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REVIEW ARTICLE

Developing synthetics as a byproduct of hybrid maize breeding

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Abstract

All-India Coordinated Research Project on maize breeding, established in 1957, started a large-scale multi-parent hybrid breeding and later focused on composite breeding. The improved cultivars did create an impact but not on the expected scale in spite of the development of some outstanding cultivars. Meanwhile, the cultivation of single-cross hybrids became popular in a large number of countries. The breeding programme in India was accordingly reoriented in the late 1980s with an almost exclusive focus on single crosses. These hybrids have created a remarkable impact by accelerating area expansion and yield enhancement in *rabi*/spring season, but the impact is lower and also variable across regions during *kharif*. The Project has developed and recommended 35 cultivars of field corn during 5 years (2017-2021) for cultivation during *kharif*. These include nine composites (including improved locals) meant for the states generally having difficult ecologies and resource-constrained farmers. Evidently, some centers are working on hybrid and composite breeding, and thus are practically conducting two independent breeding programmes. In such situations, an alternative is breeding synthetic varieties rather than undertaking population improvement, as an adjunct of single-cross breeding. Synthetics, being genotypically heterogeneous populations, are expected to have higher stability of performance than genotypically homogenous single-cross hybrids. These also have the advantage that farmers can produce seed at their own level, which is expected to enable synthetics to have a place in some constrained ecologies in the transient phase. However, single-cross breeding should continue to be the ultimate goal as single crosses have the highest performance potential among various cultivar types.

Keywords: Maize, single-cross hybrid, composite, synthetic, improved local

Introduction

Maize (*Zea mays* L.) is the first crop in which heterosis was commercially utilized through the cultivation of hybrid cultivars, which is considered a landmark in plant breeding. To make use of hybrid technology, an All-India Coordinated Research Project (AICRP), a unique national-level project – first of its kind, was started in maize in 1957 under the aegis of the Indian Council of Agricultural Research (ICAR). The AICRP was upgraded to the Directorate in 1994 and to the Indian Institute of Maize Research (IIMR) in 2015. Prior to that, some isolated efforts were going on in Punjab, Bengal, Uttar Pradesh and Maharashtra up to the mid-1940s (NCA 1973; Singh et al. 1995; Dhillon et al. 2006). In 1945, ICAR financed an ad-hoc schemes in New Delhi, Punjab (Lyalpur/Jalandhar), Uttar Pradesh (Almora and Kanpur), Bombay (Arbhavi and Dohad), Bihar (Sabour and Pusa) and Andhra Pradesh (Himayat Nagar) to develop maize hybrids.

Multi-parent hybrid breeding

With the establishment of Maize-AICRP, the breeding program was greatly strengthened and a national-level coordinated effort got initiated. Initially the focus was solely on hybrid breeding and a large-scale hybrid breeding programme was initiated. Starting in 1961, a number of multi-parent hybrids were released. These included double-cross [DC, a hybrid of two single crosses, a single-cross (SC) being a hybrid of two inbred parents] and double-top cross [a hybrid having an SC as a female parent and an open-pollinated (OP) population as a male parent] hybrids (Dhillon and Malhi 2006; Dhillon et al. 2006; Kaul et al. 2010). Of these, 'Ganga Safed 2' and 'Hi-Starch' deserve special mention. 'Ganga Safed 2' became popular in *kharif* season, and 'Hi-Starch' played a historical role by laying the foundation of

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winter maize cultivation in Bihar and South India. However, it was felt that the spread of hybrid varieties suffered from some limitations, the serious ones being lack of strong public sector seed industry accompanied by poor vigor of inbred parents, cumbersome hybrid seed production and the requirement to purchase fresh hybrid seed by farmers for every planting.

Composite breeding

To overcome these difficulties and to give due importance to maize cultivation in low-input agriculture, Maize-AICRP gave the concept of composite variety, a composite being an OP variety typically developed by recurrent selection in an OP base population created by bulking together seeds of a number of genotypes generally selected phenotypically. The breeding programme accordingly was reoriented and a number of composites were released starting in 1967 (Dhillon and Malhi 2006; Dhillon et al. 2006; Kaul et al. 2010. The first batch of six composites released in 1967 included a landmark variety, composite 'Vijay' (others being'Amber', 'Jawahar', 'Kisan', 'Vikram,' 'Sona'). The breeder seed of 'Vijay' was indented up to 2019 (Dhillon and Sandhu 2023a). Further, composites 'African Tall' and 'J1006', released in 1983 and 1992, respectively, continue to dominate the scene in fodder maize production. Composite breeding dominated for quite some time, though some centres continued small scale programmes on breeding multi-parent hybrids. Overall, the improved composites and multi-parent hybrids did create an impact on maize cultivation but not on the expected scale in spite of the development of some outstanding multi-parent hybrid and composite cultivars.

Single cross hybrid breeding

Among various types of cultivars (different types of hybrids, composites, synthetics), SC hybrid has the maximal expression of heterosis and the highest performance potential, besides having remarkable uniformity. Due to this, the cultivation of SC hybrids started in the late 1950s and early 60s in the USA. These hybrids rapidly covered practically all maize acreage in the USA and many other countries. In view of this development at the global level, the Indian maize breeding programme was reoriented in late 1980s with a main focus on SC hybrids, and first single-cross hybrid, 'Paras', was released in 1995 (Dhillon et al. 1995). Thereafter, a multitude of SC hybrids have been released (Kaul et al. 2010; Anonymous 2023; Dhillon and Sandhu 2023b).

Currently, SC hybrids are under cultivation on practically the whole maize area during *rabi*/spring season throughout the country. Similar is the coverage during *kharif* season in the states of Andhra Pradesh, Chhattisgarh, Haryana, Karnataka, Maharashtra, Odisha, Punjab, Tamil Nadu, Telangana and West Bengal (Anonymous 2023). On the whole, SC hybrids have created a remarkable impact by accelerating area expansion and yield enhancement, especially in *rabi*/ spring season. During *kharif*, SC hybrids' cultivation is not accompanied by similar yield and area enhancement in the states like Punjab, Haryana and some others. The crop performance during *kharif* season is unstable due to various abiotic stresses like drought, high temperature and waterlogging along with increased incidence of diseases and insect pests under hot and humid climatic conditions. The erratic rainfall also interferes with the efficient management of nutrients and weeds besides water.

The information based on the inputs received from various research centres of the Maize-AICRP (Anonymous 2023) indicates that OP varieties (composites including locals) are cultivated on at least 60 percent area (approx.) during *kharif* season in many states, namely Arunachal Pradesh, Jammu & Kashmir, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Uttarakhand (Table 1). Further, these varieties occupy at least 30 percent area (approx.) in states like Gujarat, Himachal Pradesh, Jharkhand, Madhya Pradesh, Rajasthan, and Tripura and predominate in certain ecologies and the tribal regions of these states.

These are difficult ecologies, not easily accessible and have inadequate infrastructure for post-harvest handling and delivery of seeds. Further, the farmers have small holdings and are resource (financially and technologically) constrained. On the other hand, the seed of SC hybrids carries high price because of many limitations, primarily low vigor and yield of the inbred parents. Thus, the public sector could not make an appreciable contribution in SC hybrid seed production which is dominated by the private sector. With public sector becoming more active in recent years, the situation is expected to improve! From 2017 to 2021, the IIMR made commendable progress by signing 25 MoUs with private seed companies to license seven IIMR hybrids for their seed production (Anonymous 2023). In addition, IIMR collaborated with a State Seed Corporation and a farmers' organization as well as produced seed in farmer-participatory mode. It is added that SC hybrids could not fully replace OP varieties in some agro-ecologies in even agriculturally progressive states, for example, sub-mountainous tract in Punjab and Haryana, due to very small land holdings of farmers in spite of strong private seed industry.

Maize-AICRP (IIMR and 32 research centers located across the country) has developed and released 69 improved cultivars during 5 years (2017-2021). These include 35 cultivars of field corn, the major maize type under cultivation, recommended for cultivation during *kharif* season, of which 26 are SC hybrids and 9 are OP varieties (composites including improved locals). These OP varieties are released in the states of Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Uttar Pradesh, Madhya Pradesh and Punjab besides agro-ecological Peninsular

Table 1. Approximate coverage of different type of maize cultivars at the Farmer's field in various states[1]

State	Area (%)[1]		Area during *kharif* season as percent of the total area (%)
	Hybrids	Open Pollinated Cultivars (Composites + Locals)	
Andhra Pradesh	100	0	36%
Arunachal Pradesh	20	80 (10 + 70)	86%
Assam	80	20 (5 + 15)	100%[2]
Bihar	95	5 (4 + 1)	31%
Chhattisgarh	90	10 (1 + 9)	100%[2]
Gujarat	60	40 (20 + 20)	72%
Haryana	90	10 (0 + 10)	100%[2]
Himachal Pradesh	60	40 (25 + 15)	100%
Jammu & Kashmir	30	70 (50 + 20)	100%
Jharkhand	70	30 (20 + 10)	97%
Karnataka	100	0	90%
Madhya Pradesh	70	30 (25 + 5)	99%
Maharashtra	100	0	70%
Manipur	30	70 (0 + 70)	39%
Meghalaya	40	60 (30 + 30)	100%[2]
Mizoram	10	90 (20 + 70)	100%[2]
Nagaland	20	80 (20 + 60)	92%
Odisha	90	10 (0 + 10)	95%
Punjab	95	5 (4 + 1)	100%[2]
Rajasthan	60	40 (10 + 30)	99%
Sikkim	40	60 (10 + 50)	100%
Tamil Nadu	100	0	55%
Telangana	100	0	66%
Tripura	70	30 (10 + 20)	76%
Uttar Pradesh	85	15 (10 + 5)	91%
Uttarakhand-Plains	20	80 (50 + 30)	100%[2]
Uttarakhand-Hills	<1	>99 (75 + 25)	
West Bengal	98	2 (1 + 1)	17%

[1]Based on the input received from various centres on the approximate coverage of different type of cultivar
[2]Maize is cultivated in seasons other than *kharif* but data are not available for those seasons

Zone (Table 2). Breeding composites is irrefutable evidence on the inadequate coverage of maize area by SC hybrids in these states, though the information presented in Table 1 is an approximation and not based on any systematic survey.

In view of quantitative-genetic expectations and practical experience, SC hybrids have the highest performance potential among all types of cultivars in maize. Thus, the ultimate goal should be SC hybrids. At the same time, it is worth noting that, in spite of almost exclusive focus in the mandate to develop and popularise SC hybrids for at last 35 years, many research centers of the Maize-AICRP are still working on composite breeding (including improvement of local) too, and thus are conducting practically two breeding programmes. This underscores a need for reflection on and identification of the alternative approaches that connect with SC hybrid breeding, as an adjunct.

Synthetic variety breeding

An alternative to breeding composites and improving locals is breeding synthetic varieties while sticking to the ultimate goal of developing SC hybrids. A synthetic variety is synthesized by crossing *inter se* a number of genotypes (inbreds, clones, other materials) selected on the basis of good general combining ability (GCA), with subsequent maintenance by open pollination. Hayes and Garber (1919) proposed the development of synthetic varieties in maize. Synthetic breeding deploying clones as parents

Table 2. Nine field corn OP varieties developed by public sector for cultivation during *kharif* season

Year	Cultivar	Developed by[1]	Recommended area	Duration
2018	JMC 3	SKUAST-J	Jammu	Medium
	Comp. Jawahar Maize 218[2]	JNKVV	Madhya Pradesh	Medium
2019	Comp. SHIATS Makka 2	SUHAST	Uttar Pradesh	Medium
2020	Comp. Jawahar Maize 215	JNKVV	PZ[3], Jabalpur (Madhya Pradesh)	Early
2021	Him Palam Maize Composite 1	CSKHPKV	Palampur (HP), Jammu & Kashmir, Uttarakhand	Medium
	Comp. Sikkim Sankul Makka-1	NOFRI	Sikkim	Medium
	Comp. Sikkim Sankul Makka-2	NOFRI	Sikkim	Medium
	Comp. JC 4	PAU	Punjab	Medium
	Comp. JC 12	PAU	Punjab	Late

[1] SKUAST-J Shere Kashmir University of Agriculture and Technology, Jammu, SUHAST = Sam Higginbottom University of Agriculture, Technology &Sciences, Prayagraj, JNKVV = Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, CSKHPKV = Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur, NOFRI = National Organic Farming Research Institute, Gangtok, and PAU= Punjab Agricultural University, Ludhiana
[2]Released for cultivation during *kharif* as well as *rabi* seasons
[3]PZ = Peninsular zone: Comprising States of Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu

was adopted in forage crops but there were only a few experiments in maize (Allard 1960). Meanwhile, hybrid maize breeding became popular and overshadowed synthetic variety breeding.

Inbreeding to develop inbred lines and the evaluation of combining ability of inbreds are regular activities in hybrid breeding. To develop a synthetic variety, inbred lines (parental generation, designated as Syn_0 generation) having good GCA are selected and crossed in all possible hybrid combinations to produce F_1 hybrids. An equal quantity of seed of each hybrid is bulked to have F_1 bulk (Syn_1), which is open-pollinated to produce F_2 generation (Syn_2). The Syn_2 seed is used by farmers for cultivation. In case enough quantity of Syn_1 seed is available, it may be distributed to the farmers to enable them to exploit heterosis expressed in F_1 generation. The theoretical expectation is that a Syn_2-generated deploying *n* parents will have inbreeding depression equal to $1/n^{th}$ of the mean superiority of F_1 generation over the parents. In succeeding random-mated generations, there should be no further decline in performance since as per Hardy-Weinberg law, genetic equilibrium is, in general, attained with one generation of random mating. Thus, the expectation is that the performance of subsequent generations will be the same as that of Syn_2. Thus, farmers can produce seed at their own level for some generations following the guidelines of seed production of OP varieties. This approach may be of some help in lowering the demand and price of hybrids seed. However, the best synthetic is expected to have a lower yield and less uniformity than the best SC hybrid as synthetic is created by putting together the best SC hybrid and many others.

Unlike composite breeding, synthetic breeding has the advantage of being fully integrated with SC hybrid breeding. Further, synthetics, compared to composites, may have an advantage as these are synthesized using inbred lines. During inbreeding, selfing exposes undesirable alleles, enabling their identification and rejection. Thus, constituent inbreds are cleaned off undesirable alleles, unlike the constituents of a composite. The farmers can save the seed of both composites and synthetics but it is easier to maintain seed quality of synthetics than that of composites. In case of deterioration of seed quality, synthetics can be reconstituted using original parents unlike that of composites.

Factors affecting performance of synthetic variety

Theoretically, the performance of advanced generations of synthetic varieties depends on the number of parental lines, mean performance of the parental lines, and mean performance of all possible cross combinations among the parental lines, and it can be upgraded by manipulating any one or a combination of these (Allard 1960). The studies by Kinman and Sprague (1945) and Kutka and Smith (2007) showed that the optimal of parents is 5 to 8 and Gallais (1990) reported the optimum number is rather broad and greater than four. Though increasing the number of parents seems to be the easiest approach but, practically, it is very difficult to identify a large number of inbred lines having nearly equally good performance per se as well as GCA as the best inbred. The mean performance of parents and hybrids progressively declines as the number of parental inbred lines increases. Upgrading the performance of parents may be the most effective avenue to minimize the inbreeding depression in Syn_2 (Allard 1960).

In hybrid breeding, early testing is carried out to estimate the combining ability of early-generation lines. These lines generally have better performance per se than advanced generation lines. These early lines having good GCA may be used to develop synthetics, as homozygosity/phenotypic uniformity is not an issue in synthetic varieties. However, the selfing of these early generation lines has to continue to develop homozygous inbred lines, as the ultimate objective is SC hybrid breeding. Thus, it may be difficult to reconstitute a synthetic generated by using early-generation inbred lines.

Genetic structure of a variety and stability of performance

A cultivar needs to possess high and stable performance. The importance of stability of performance has increased with climate change, the occurrence of which is widely acknowledged (Dhillon and Sohu 2024). The frequency of extreme events, such as increased frequency of heatwaves, droughts, erratic rains (untimely and heavy rains, reduction of rainy days), hailstorms, cloudbursts, floods, landslides etc., has increased in recent years, leading to aggravation of abiotic and biotic (disease-insect pest) stresses. The projections are that the effects of climate change will intensify, particularly in developing countries like India.

According to Allard and Bradshaw (1964) there are two pathways by which a cultivar can achieve the stability of performance: Individual and population buffering. Individual buffering is a property of an individual genotype that shows a plastic response to variable environmental conditions. On the other hand, a heterogeneous population being an aggregate of a number of genotypes, each adapted to somewhat different environments, possesses both population and individual buffering. An SC hybrid has plants of only one genotype and thus is genetically homogenous and possesses only individual buffering. On the other hand, OP variety (synthetic, composite, local) has genetic heterogeneity, and it has individual as well as population buffering. Thus, the genetic homogeneity of SC hybrids, compared to OP varieties, renders them more vulnerable to abiotic and biotic stresses. Due to their stable yield and wide adaptation as compared with SC hybrids, there is some renewed interest in commercializing OP varieties and OP varietal hybrids of maize in certain agricultural sectors of the USA, Europe and Africa, especially among low-input and organic farmers (Carena 2005; Jaradat et al. 2010). Thus, synthetics may be helpful in meeting the challenge of increasing weather vagaries due to climate change, besides having a place in resource-poor ecologies. Further, being broad-based, synthetics are reservoirs of desirable genes and will be useful in germplasm conservation. The synthetics generated by using inbred parents belonging to one heterotic group can serve as a good source population for cyclic improvement of inbred lines.

Authors' contribution

Conceptualization (BSD); Preparation of the manuscript (BSD, SLJ).

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