from the mixed harvested of the selections. This method has been quite successful in improving the frequency of favourable alleles in a given population.

3.1.2 | Pedigree Breeding

In spite of being prone to certain degrees of natural cross-pollination, most breeders dealing with the often-cross-pollinated crops opt for pure line breeding. It seems that in the absence of any alternate option, the breeders will continue with the same strategy. Although in most crops, such cultivars had helped in increasing cropped area but not the yield. To meet the enhanced food demand of the expanding population, this plant breeding approach would need diversification, and the method like sybrid breeding is a viable option.

3.1.3 | Hybrid and Composite Breeding

After the successful application of hybrid technology that evolved in corn Shull (1908), the plant breeders explored the possibility of breeding hybrids in other cross- and often-cross-pollinated crops but with the visible exclusion of legumes. Lately, some legume breeders also attempted to exploit heterosis in crops where certain levels of cross-pollinations occur. Among these, two crops—faba bean and pigeonpea—need mention, where considerable research investments were made to develop viable hybrid breeding technologies. These efforts, however, did not meet the expected success. In case of faba bean, the instability of male-sterility systems (Bond 1995; Gnanasambandam et al. 2012; Bishnoi et al. 2012) and, in pigeonpea, the maintenance of hybrid seed quality were the major bottlenecks (Saxena, Sharma, and Vales 2018 and Saxena et al. 2024).

Besides breeding hybrids, some alternate breeding approaches such as synthetic and composite breeding were proposed (Hays and Garber 1919) to enhance the frequency of favourable alleles from diverse sources into a single random mating population. This is done by crystallizing the elite crosses into a single breeding entity through the cycles of recombination, segregation and selection. In pigeonpea (Saxena et al. 2022) also, the similar population breeding methods were tried but with no commercial success due to limited recombination, poor heritability of selections, high genotype x environment interactions and inbreeding depression.

3.2 | Defining a 'Sybrid Population'

Sybrid is a two-parent plant breeding population (Saxena 2020). It is especially designed for often-cross-pollinated food crops. In principle, this scheme amalgamates the two established plant breeding concepts—the hybrids and synthetics into a single product. This breeding method has been designed in such a way that portions of both additive and nonadditive genetic variances are exploited for enhancing the productivity of the often-cross-pollinated crops. The primary breeding tool in this technology is the insect-aided cross-pollination with no male-sterility system involved.

3.3 | Method of Breeding a Sybrid Population

3.3.1 | Step 1: Selection of Parents

The plant breeders over the years observed that the performance of parents and their F_1 hybrids are associated with each other. Also, the genetic diversity of the parents plays a significant role in the expression of hybrid vigour. Therefore, for launching a sybrid breeding programme and selecting the two fully fertile inbred parents, the following points should be given due consideration.

3.3.1.1 | Per Se Performance. For the success and acceptance of a sybrid population, it is imperative that the two selected parental lines carry the farmer-preferred traits, besides yield and adaptation. They should also produce heterotic hybrids, when mated with each other. In this context, a lot of research has been published in a range of crop species (Moll et al. 1965; Lippman and Zamir 2007; Chandra et al. 2024 and many more). Sharma and Dwivedi (1995), covering a range of crops, concluded that the legumes are similar to cereals and other groups of crops and follow the central dogma of strong relationship between the per se performance of parents and their hybrids. In case of pigeonpea, the reviews published by Saxena et al. (1992), Pandey et al. (2015), Bohra et al. (2020), Saxena and Gangashetty (2021) and Chandra et al. (2024) also revealed that in most cases, the per se performances of parent lines and their hybrids were closely associated.

3.3.1.2 | Genetic Diversity. Since the elucidation of the phenomenon of heterosis, a lot of research has been directed towards studying the effects of genetic diversity on the expression of hybrid vigour. In fact, the plant breeding literature is full of reports showing the importance of genetic diversity in realizing heterotic yields in almost all the crops. Hence, it can be conclusively said that a strong and positive relationship exists between the genetic diversity and heterosis. Considering this fact, due importance should be given to genetic divergence while breeding sybrid populations. This will ensure the exploitation of hybrid vigour arising due to both additive as well as nonadditive genetic variances. To achieve this, as a first step, a diverse pair of inbred lines is selected. This may be done by comparing their origin/pedigree and application of heterotic groupings or using the modern genomics tools. Among these, the molecular approach seems to be the best as the results would be free from any bias arising due genotypes x environment interactions (Devi and Singh 2011; Mudaraddi and Saxena 2015). Also, Saxena and Sawargaonkar (2014), Raghu et al. (2019) and Sawargaonkar and Saxena (2020) demonstrated that matings of the genotypes representing highly diverse heterotic groupings produced the best F_1 hybrids. Hence, it is concluded that the application of heterotic groupings in selecting the parents would be the smartest way to obtain positive results from the sybrid populations breeding programmes.

Besides high yield, it is also important that the two sybrid parents are genetically distant, but phenotypically more or less similar to each other with respect to traits such as flowering, maturity, plant height and the colours of flower, pod and seed. This will provide visual uniformity to the end product (sybrid populations) and ensure farmers' acceptability, competitive marketing and consumer acceptability.

3.3.2 | Step 2: Selection of the Heterotic F_1 Hybrid

To breed a sybrid population, selection of a heterotic cross combination is the key factor, and this can be done either on the basis of reliable data from repositories or by synthesizing and evaluating hybrid combinations for productivity.

To achieve this, the crop breeders need to follow a breeding programme as suggested in Figure 2. As a first step, three to four high yielding diverse inbred lines should be selected, and these should be crossed in a half-diallel mating scheme. The resultant F_1 hybrids should be evaluated along with their parents in a replicated trial and assess them with respect to per se performance, combining ability and heterosis for yield and related traits. Based on their overall performance, the top performing single cross hybrid should be selected. This selection process can also be supplemented by using the concept of early generation testing (Saxena and Sharma 1983). Alternatively, a known heterotic cross that is available with the crop breeder can be selected. This will cut down the breeding time considerably, and the sybrid breeding activity can be launched instantaneously using the parents of the selected cross combination. The thumb rule of this breeding procedure is that the breeder should always use genetically pure seed of the diverse inbred parents and grow them in isolation with high insect pollinator activity.

3.3.3 | Step 3: Production of a Sybrid Population

In comparison to a three-parent (A-, B- and R-)hybrid system, the seed production of a sybrid population is easy, cost-effective and hassle-free. The key points are discussed herein.

3.3.3.1 | Selection of Isolation. The sybrid seed production should be carried-out in an isolation (about 500 m). The seed production plot should preferably be located at a site where some water bodies are present because this will help in harbouring the pollinators and ensure their high activity in the field.

3.3.3.2 | Cultural Practices. The two inbred parents are sown alternatively in single/paired rows. The crop should be grown with recommended agronomic practices. Both the parental lines should be rouged at flowering for the off-type plants. An important operation in the seed production is the chemical control of pod borers. Because we need to protect the friendly pollinators and kill the enemy pod borers, the insecticidal sprays should be done either in the early morning or late in the evening because at these times the pollinators move to their hives.

3.3.3.3 | Cross-Pollinations. A healthy crop will attract a variety of insects for foraging and robbing the nectar. In this scenario, the insects will move from one genotype/plant to the other freely and land on the open flowers frequently and transfer the pollen. This random process of cross-pollinations would produce hybrids on both the inbred lines (i.e., P_1 x P_2 and P_2 x P_1). Thus, on each inbred plant there would be both, the cross-pollinated (hybrid) as well as its indistinguishable self-pollinated pods. Their proportion, however, would vary from plant to plant due to variation in the frequencies of insect visitations to different plants.

3.3.3.4 | Harvesting the Sybrid Seeds. At full maturity, the entire crop should be harvested as a single bulk, and this would be the targeted 'sybrid population'. This population would be a true mixture of three different genotypes: the two inbred parents and one F_1 hybrid, each with different quantity/proportion.

3.4 | Estimated Yield and Production Cost

Because at present no data are available on the cost–benefit ratio of sybrid seed production, the information generated in

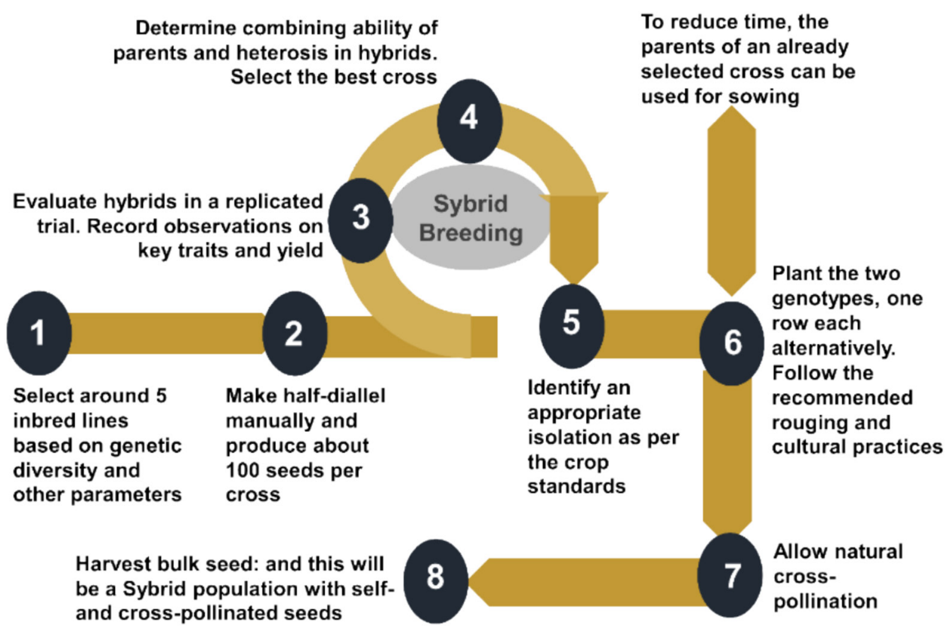

FIGURE 2 | Schematic diagram showing eight chronological steps involved in breeding a sybrid population.

pigeonpea on CMS-based hybrid is referred here for the sake of discussion. In this context, Verma et al. (1994) and Singh (1996) reported that the cost of genetic male sterility-based hybrid at different places varied between Rs 39–50/kg (1 US $ = approx. 80 IRs). Saxena et al. (2011) studied the cost of hybrid seed and reported that the seed cost could further be reduced by 50%, if the cytoplasmic male sterile line was used in producing hybrid seed, and this technology yielded a net profit of about Rs. 70,000/ha. It should be noted here that the seed cost reported here was estimated using a row ratio of four female:one male. It is expected that in case of sybrid, where all the rows are harvested, the seed cost may be reduced by 20% or so.

4 | Salient Features of Sybrid Populations

Since the sybrid population is a new breeding product, it is natural that the crop breeders, seed producers and grower-farmers would like to acquaint themselves with its pros and cons in relation to pure line, hybrid and synthetis/composite cultivars. Some of the key points related to these are outlined herein:

I. The sybrid breeding method amalgamates the principles of breeding synthetic populations and single cross hybrids.

II. In comparison to a three-parent (A-, B- and R-)hybrid system, the breeding of sybrid population involves only two fertile inbred parents (P_1 and P_2) and excludes any male-sterile system.

III. In sybrid breeding, the natural cross-pollination is an important tool for pollen-transfers. The pollination events help in producing hybrid pods on each of the two inbred parents (i.e., P_1 x P_2 and P_2 x P_1). Because the cross-pollination in plants takes place only in some flowers, each plant will have both, the self- and cross-pollinated (hybrid) pods. But the proportion of the two pod types would vary and depend on the visits of pollen-loaded insect pollinators on different plants.

IV. Because the seed production of sybrids does not involve any male-sterile and fertility restorer line, the issues related to poor pod-setting and pollen-shedding do not arise. Hence, in comparison to the three-parent hybrids, the seed production of sybrids is relatively easier, cost-effective and hassle-free and does not require highly skilled technical personnel.

V. Because the extent of cross-pollination varies from one environment to another, the identification of seed production hot spots with high insect activity would be a boon to the sybrid seed production programmes.

VI. At genotypic level, both the inbred and hybrid cultivars are expected to be quite uniform, but a sybrid population will not be the same because it would contain three genotypes (a hybrid and two parents). Therefore, in relation to inbreds and hybrids, a sybrid population would carry a broader spectrum of genetic base. Theoretically, such heterogeneous populations are expected to exhibit greater buffering capacity to encounter the challenges of various biotic/abiotic stresses and environment changes.

VII. With respect to commercial yields, a sybrid population is expected to be inferior to hybrids but superior to inbred and synthetic cultivars.

VIII. Overall, the superiority of sybrid populations over inbred cultivars is determined by the proportion of hybrid plants. These will contribute positively towards speedy germination (Saxena et al. 2020), greater seedling growth (Bharathi and Saxena 2012; Thakare et al. 2013), greater root and canopy biomass (Saxena et al. 1992), besides tolerance to water-logging (Sultana et al. 2013), high salinity (Srivastava et al. 2005) and drought (Lopez et al. 1996). These qualities of sybrids would definitely provide some relief to farmers from various stresses and competition from weeds and companion crop.

5 | Legume Crops Identified for Breeding Sybrid Populations

Considering potential benefits of sybrid populations, it seems logical to try this technology for genetic enhancement of the often-cross-pollinated legumes. Initially, these may include grasspea, soybean, faba bean and pigeonpea. A brief of about the candidate crops is presented herein.

5.1 | Pigeonpea

In pigeonpea, the hybrid vigour for seed yield has been ably demonstrated in hundreds of on-farm trials conducted by ICRISAT under diverse environmental conditions. But it is a pity that the farmers could not reap the benefits of hybrid breeding technology. The main bottleneck in this endeavour is the control of its seed purity at production level. This is due to inability of breeders to conduct the grow-out tests that is attributed to the photo-sensitivity of crop. The details about its out-crossing, heterosis and seed production of pigeonpea hybrids are elaborated in a recent review (Saxena, Sharma, and Vales 2018). Pending the availability of an amicable solution to the seed quality issue through genomics tools, the authors believe that some high-yielding sybrids could be bred and distributed to farmers.

5.2 | Faba Bean

In faba bean, adequate levels of both partial cross-pollination and hybrid vigour are present (Link 1990; Bond 1995). But the breeding of hybrid cultivars is marred due to instability of the male sterility system. Therefore, to increase the crop productivity, the breeding of synthetic varieties was tried, but these populations were found inferior to the experimental hybrids. Under this scenario, the goal of developing commercial hybrids cannot be visualized in the near future. However, through sybrid breeding, certain extent of hybrid vigour can be exploited without bothering about the issues related to the instability of male sterility systems.

5.3 | Soybean

According to Fang et al. (2023), the cultivated area of soybean in North and South America has expanded by more than 900% since the 1960s. However, its productivity did not change significantly. In order to enhance yield, breeders were on the lookout for some alternative breeding technology such as hybrid breeding and research started to fulfil this goal. Davis (1985) succeeded and reported the first case of male sterility in soybean whereas the other reported up to 19% natural out-crossing in certain genotypes. Subsequently in China, the world's first commercial soybean hybrid 'HybSoy 1' was released in 2002 with 20.8% standard heterosis (Zhao et al. 2004). The unstable nature of male sterility and the high cost of hybrid seed production constrained the large-scale utilization of heterosis in soybean.

Carter et al. (1986) and Perez et al. (2009) reported that the out-crossing rate in some male sterile plants could be as high as 74%. Also, Palmer et al. (2001) observed that the flower size can play an important role in enhancing cross-pollination in soybean. Besides this, the management of insect pollinators for cross pollination and selection of suitable environment can enhance cross-pollination in this crop (Palmer et al. 2001; Garibaldi et al. 2021). The authors believe that this scenario can easily be exploited to breed some sybrid populations with enhanced yields.

5.4 | Grasspea

Grasspea is a hardy legume that can grow well in nutritionally depleted soils and dry growing environments. In fact, it can produce a reasonable quantity of grains when other legumes even fail to establish. Rahman et al. (1995) reported a fair extent of natural out-crossing in this crop and found that flower colour plays a significant role in determining the level of out-crossing. The cross-pollination in the lines with attractive red flowers was as high as 27.8%. whereas in the white flowered lines, it was only 9.8%. This difference was attributed to the preference of pollinating insects towards red coloured flowers. It seems that the out-breeding in grasspea is quite high to implement a sybrid population breeding programme. For this purpose, red flowered genetically diverse high yielding inbred lines should provide good genetic materials.

6 | Enhancing Breeding Efficiency of Sybrid Populations

The efficiency of breeding sybrid populations can be increased by following certain breeding procedures, briefly discussed herein.

6.1 | Enhancement of Cross-Pollination Rates

The natural out-crossing in crop plants is the consequent of their floral morphology and physiology. These factors may include protruding stigma beyond the anther level and production of greater quantities of pollen grains, nectar fluids and organic volatiles. Ficher and Leal (2006) reported that bigger flowers produced more nectar in *Passiflora coccinea* whereas Heinrich (1979) observed that the amount of nectar secreted by an individual flower is determined on the balance between plant frugality and its requirement to attract pollinators.

Palmer et al. (2001) postulated that certain structural changes in soybean flowers and reproductive organs could increase the level of cross-pollination in soybean. Severson and Erickson (1984) reported that in soybean, its flower size was positively associated with the amount of nectar production. These changes could be achieved through breeding for an ideal floral type. Similarly, there is plenty of scope to enhance the level of out-crossing in faba bean also (Suso 2004).

6.2 | Enhancement of Genetic Diversity

The selection of heterotic cross combinations is the key for developing high yielding sybrid populations, and for this purpose, the enormous diversity that is conserved in genebanks can be used for crop improvement programmes. For example, in pigeonpea, around 14,000 germplasm accessions comprising landraces, obsolete varieties, breeding lines and wild relatives are conserved at ICRISAT. For using this in breeding programmes, some small-sized subsets core or minicore germplasm collections can be created to list the diverse accessions for different qualitative and quantitative traits (Upadhyaya et al. 2010). Besides, these some useful heterotic pools can also be established by grouping the genetically diverse germplasm (Yong et al. 2013; Saxena and Sawargaonkar 2014; John-Bejai et al. 2024). The use of high-throughput genotyping and precise phenotyping can also help in identifying useful genotypes for improving the often-cross-pollinated crops (Dwivedi et al. 2017; Nguyen and Norton 2020). Such an exercise would help in the identification and efficient utilization of germplasm for breeding high yielding sybrid populations in the often-cross-pollinated legumes.

6.3 | Integration of Genomics Knowledge and Tools

Genomic science and technologies have transformed the landscape of plant breeding, particularly into certain key cereal crops. This approach provides unprecedented insights into the genetic architecture of the crops. The emergence of agrigenomics in legume crops, however, started late. But now, the breeders have access to different genomic tools, which can help in accelerating the genetic enhancement of economically important legumes. By harnessing the power of genetic markers and diversity analyses, the crop breeders can now precisely identify and select genotypes with greater speed and accuracy.

It is believed that the deployment of genomic resources like genome-wide markers, genomic enriched libraries, high-throughput genotyping assays, saturated genome maps, marker/gene-trait associations, whole-genome sequence and germplasm resequencing would provide a brighter insight into trait-specific breeding programmers (Bohra et al. 2020). These technologies would help breeders to tap into the vast reservoir of genetic diversity with greater accuracy. As far as the often-cross-pollinated crops is concerned, the authors believe that first there is need to increase their levels of natural cross-pollination by establishing gene pools with diverse flower structure and enhanced nectar production. To achieve this, new breeding materials is now available to identify suitable genotypes for use in breeding high-yielding sybrid populations.

7 | General Discussion and Outlook

In order to break the shackles of low productivity in often-cross-pollinated legumes, the farmers are eagerly waiting to replace their local varieties with new high yielding cultivars. In this context, breeders regularly produce new inbred cultivars, but unfortunately, these are not helping in increasing the crop productivity. The reviews published by Sharma and Dwivedi (1995), Bishnoi et al. (2012), Sawargaonkar and Saxena (2020), Saxena, Dalvi, et al. (2021) and Chandra et al. (2024) revealed that some of the hybrid combinations exhibit ≥100% better parent heterosis. But no hybrid could be developed due to the reasons discussed earlier. The authors, however, believe that, now, an opportunity exists to utilize portion of heterosis through the proposed sybrid breeding programme.

The sybrid breeding endeavour is a two-parent activity, which ably exploits both additive and non-additive genetic variances. It is also likely to have broad genetic base and contribute to greater stability through genetic homeostatic effects. The yield levels of sybrids will be determined by the degree of hybrid vigour expressed in a particular cross and the proportion of hybrid plants present in the population.

In the absence of experimental data, the authors estimate the productivity of sybrid populations produced under different levels of both out-crossing and heterosis. For example, with mean parent yield of 2000 kg/ha, 40% heterosis and 50% out-crossing, the sybrid would theoretically produce a population with a potential yield of about 2400 kg/ha (Table 3). Similarly, a cross exhibiting 100% hybrid vigour would produce a population with potential yield of 3000 kg/ha grains and recording an advantage of 1000 kg/ha over the inbred control. This level of sybrid productivity would fall short of the potential hybrid yield by a margin of 1000 kg/ha. These theoretical productivity estimates of the sybrid populations should be viewed in the backdrop of yield stagnation and need of enhancing the productivity of the often-cross-pollinating crops.

Due to the peculiar design of sybrid breeding technology, there may be some variation in the genetic constitution of the populations produced at different times. This variability could arise due to variations in the extent of out-crossing and consequently adding variable number of hybrid plants. Therefore, to ensure high heterotic effects (and yield), care should be taken in selecting a seed production site with high pollinator activity.

The other important thing that is associated with a sybrid population is the presence of some degree of phenotypic variability in the final product. This situation may arise when the parents of the population differ massively with respect to the visible trait(s). To overcome this concern, attempts should be made to select the inbred parents with matching key morphological traits so that their hybrid also appears phenotypically similar to its parents. At the first sight, this approach may look challenging but not impossible to tackle. The pigeonpea breeders at ICRISAT developed a cross combination that involved two high yielding inbred lines ICPB 2047 (P_1) and ICPL 87119 (P_2). These inbred parents were highly diverse at molecular level (Saxena et al. 2015, Saxena, Sharma, and Vales 2018) but matched fairly well with respect to various plant and grain characteristics (Table 4). The sybrid population derived from such a pair of inbred parents will appear quite uniform and will have no issues of acceptability by farmers and consumers.

TABLE 3 | Expected yield of sybrid populations at different levels of out-crossing and heterosis.

No.	Genotype	% out-crossing	Yield (kg/ha) at different levels of heterosis			
			40%	50%	60%	100%
1	Inbred lines	00	2000	2000	2000	2000
2	SyBrid	10	2080	2100	2120	2200
3	SyBrid	20	2160	2200	2240	2400
4	SyBrid	30	2240	2300	2360	2600
5	SyBrid	40	2320	2400	2480	2800
6	SyBrid	50	2400	2500	2600	3000
7	Hybrid (C)	100	2800	3000	3200	4000

TABLE 4 | The matching traits of two parental inbred lines and the sybrid/hybrid population developed from these parents at ICRISAT.

Trait	Inbred parent 1 (ICPB 2047)	Inbred parent 2 (ICPL 87119)	Sybrid/hybrid population
Days to flowering	120–125	115–120	115–129
Days to maturity	175–185	180–190	179–188
Plant height (cm)	> 200	> 200	> 200
Branches	Profuse	Profuse	Profuse
Stem colour	Green	Green	Green
Flower colour	Yellow, streaked	Yellow, streaked	Yellow, streaked
Pod colour	Green, streaked	Green, streaked	Green, streaked
Seeds/pod (No.)	4–6	5–6	5–6
100-seed wt. (g)	11–12	12–13	12–14
Seed colour	Brown, shining	Brown, shining	Brown, shining
Seed shape	Round	Round	Round
Fusarium wilt	Resistant	Resistant	Resistant
Sterility mosaic virus	Resistant	Resistant	Resistant
Yield (kg/ha)	1200–1450	1420–1810	2200–2440

Source: ICRISAT Pigeonpea Breeding Unit.

8 | Conclusions

Historically, the hybrid breeding technology has not only benefitted scores of farmers but also saved the masses from hunger, particularly in the rainfed tropics and subtropics. Besides high productivity, the hybrids also demonstrate high degree of resilience against a range of abiotic and biotic stresses. Till now, the benefits of hybrid technology have been reaped in various cereal, fruit and vegetable crops. It is believed that this technology in the near future should be extend to other crops also. This may be important particularly in view of shrinking agricultural area and unconquerable population growth. It is pitying that legumes, the mainstay of nutritional security, were wilfully excluded from the group of hybrid crops due to their self-pollinating nature. In fact, the breeders started exploring the production of hybrids in pigeonpea and faba bean in the middle of the 20th century. But, unfortunately, even after extensive research efforts, the desired goals could not be achieved (Bond et al. 1966; Gnanasambandam et al. 2012; Saxena, Tikle, et al. 2021).

In this context, a beginning has been made by presenting a proposal for breeding sybrids. This technology utilizes natural cross-pollination to harnesses portions of dominance, epistasis and additive genetic variances to harvest more grain yields to augment the conventional inbred breeding programmes. Also, it is estimated that 1 ha of sybrid seed production plot can easily yield about 1500–2000 kg of seed. This high seed-to-seed ratio can help in making the sybrid seed available to farmers at affordable costs. Like hybrids, the sybrid seeds are also designed for a single use, and hence, it should be able to attract the private seed sector as well.

Author Contributions

K. B. Saxena: conceptualization, methodology, validation, writing – review and editing. **V. A. Dalvi:** writing – review and editing, writing – original draft. **Manish Pandey:** writing – review and editing. **Prakash I. Gangashetty:** writing – review and editing. **R. K. Srivastava:** writing – review and editing. **R. K. Saxena:** writing – review and editing. **R. V. Kumar:** writing – review and editing. **Shivali Sharma:** writing – review and editing.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All the data are available in public domain.

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