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RESEARCH ARTICLE

Conservation agriculture facilitated assessment of genetic potential of new generation maize hybrids and improving the breeding efficiency

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Abstract

To meet the increasing demand for maize grains in India, high-yielding maize hybrids have to be released in the farmer's field for adoption during kharif. The current study was carried out to estimate the potential of new generation hybrids generated by crossing the inbreds developed through a repeated cycle of recurrent selection in maize (Zea mays L.) under conservation agriculture conditions maintained under a maize-wheat cropping system. We hypothesised that soil health is a major determinant of yield realisation, particularly during Kharif in northern plain conditions, and therefore conservation agriculture can facilitate the identification of hybrids with high yield potential. In contrast, conventional tillage does not support the hybrids of high yield potential. To test the hypothesis, 91 hybrids developed by crossing 14 inbreeds in a half-diallel fashion were grown along with parents in both conservation and conventional tillage conditions. The result of the analysis of variance (ANOVA) showed significant variance for all the traits under study in both conditions. Combining ability estimates showed that most of the traits involved both additive and non-additive gene actions. Phenology along with radiation use efficiency by better capturing the sun light plays an important role in yield maximisation as indicated by the contribution of PMICS20, PMICS11, PMICS13 PMICS17 and PMICS12 for optimization of days to silking, maximising LAI and stem girth for higher yield realisation at least under conservation agriculture through additive gene action of complementary alleles dispersed in the parents or because of non-additive gene action at some of loci in hybrids like PMICS20/PMICS11, PMICS17/PMICS12 and PMICS15/PMICS12. Population improvement programme through repeated crossing to combine the favourable genes and selection under conservation agriculture for slightly delayed silking, along with higher LAI, more number of grains per row, grain weight and stay grain trait can lead to the development of hybrids competing with rice in terms of economic return.

Keywords: Maize, conservation agriculture, phenology, leaf area, stem girth, combining ability

Introduction

Maize (*Zea mays* L.) is an important cereal crop belonging to the tribe *Maydeae* of the grass family, Poaceae. It is becoming and more and more versatile over the years, and now is being grown from 58° N to 40° S and from below sea level to altitudes of more than 3000 m with an annual rainfall of around 250 mm to more than 5000 mm (Shaw 1988).

The popularity of maize as a crop in India is continuously increasing over the years because of multiple use patterns (28% for food purposes, 11% as livestock feed, 48% as poultry feed, 12% in the wet milling industry and 1% as seed and now for ethanol production). Its high nutritive value with 10% protein, 4% oil, 70% carbohydrate, 2.3% crude fibre, , and 1.4% (Langyan et al. 2022) ash along with sufficient quantities of vitamin A, nicotinic acid, riboflavin and vitamin E makes it as a *Poor Man's Nutricerea"* Production (34.61 m

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t in 2022-23) (PJTSAU Maize Outlook April 2023) of maize in India is continuously increasing since last many years largely because of increase in area mainly under winter maize in states like Andhra Pradesh, Telangana, Karnataka, Rajasthan, Bihar and Madhya Pradesh and Uttar Pradesh. The demand of maize is likely to increase further because of new initiative on use maize grain for the production of ethanol and raising the limit of blending to 20% of bio-ethanol into petrol and diesel by the year 2030 (NAAS News/ICAR-IIMR 2024) If supported by marketing demand, more and more farmers are going to adopt maize under various cropping system and season and there is going to be very high demand of phenologically different maize hybrids. However, a major challenge for the maize breeders and agronomists is to increase the economic return to maize growers during *kharif*. Maize crop faces a dual challenge of better adaptability by pearl millet under rainfed and higher returns by rice under irrigated conditions of *kharif* in Northern India. Degrading soil health and depleting natural resources, coupled with changes in rain patterns experienced during the last two decades, are restricting the identification of high-yielding genotypes (Yadav et al. 2017, 2021). Conservation agriculture, being a smart agriculture practice, addresses all of these issues holistically and sustainably (Yadav et al. 2021). Average productivity of *kharif* maize is still less than 4.0 t/ha and in the majority of states, yield realisation beyond 5 tonnes is a rare event and therefore replacing rice even marginally by maize during *kharif* is a big challenge. Exploitation of heterosis is a quick, cheap and easy method of attaining maximum yields in cross-pollinated crops. However, deteriorating soil health and erratic rainfall under conventional tillage conditions restrict the identification of hybrids of around 7-9 t/ha of yield potency. Traditional understanding of heterosis says that higher yield realisation in F_1 hybrids is either because of a constellation of favourable alleles in the hybrid, which are otherwise dispersed in parents, or because of allelic or epistatic interaction. However, recent research indicates the role of epigenome, differentially expressed transcriptome and gene network (Wu et al. 2021; Yu et al. 2021). We assume that conservation agriculture conditions, being a totally different production environment with completely different microbes, may result in differentially expressed genes, which may result in completely different behaviour of hybrids. Though identification of the reason for differential expression is beyond the scope of this paper, through this experiment, we want to verify whether CA can help in the identification of some very high-yielding hybrids in maize during *kharif*.

Materials and methods

The experiment was carried out using a Randomized Block Design with two replications for two environmental conditions, viz. conservation agriculture (CA) and conventional tillage (CT) at the Crop Research Farm of the Division of Genetics, Indian Agricultural Research Institute, Delhi, during the *rabi* of 2019-20. The experimental material for present investigation comprised of 91 F_1s developed by crossing 14 lines *viz*., PMICS11, PMICS12, PMICS13, PMICS14, PMICS15, PMICS16, PMICS17, PMICS18, PMICS19, PMICS20, PMICS21, PMICS22, PMICS23 and PMICS24 following half diallel mating design. These 14 inbreds of maize (*Zea mays* L) were developed through repeated selection and crossing for adaptation to conservation under CA conditions maintained since 2009 a in Indian Agricultural Research Institute, New Delhi, research farm. All 14 genotypes were grown during the *Rabi* 2018-19 for making crosses in a half diallel fashion and resultant seeds of 91 hybrids were harvested.

A total of 105 treatments with 14 parents (the pedigree of inbred lines is described below) and 91 F_1s were evaluated for the study of nine characters in maize. The entries were sown in three rows of 3 m length with inter and intra-row spacing of 22.5 and 10 cm, respectively, both under conservation agriculture (CA) in a plot maintained under CA for more than 10 years and conventionally tilled conditions. All the recommended cultural practices were applied to raise a good crop. Data on various phenological and important physiological traits like leaf area and leaf area index, stem girth, no of nodes per stem, number of kernels per row and grain yield (kg/ha) were observed on five randomly selected plants. Soil physical and chemical properties are improved under conservation agriculture due to minimum soil disturbance and retention of previous crop residue. In CA, the adoption of PB/ZT resulted in ~a 22.5% higher soil quality index (SQI) compared with CT (Parihar et al. 2020). Similarly, the soil microbial biomass carbon (MBC) under CA-based systems increased by 45 to 48.9% in the 0–30 cm profile depth of a sandy soil (Parihar et al. 2016).

For leaf area estimation, leaves from different positions on the stem were measured for length and maximum width and area was calculated as per the procedure given by Watson (1947). According to the formula mentioned by Elings (2000), the area of the green leaves was calculated using the length–width coefficient method. Then it was transformed into green LAI per unit of ground area (Elings 2000).

Leaf area= LWp

Leaf Area Index = total leaf area /unit ground area

Where *L* and *W* are the length and maximum width of a green leaf, respectively; *p* is the correction coefficient, 0.75 for the fully expanded leaves and 0.5 for the not fully expanded leaves (Elings 2000).

Baker's ratio was also computed to estimate the parental performance associated with the variance of GCA and SCA effects using the following formula: Baker's ratio = $2\sigma^2$GCA/ (2 σ^2GCA + σ^2SCA). Analysis of variance and estimation of general and specific combining ability effects were estimated by using method II and model I of diallel mating

Description of the parents

Inbred Line	Parentage
PMICS11	AH11120-202/PMH 1-S2-01//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS12	AH11120-202/PMH 1-S2-02//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS13	AH11120-202/PMH 1-S2-03//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS14	AH11120-202/PMH 1-S2-04//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS15	AH11120-202/PMH 1-S2-05//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS16	AH11120-202/PMH 1-S2-06//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS17	AH11120-202/PMH 1-S2-07//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS18	AH11120-202/PMH 1-S2-08//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS19	AH11120-202/PMH 1-S2-09//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS20	AH11120-202/PMH 1-S2-10//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS21	AH11120-202/PMH 1-S2-11//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS22	AH11120-202/PMH 1-S2-12//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS23	AH11120-202/PMH 1-S2-13//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)
PMICS24	AH11120-202/PMH 1-S2-14//Bulk pollen(NMH713, Bio562, CP33, NR6246, A7501, MN1107, JKMN101, Biscos11)

design (Griffing 1956 b).

The mathematical model for the combining ability analysis is assumed to be $X_{ijkl} = \mu\mu + g_i + g_j + S_{ij} + e/bc \sum\sum e_{ijkl}$

$X_{ij..}$ = the mean of ij^{th} genotype over k and l.

$\mu\mu$ = The population mean

gi = The general combining ability (gca) of the i^{th} patent

gj = The gca of j^{th} parent

S_{ij} = the specific combining ability (sca) for the cross between i^{th} and J^{th} parents such that $S_{ij} = S_{ji}$

e_{ijkl} = The environmental effect (mean error effect) with the $ijkl^{th}$ observation on i^{th} individual in k^{th} block with i^{th} as femal parent and j^{th} as male parent.

Results

The results of conservation agriculture vis-a-vis a combined environment obtained were analyzed and presented in (Tables 1 and 2). Mean sum of squares due to treatment, including parents, and hybrids were found to be significant for all the characters under study, both under conservation agriculture and combined environmental conditions. The ratio between variance due to general combining ability (GCA) to specific combining ability (SCA) effect clearly showed the preponderance of additive gene action for both phenological traits, stem girth and number of nodes under both environments (Tables 1 and 2); it was more prominent for kernel row number and number of kernels.

On the basis of days to silking and days to tasselling, parents PMICS18 and PMICS20 were found to have quite

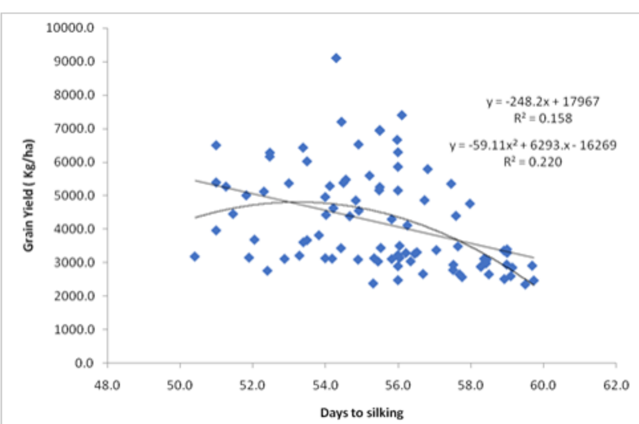

Fig. 1. Days to silking accounting the variation in grain yield in maize under conservation agriculture

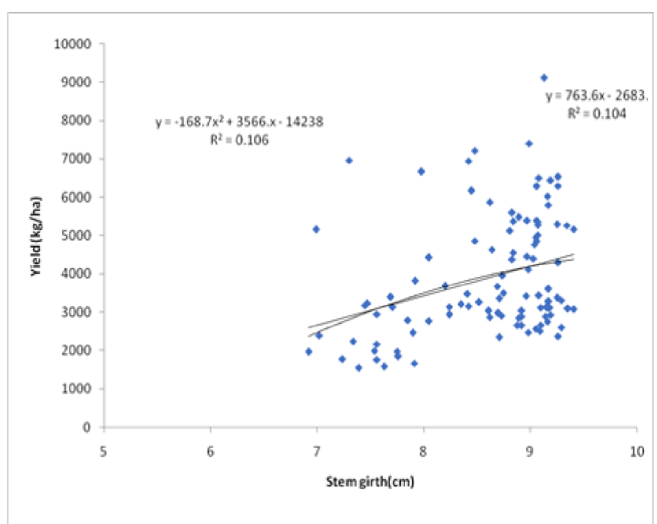

Fig. 2. Stem Girth accounting for the variation in grain yield in maize under conservation agriculture

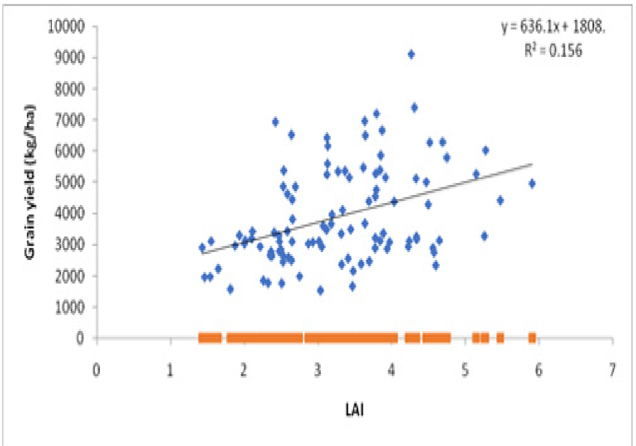

Fig. 3. Role of LAI in explaining variation in grain yield under conservation agriculture

high and significantly positive GCA effects under both conditions (Tables 3 and 4) and therefore are likely to throw heterotic hybrids in the long-duration group. Combined ANOVA analysis of the present experiment clearly shows more importance of additive genetic variance than non-additive genetic variance for both phenological traits. Some of the parents like PMICS11 showed good combining ability for multiple traits like plant height, stem girth, leaf area index and grain yield; however, positive GCA effects were more pronounced under conservation agriculture (Tables 3 and 4). Similarly, the genotype PMICS23 showed positive and significant GCA for GY, LAI, number of nodes and KPR but only under conservation agriculture conditions. The genotype PMICS19 and PMICS20 showed positive GCA effects for both kernel row number and number of kernel rows, though with delayed tasseling and silking again under conservation conditions (Tables 3 and 4).

Some of the hybrids with specifically larger and positive SCA effects for days to tasselling and silking are PMICS13 ×PMICS12, PMICS14 ×PMICS13, PMICS15 ×PMICS16, PMICS14 ×PMICS19 and PMICS18 ×PMICS12. Since the hybrids were evaluated during *Kharif*, where extreme phenology does not have a direct bearing on yield so we tried to explain yield variation in hybrids through a linear regression equation with days to silking. It indicated that days to silking accounted for more than 15% variation in hybrid yield (Fig. 1). However to check whether polynomial regression improves the fitness of data, we used 2nd order regression for curvilinear relationship to capture the more complex relationship between days to silking and yield and found that it significantly improved the fitness and explained 22% of yield variation in hybrids. Curvier relationship clearly showed that yield in hybrids increases up to the level of 55 to 56 days of silking and it significantly drops if the silking is delayed beyond this level (Fig. 1). The present study indicates significant GCA and SCA effects for stem girth under conservation agriculture conditions, with a preponderance of additive gene action for stem girth under CA. The relevance of stem girth for yield was assessed through regression analysis in the hybrids (Fig. 2) and it was found that under conservation agriculture conditions, stem girth accounted for 10.4% variation in grain yield and there was a linear relationship between stem girth and grain yield. The leaf area was found to have a linear association with grain yield and accounted for around 15% of its variation (Fig. 3), which is quite substantial and can be exploited for yield consolidation in maize. On the basis of the overall environment, the mean square due to GCA and SCA for leaf area index (Table 2) are equally important and therefore have equal contributions of additive and non-additive components in their inheritance. Parent PMICS22, PMICS23 and PMICS11 have positive and significant GCA effects for leaf area index. The three best specific combiners with high SCA effect for LAI are PMICS12/PMICS22, PMICS14/PMICS21 and PMICS18/PMICS21. Combining ability analysis showed highly significant mean sum of squares due to GCA and SCA for grain yield, indicating a preponderance of both additive and non-additive gene effects; however, Baker ratio showed a clearly abundance of additive gene effects. A large proportion of additive gene effects for grain yield offers a very good opportunity for crossing the inbreds with large GCA effects and making selection for the improvement of the inbreds. Inbred lines, namely, PMICS11, PMICS12, PMICS17, PMICS23 and PMICS22 showed very high and positive GCA effects and can be crossed in a specific mating design to develop high-yielding maize hybrids. The highest yielding hybrids on the basis of mean value over two environments like PMICS20/PMICS11, PMICS17/PMICS13, PMICS17/PMICS12 and PMICS15/PMICS12 show involvement of at least one of the parents with high gca and thus carrying and transferring many favourable genes to the hybrid progeny. Many of the cross combinations such as PMICS12/PMICS17, PMICS13/PMICS17, PMICS14/PMICS17, PMICS20/PMICS11, have very high SCA effects and also had higher yield.

Discussion

The study indicates sufficient variation for almost all characters under study in parents as well as in hybrids and therefore, provides enough scope for selection and further improvement in the hybrid breeding programme. Since the parents used in diallel mating design were chosen with diverse pedigree information, it is likely that they inherited different alleles or genetic makeup for different characters, which is reflected by variation as observed in the present study. Since many of the inbred lines used in the diallel mating design were derived from experimental hybrids and went through repeated cycles of selection and mating under conservation agriculture conditions, significant differences

Table 1. Analysis of variance of combining ability for phenological, physiological and important yield component traits under conservation agriculture

Source of variation	DF	DT	DS	PH	GIRTH	NODE	LAI	GY	KR	KPR
GCA	13	36.02**	27.84**	1209.16**	1.01**	7.8166**	1.95**	53204**	4.81**	8.81**
SCA	91	8.69**	9.49**	954.72**	0.84**	3.88**	1.84**	47186**	7.07**	25.57**
Error	104	0.89	1.36	6.25	0.29	0.10	0.09	95238.08	0.10	0.82
σg		4.24	3.73	24.59	0.71	1.98	0.99	1631.02	1.55	2.10
σs		2.08	2.18	21.85	0.65	1.39	0.96	1536.00	1.88	3.58
σg/σs		2.04	1.71	1.13	1.10	1.42	1.03	1.06	0.83	0.59
(σg/σs)^0.5		1.43	1.31	1.06	1.05	1.19	1.02	1.03	0.91	0.77

*, ** significant at 5% and 1% level, respectively
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= kernel number per row

Table 2. Analysis of variance of combining ability for phenological, physiological and important yield component traits for combined environments

Source of variation	DF	DT	DS	PH	GIRTH	NODE	LAI	GY	KR	KPR
Gca	13	60.70**	53.84**	1867.55**	23.49**	14.49**	3.33**	1041182**	8.82**	17.32**
sca	91	16.20**	17.38**	1696.31**	9.66**	7.79**	3.24**	929077**	11.91**	49.23**
Error	104	0.92	1.14	17.39	11.97	0.33	0.10	57260.06	0.62	1.12
s g		5.51	5.19	30.56	3.43	2.69	1.29	2281.65	2.10	2.94
s s		2.85	2.95	29.12	2.20	1.97	1.27	2155.32	2.44	4.96
s g/ s s		1.94	1.76	1.05	1.56	1.36	1.02	1.06	0.86	0.59
(ss/ s g) ^0.5		1.39	1.33	1.02	1.25	1.17	1.01	1.03	0.93	0.77

*, ** significant at 5% and 1% level, respectively;
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= Kernel number per row

Table 3. General combining ability effects for 14 inbreds for phenological and important physiological traits in maize under CA

Var.	Parent/ Hybrids	DT	DS	PH	GIRTH	NODE	LAI	GY	KR	KPR
1	PMICS11	-1.81**	-1.36**	3.02**	0.25*	-0.03	0.27**	966.82**	0.14*	0.16
2	PMICS12	-0.37*	-0.39	7.71**	-0.31**	-0.34**	-0.14*	439.94**	0.33**	-0.77**
3	PMICS13	-0.53**	-0.74**	-3.83**	-0.34**	0.15*	-0.06	-101.64	0.33**	0.16
4	PMICS14	0.65**	0.63**	-0.46	-0.17	-0.47**	-0.05	-496.28**	-0.29**	-0.71**
5	PMICS15	0.49**	0.25	1.70**	-0.08	0.46**	0.03	49.91	-0.23**	-0.62**
6	PMICS16	0.68**	0.50*	8.21**	0.09	0.43**	0.25**	-191.36**	-0.66**	-0.62**
7	PMICS17	0.49**	0.19	3.40**	0.20*	-0.19**	-0.12*	245.13**	0.01	0.34*
8	PMICS18	1.40**	1.32**	0.36	-0.04	0.15*	-0.05	-676.71**	-0.41**	0.12
9	PMICS19	0.46*	0.60**	-10.69**	0.09	-0.84**	-0.36**	-113.74*	0.51**	0.37*
10	PMICS20	1.21**	1.16**	-1.56**	0.05	-0.72**	-0.32**	19.32	0.58**	0.69**
11	PMICS21	0.30	0.29	-2.28**	0.10	0.33**	0.09	-32.73	0.20**	-0.49**
12	PMICS22	-2.06**	-1.80**	7.06**	0.06	0.96**	0.42**	83.07	0.08	0.56**
13	PMICS23	-1.19**	-1.02**	-0.26	-0.01	0.21**	0.32**	203.89**	-0.54**	0.34*
14	PMICS24	0.27	0.35	-12.39**	0.10	-0.09	-0.26**	-395.61**	-0.04	0.44*

*, ** significant at 5% and 1% level, respectively
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= Kernel number per row

among the parents and hybrids for flowering can be of great significance for developing slightly longer duration maize hybrids for realizing higher yield potential in *kharif* maize.

Both GCA and SCA effects are important in the selection or development of breeding populations (Viana and Matta 2003) for meeting long-term targets. From the large number of inbred lines developed in the breeding programme, breeders are generally interested in segregating this material

Table 4. General combining ability effects for 14 inbreds for phenological and important physiological traits in maize for combined environments

Var.	Parent/ Hybrids	DT	DS	PH	GIRTH	NODE	LAI	GY	KR	KPR
1	PMICS11	-1.67**	-1.52**	2.48**	0.08	-0.10	0.26**	936.08**	0.09	0.40**
2	PMICS12	-0.24*	-0.47**	5.13**	-0.46	-0.25**	-0.12**	415.81**	0.34**	-0.71**
3	PMICS13	-0.33**	-0.66**	-3.07**	-0.50	0.10	-0.08**	-130.71**	0.28**	0.23*
4	PMICS14	0.60**	0.61**	-0.32	-0.32	-0.36**	-0.03	-478.05**	-0.30**	-0.73**
5	PMICS15	0.50**	0.33**	1.82**	-0.25	0.39**	-0.001	66.84**	-0.21**	-0.57**
6	PMICS16	0.54**	0.44**	7.70**	-0.06	0.49**	0.24**	-208.06**	-0.65**	-0.60**
7	PMICS17	0.50**	0.35**	3.30**	0.05	-0.17**	-0.12**	231.56**	0.06	0.35**
8	PMICS18	1.32**	1.22**	-0.01	-0.20	0.05	-0.08**	-699.96**	-0.46**	0.04
9	PMICS19	0.33**	0.66**	-9.36**	-0.05	-0.85**	-0.33**	-75.98**	0.47**	0.39**
10	PMICS20	1.02**	1.03**	-1.19**	-0.10	-0.72**	-0.30**	18.90	0.41**	0.60**
11	PMICS21	-0.03	0.27*	-2.13**	-0.04	0.33**	0.11**	-38.17	0.41**	-0.60**
12	PMICS22	-1.92**	-1.66**	6.68**	-0.08	0.93**	0.38**	140.17**	0.09	0.53**
13	PMICS23	-1.13**	-1.04**	0.17	2.01**	0.22**	0.29**	215.43**	-0.46**	0.29**
14	PMICS24	0.50**	0.42**	-11.189***	-0.05	-0.06	-0.22**	-393.8**	-0.08	0.37**

*, ** significant at 5% and 1% level, respectively
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= Kernel number per row

Table 5. Specific crosses with high and significant SCA effects in desirable direction under conservation agriculture

DT	PMICS22 ×PMICS13	PMICS16 ×PMICS15	PMICS22 × PMICS18	PMICS23 ×PMICS18	PMICS22 × PMICS21	PMICS21 × PMICS13*(-)	PMICS23 ×	PMICS20 × PMICS19*(-)
DS	PMICS21 ×PMICS17	PMICS22 × PMICS18	PMICS20 × PMICS19	PMICS24 × PMICS13	PMICS24 ×PMICS16			
PH	PMICS24 × PMICS19	PMICS14× PMICS12	PMICS24 × PMICS21	PMICS24× PMICS15	PMICS15 × PMICS11			
GIRTH	PMICS14 × PMICS12	PMICS12 × PMICS11*	PMICS23 × PMICS18*	PMICS16 ×PMICS12	PMICS24×PMICS18			
NODE	PMICS20 × PMICS17*	PMICS19 ×PMICS11*	PMICS22 × PMICS13*	PMICS24×PMICS20	PMICS19 ×PMICS13			
LAI	PMICS22 × PMICS12	PMICS21 ×PMICS14	PMICS18 × PMICS16	PMICS19 × PMICS15	PMICS24× PMICS14			
GY	PMICS21 × PMICS20	PMICS19 × PMICS17	PMICS18 × PMICS17	PMICS24 × PMICS12	PMICS24 × PMICS15			
KR	PMICS15× PMICS13	PMICS20 × PMICS11	PMICS15 × PMICS11	PMICS20 × PMICS12	PMICS18 ×PMICS16			
KPR	PMICS24 × PMICS21	PMICS23 ×PMICS15	PMICS18× PMICS16	PMICS19× PMICS11	PMICS15 × PMICS13			

*, , -, significant at 5% and 1% level, respectively and consider negative value for DT only
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= Kernel number per row

into heterotic pools, a group of phylogenically related or unrelated genotypes with similar kinds of combining ability and heterotic response when crossed with some unrelated and untested genotypes (Melchinger and

Table 6. Specific crosses with high and significant SCA effects in desirable direction for combine environments

DT	PMICS22 × PMICS13	PMICS16 × PMICS15	PMICS22 × PMICS18	PMICS19 × PMICS14	PMICS22 × PMICS21	PMICS23 × PMICS18(-)	PMICS13 ×	PMICS22 × PMICS20*(-)
DS	PMICS22 × PMICS18	PMICS22 × PMICS13	PMICS23×PMICS14	PMICS23 × PMICS18	PMICS19 × PMICS14			
PH	PMICS24 × PMICS21	PMICS23 × PMICS17	PMICS21 × PMICS18	PMICS15 × PMICS11	PMICS13 × PMICS11			
GIRTH	PMICS12 × PMICS11							
NODE	PMICS19 × PMICS15	PMICS22 × PMICS15	PMICS21 × PMICS14	PMICS24 × PMICS18	PMICS17 × PMICS13			
LAI	PMICS22 × PMICS12	PMICS21 × PMICS14	PMICS24 × PMICS18	PMICS19 × PMICS15	PMICS18 × PMICS16			
GY	PMICS16 × PMICS12	PMICS16 × PMICS13	PMICS24 × PMICS22	PMICS21 × PMICS15	PMICS13 × PMICS11			
KR	PMICS15 × PMICS13	PMICS15 × PMICS11	PMICS20 ×PMICS11	PMICS16 × PMICS13	PMICS20 × PMICS12			
KPR	PMICS24 × PMICS21	PMICS23 × PMICS15	PMICS18 × PMICS16	PMICS15 × PMICS13	PMICS17 × PMICS16			

*, ,-, significant at 5% and 1% level, respectively and consider negative value for DT only per row
DTT= Days to tasselling, DTS= Days to sillking, PHT= Plant Height, LAI= Leaf Area index, GY= Grain yield, KRN= Kernel row number, KNPR= Kernel number per row

Gumber 1998; Melchinger 1999; Reif et al. 2003). To meet the SDG agenda, researchers and policy planners in India are pushing for very high-yielding maize hybrids to fit in the maize-wheat cropping system in India and provide an equally remunerative and competitive cropping system like rice-wheat. Replacement of rice by maize hybrids has largely failed due to comparatively lesser yield of maize hybrids during *kharif,* largely because of comparatively shorter to medium duration hybrids, which have inherently lower yield (Zhao et al. 2021). Duration plays an important role in an above-ground matter accumulation irrespective of crops (Yadav et al. 2017), and therefore characteristics facilitating dry matter accumulation and its transfer toward sink with adequately large sink size are the important determinants of high yield (Saïdou et al. 2003; Yadav 2017; 2021; 2021). Our study clearly indicates that to achieve a yield level of more than 8 tonnes per ha consistently, the hybrids silking around 54-56 days with comparatively higher leaf area index and stem girth need to be essentially tested under conservation agriculture conditions, ensuring continuous moisture and nutrient supply and countering the negative impact of sudden downpour through better percolation. GCA and SCA estimates, particularly for some newly explored traits like delayed flowering, LAI, greater nod number and stem girth, can help in dividing the inbred lines into complementary heterotic pools. Maize in Indian is comparatively more (85%) grown during the Kharif season; however, in recent years major increase in area in spring and winter maize has been observed because of higher productivity, largely because of prolonged duration in these conditions. Phenology can also be manipulated by agronomic management. Conservation agriculture (CA) facilitates quick germination (data not presented) but has comparatively more duration for tasselling and silking because of continuous supply of moisture under elevated temperature of *kharif* and, therefore, achieves comparatively higher yield. Water stress during flowering is the most important factor hindering potential yield realization in maize. Faster depletion of water in the upper layer of soil under conventionally tilled conditions can drastically reduce the yield. (Yadav et al. 2017, 2021, and 2018). Under conventionally tilled conditions, delay in irrigation and, in contrast, flooding due to heavy rain, both affect the root development and plant growth adversely (Lynch 1995). However, under conservation agriculture conditions, because of more water retention and movement of water through capillary action, along with faster percolation under heavy rain conditions, ensure a more optimum environment for root and plant development during the flowering and grain filling stage (Yadav 2021; 2018; Sehgal et al. 2018). Although the majority of breeders and researchers have reported the hybrid crosses with large and negative SCA effects in their research findings (Zoric et al. 2022), the objectives of the present study were to identify the specific combination with prolonged duration to realize maximum yield. For improving radiation use efficiency, manipulation of plant canopies for better capturing of sunlight in the middle and upper leaf layer with larger leaf areas with compact plant and strong stem has been advocated (Ci et al. 2012; Wang et al. 2011) as a means to increase maize yield under dense plant population.

In high-yield maize populations, the optimized canopy structure intercepts more solar radiation in the middle and upper leaf layers and thus increases their contribution to GY. Positive impact of higher leaf area index on grain yield has been highlighted by number of researchers (Wang et al. 2019; Tian et al. 2020; Huang et al. 2017) Leaf area index explaining more than 15% grain yield variation in the hybrids in linear fashion along with almost equal proportion of both additive and non-additive gene effects offers an opportunity to the Indian breeders for its integration in the population improvement programme targeting higher yield realization. This can be largely attributed to better water supply from lower layer under water stress, better percolation under flooding after heavy rain and better nutrient use efficiency under conservation agriculture conditions. Leaf area and light interception in the lower canopy have an impact on stem strength and, therefore, on lodging tolerance (Xue et al. 2016). The present study also clearly shows the role of stem girth in explaining the yield variation in hybrids under conservation agriculture and the regression graph clearly supports further consolidation of this trait. Inbred PMICS11 and PMICS23 show very good general combining ability for multiple contrasting traits besides grain yield under CA and can be used for heterotic pooling in tropical maize. Further fine-tuning of dry matter accumulation around 50% toward the post-silking stage can be equally rewarding (Rajcan and Tollenaa 1999; Tollenaar et al. 2004; Lee and Tollenaar 2007). Some of the by hybrids with comparatively higher LAI with longer green leaf retention capacity and strong stem girth at least under conservation agriculture condition like PMICS20/PMICS11, PMICS17/PMICS13, PMICS17/PMICS12 can have an immediate commercial value or at least their inbreeds can be the basis of further improvement (Ma and Dwyer 1998; Borrell et al. 2001; Duvick 2005).

Authors' contributions

Conceptualization of research (RY); Designing of the experiments (RA); Contribution of experimental materials (RY, RA); Execution of field/lab experiments and data collection (RA, AGS, RK, KK, SKS); Analysis of data and interpretation (RA, MK, KBG, SK); Preparation of the manuscript (RY, RA).

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