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Heterotic response of hybrids for yield and its contributing characters in sunflower (*Helianthus annuus* L.)

Rushabh Jadhao, Sanjay Sakhare and Sangita Fatak

Abstract
A field trial was conducted to study the effect of heterosis on yield contributing parameters at Oilseeds Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, during *Rabi* 2019-20 and *Kharif* 2020-21. Forty F_1 hybrids were obtained through line x tester mating design by crossing five CMS lines with eight restorer lines during *Rabi* 2019-20. Their evaluation was carried out during *Kharif* 2020-21 which consisted of 56 genotypes including 40 F_1 hybrids, 8 restorer lines, 5 maintainer of CMS (B lines) and 3 standard checks, laid out in Randomized Block Design with three replications. The analysis of all the characters under study indicated significant differences among the genotypes, parents, hybrids and parents vs hybrids which indicated the presence of substantial genetic variability among the genotypes for the characters studied.
Significantly higher average heterosis and heterobeltiosis for seed yield was recorded by hybrid combination CMS-248A x 189/1R followed by CMS 102A × AKSF-5R. The hybrid CMS-102A × AKSF-5R displayed highest magnitude of standard heterosis for seed yield and was found to be statistically at par with the hybrids CMS-108A × 3/148R and CMS-102A × 3/147R over all the three checks.

Keywords: Hybrids, heterosis, sunflower, yield components, *Helianthus annus*

Introduction
Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops in the world and ranked third after soybean and rapeseed in the production of oil globally. Earlier it was domesticated as a food crop in North America but commercial cultivation of sunflower started in 1969 after its introduction from former USSR. Because of its light yellow colour, pleasant flavor, high level of linoleic acid (55-60%), low oleic acid (25-30%), fairly high oil content of poly unsaturated fatty acids (PUFA) and absence of linolenic acid, it is considered as premium source of oil compared to the other vegetables oils (Atlagic, 1996) [5]. It contains vitamin K and E (Anonymous, 2021) [2].
During the year 2020-21 area under sunflower cultivation in India was 218.18 lakh ha with production of 365.65 lakh tones and yield of 1269 kg/ha. In Maharashtra area under sunflower cultivation was 0.02 million ha with production of about 0.01 million tons and average productivity of 507 kg/ha. (Anonymous, 2021) [1].
With the increase in demand for edible oils, there is need to develop new sunflower hybrids suited to different agro-climatic zones of Maharashtra with improved seed yield and oil content. The phenomenon of heterosis is directly related to hybrid Vigour which in turns plays an important role in the expression of seed yield. In view of the above facts, the present study was undertaken to estimate the average heterosis, heterobeltiosis and standard heterosis for seed yield and yield contributing characters.

Materials and Methods
The five CMS lines were crossed with eight restorers (Table 1) according to line x tester mating design at the research farm of Oilseeds Research Unit, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola (Maharashtra) during *rabi* 2019-20.
For evaluation, experimental material consisted of 56 genotypes (40 hybrids, eight restorer lines, five maintainer (B) lines and three standard checks) laid out in Randomized Block Design (RBD) with three replications during *kharif* 2020-21.

In each replication each entry was sown in one row of 3.0 m length. The inter and intra-row spacing was 60 cm and 30 cm, respectively. The F_1's, lines, testers and checks were randomized within the replications. The crop was raised under rainfed condition with satisfactory crop stand and growth. All the recommended practices were followed for raising successful crop.

Table 1: List of genotypes

Sr. No.	Lines	Sr. No.	Testers	Sr. No.	Checks
1.	CMS 248 A	1.	AKSF 5 R	1.	LSFH 171
2.	CMS 302 A	2.	AKSF 11 R	2.	PDKVSH 952
3.	CMS 138 A	3.	AKSF 14R	3.	DRSH 1
4.	CMS 108 A	4.	3/147 R		
5.	CMS 102 A	5.	3/148 R		
		6.	RHA-138-2 R		
		7.	189/1 R		
		8.	PKV 105 R		
(Source of CMS lines: UAS, Bangalore)		(Source of Testers & checks: ORU, Dr. PDKV., Akola)			

The observations for days to 50 per cent flowering and days to maturity were recorded on plot basis. The remaining observations like plant height, head diameter, hundred seed weight, volume weight, seed filling percentage, hull content, oil content and seed yield plant^{-1} were recorded on plant basis from each genotype in each replication on 5 randomly selected plants and their average values were computed. The estimates of average heterosis, heterobeltiosis and standard heterosis were calculated for all the characters under study.

Results and Discussion

The analysis of variance (Panse and Sukhatme, 1967) indicated the presence of substantial genetic variability among the genotypes for the characters under study. Mean values in the present study indicated that, among the five lines, the lines CMS-138B, CMS-302B and among eight testers, the testers PKV-105R, 3/147R, AKSF-11R and 3/148R recorded high mean performance for seed yield. The parents PKV-105R (48 days), AKSF-11R (49 days) and 189/1R (49 days) were found to be earliest to 50% flowering. Maximum head diameter was recorded by the parents RHA-138-2R (15.12cm), 189/1R (14.24cm) and 3/147R (13.92cm). Comparable results were reported by Saleem *et al*. (2014) [17], Janjal *et al*. (2016) [7] and Khandagale *et al*. (2019) [10] for head diameter in per se performance.

The highest 100 seed weight recorded by the parents, 3/148R (5.97g), PKV-105R (5.90g) and CMS-248B (5.14g) whereas the highest volume weight was recorded by the parents 3/147R (44.21g), 189/1R (44.20g) and PKV-105R (43.77g). On the other hand, minimum hull content was recorded by the parents, 3/148R (28.18%), AKSF-14R (29.36%) and RHA-138-2R (32.66%).

Among the hybrids, CMS-102A × AKSF-5R (48.94g), CMS-302A × 3/147R (48.46g), CMS-108A × 3/148R (48.18g), CMS-102A × 3/147R (45.47g), CMS-108A × AKSF-5R (45.42g), CMS-108A × AKSF-11R (45.06g) CMS-108A × 189/1R (44.78g) and CMS-248A × 189/1R (44.4g) were top ranking hybrids and found to be statistically at par with each other for seed yield per plant. These hybrids also showed superiority for other component characters. The hybrids CMS-102A × AKSF-5R, CMS-108A × 3/148R and CMS-108A × AKSF-11R showed superiority for 100 seed weight. Similar results were reported by Madrap and Nerker (1996)[14], Kumar *et al*. (1999) [11], Alone *et al*. (2003) [3], Kalpande *et al*. (2004) [9], Machikowa *et al*. (2011) [13] and Asif *et al*. (2013) [4], Rathi *et al*. (2016) [16] and Kulkarni and Supriya (2017) [12]. The hybrids CMS-102A × AKSF-5R and CMS-108A × AKSF-11R having high seed yield also recorded high mean values for head diameter. Thus, this indicated that there was high influence of 100 seed weight and head diameter on the expression of high seed yield. Therefore, these characters need to be focused during breeding Programme to enhance the seed yield in sunflower.

Character wise results of average heterosis (H1), heterobeltiosis (H2) and standard heterosis over LSFH-171 (H3), PDKVSH-952 (H4) and DRSH-1 (H5) respectively were observed in 40 hybrids and are presented in Table 2. Out of 40 hybrids, 31 hybrids recorded significant positive average heterosis for seed yield plant^{-1} whereas, maximum mid-parent heterosis for seed yield plant^{-1} was expressed by hybrids CMS-248A × 189/1R (68.19%), CMS-102A × AKSF-5R (64.89%), CMS-248A× AKSF-5R (59.54%) and CMS-108A × 3/148R (58.08%). Highest significant negative average heterosis for days to 50% flowering was recorded by the hybrid CMS-138A × 3/147R (-14.45%) followed by CMS-302A × AKSF-14R (-13.45%) and CMS-302A × AKSF-5R (-12.78%). The hybrids CMS-108A × AKSF-11R (20.43%), CMS-108A × AKSF-5R (20.09%) and CMS-248A × PKV-105R (17.13%) recorded highest significant average heterosis in positive direction for head diameter. The hybrid CMS-108A × PKV-105R (4.29%) exhibited maximum positive average heterosis for 100 seed weight followed by the hybrid CMS-302A × RHA-138-2R (1.05%). CMS-102A × AKSF-14R (18.20%) recorded highest significant positive heterosis for volume weight followed by CMS-138A × RHA-138-2R (16.21%), CMS-108A × RHA-138-2R (16.19%) and CMS-108A × AKSF-14R (16.05%). On the other hand, hybrid CMS-108A × PKV-105R (-26.16%) showed highest negative average heterosis for hull content followed by CMS-108A × 189/1R (-25.19%) and CMS-302A × 3/147R (-23.64%).

(Thakare (2014) [18], Depar *et al*. (2017) [6] and Kale *et al* (2019) [8]).

For heterobeltiosis, 13 hybrids showed significant positive heterobeltiosis. The top-ranking hybrid for seed yield plant^{-1} were CMS-248A × 189/1R (60.03%) followed by

Table 2: Heterosis (%) over mid-parent (MP), better-parent (BP) and standard checks [LSFH-171 (H_3), PDKVSH-952 (H_4) and DRSH-1 (H_5)] for different characters in sunflower

Sr. No.	Hybrids	1. Days to 50% Flowering					2. Days to Maturity				
		MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)	MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)
1	CMS-248A × AKSF-5R	-6.86*	-8.94*	1.88	5.16*	-1.81	-3.49	-4.36	-2.59	-6.07	-6.41
2	CMS-248A × AKSF-11R	-5.03*	-11.70**	-5.63	-2.58	-9.04*	-6.47*	-9.09*	-3.70	-7.14	-7.47*
3	CMS-248A × AKSF-14R	0.60	-2.34	4.37	7.74**	0.60	-2.01	-3.25	-0.74	-4.29	-4.63
4	CMS-248A × 3/147R	-2.06	-2.92	3.75	7.10**	0.00	3.07	-0.37	-0.37	-3.93	-4.27
5	CMS-248A × 3/148R	-11.57**	-12.87**	-6.88	-3.87	-10.24**	-3.97	-6.34	-1.48	-5.00	-5.34
6	CMS-248A × RHA-138-2R	1.08	-6.47	17.50**	21.29**	13.25**	1.07	-2.41	4.81	1.07	0.71
7	CMS-248A × 189/1R	-6.92*	-13.45**	-7.50*	-4.52	-10.84**	-5.00*	-8.52*	-8.52**	-11.79**	-12.10**
8	CMS-248A × PKV-105R	-4.13	-11.70**	-5.63	-2.58	-9.04*	2.82	1.11	1.11	-2.50	-2.85
9	CMS-302A × AKSF-5R	-12.78**	-13.26**	-1.88	1.29	-5.42	-10.60**	-13.06**	-6.30	-9.64*	-9.96**
10	CMS-302A × AKSF-11R	-10.37**	-18.78**	-8.13*	-5.16	-11.45**	-12.31**	-13.06**	-6.30	-9.64*	-9.96**
11	CMS-302A × AKSF-14R	-13.45**	-18.23**	-7.50*	-4.52	-10.84**	-5.63*	-7.90	-0.74	-4.29	-4.63
12	CMS-302A × 3/147R	-10.60**	-13.81**	-2.50	0.65	-6.02	-6.08*	-12.37**	-5.56	-8.93*	-9.25**
13	CMS-302A × 3/148R	-11.82**	-15.47**	-4.38	-1.29	-7.83*	-10.61**	-11.68**	-4.81	-8.21*	-8.54*
14	CMS-302A × RHA-138-2R	1.05	-3.98	20.63**	24.52**	16.27**	-3.27	-3.44	4.07	0.36	0.00
15	CMS-302A × 189/1R	-6.71*	-15.47**	-4.38	-1.29	-7.83*	-7.95*	-14.43**	-7.78*	-11.07**	-11.39**
16	CMS-302A × PKV-105R	-0.92	-11.05**	0.62	3.87	-3.01	-7.97*	-12.71**	-5.93	-9.29*	-9.61**
17	CMS-138A × AKSF-5R	-11.43**	-13.41**	-3.13	0.00	-6.63	-6.64*	-8.00*	-6.30	-9.64*	-9.96**
18	CMS-138A × AKSF-11R	-6.92*	-13.45**	-7.50*	-4.52	-10.84**	-9.22*	-12.24**	-7.04*	-10.36**	-10.68**
19	CMS-138A × AKSF-14R	-10.24**	-12.87**	-6.88	-3.87	-10.24**	-9.93*	-11.55**	-9.26**	-12.50**	-12.81**
20	CMS-138A × 3/147R	-14.45**	-15.20**	-9.38*	-6.45	-12.65**	-5.59*	-8.24*	-9.26**	-12.50**	-12.81**
21	CMS-138A × 3/148R	-9.79**	-11.11**	-5.00	-1.94	-8.43*	-7.80*	-10.56**	-5.93	-9.29*	-9.61**
22	CMS-138A × RHA-138-2R	-2.15	-9.45*	13.75**	17.42**	9.64*	2.33	-1.72	5.56	1.79	1.42
23	CMS-138A × 189/1R	-10.69**	-16.96**	-11.25**	-8.39**	-14.46**	-2.13	-5.24	-6.30	-9.64*	-9.96**
24	CMS-138A × PKV-105R	-9.21**	-16.37**	-10.63**	-7.74*	-13.86**	-3.41	-4.49	-5.56	-8.93*	-9.25**
25	CMS-108A × AKSF-5R	-11.83**	-16.76**	-6.88	-3.87	-10.24**	-5.38*	-6.71	-2.22	-5.71	-6.05
26	CMS-108A × AKSF-11R	-3.92	-7.55*	-8.13*	-5.16	-11.45**	-11.78**	-12.24**	-7.04*	-10.36**	-10.68**
27	CMS-108A × AKSF-14R	-3.75	-4.35	-3.75	-0.65	-7.23*	-11.07**	-12.01**	-7.78*	-11.07**	-11.39**
28	CMS-108A × 3/147R	-5.81*	-8.33*	-3.75	-0.65	-7.23*	-1.68	-7.07	-2.59	-6.07	-6.41
29	CMS-108A × 3/148R	0.31	-1.81	1.88	5.16*	-1.81	-11.46**	-11.62**	-7.04*	-10.36**	-10.68**
30	CMS-108A × RHA-138-2R	-5.00*	-14.93**	6.87**	10.32**	3.01	-4.71	-5.86	1.11	-2.50	-2.85
31	CMS-108A × 189/1R	-3.27	-6.92	-7.50*	-4.52	-10.84**	-6.57*	-12.01**	-7.78*	-11.07**	-11.39**
32	CMS-108A × PKV-105R	4.29*	3.14	2.50	5.81*	-1.20	12.32**	-10.60**	-6.30	-9.64*	-9.96**
33	CMS-102A × AKSF-5R	-8.78**	-10.06**	0.62	3.87	-3.01	3.11**	2.55	4.44*	0.71	0.36
34	CMS-102A × AKSF-11R	-0.31	0.63	0.00	3.23	-3.61	-3.58	-5.94	-0.37	-3.93	-4.27
35	CMS-102A × AKSF-14R	-8.66**	-3.77	-4.38	-1.29	-7.83*	-4.55	-5.42	-2.96	-6.43	-6.76
36	CMS-102A × 3/147R	-7.60**	-0.63	-1.25	1.94	-4.82	8.02**	4.04	4.81*	1.07	0.71
37	CMS-102A × 3/148R	-11.18**	-5.03	-5.63	-2.58	-9.04*	-7.19*	-9.15*	-4.44	-7.86	-8.19*
38	CMS-102A × RHA-138-2R	-4.53*	-10.95**	11.88**	15.48**	7.83**	0.36	-2.76	4.44*	0.71	0.36
39	CMS-102A × 189/1R	-7.79**	-6.92	-7.50*	-4.52	-10.84**	-3.83	-7.72	-7.04*	-10.36**	-10.68**
40	CMS-102A × PKV-105R	-9.43**	-9.43**	-10.00**	-7.10*	-13.25**	-3.94	-5.88	-5.19	-8.57*	-8.90*
	Range	-14.45 to 4.29	-18.78 to 3.14	-11.25 to 20.63	-8.39 to 24.52	-14.46 to 16.27	-12.31 to 12.32	-14.43 to 4.04	-9.26 to 5.56	-12.5 to 1.79	-12.81 to 1.42
	SE(d)±	0.79	1.30	1.30	1.30	1.30	0.73	1.19	1.19	1.19	1.19
	CD (5%)	1.57	2.57	2.57	2.57	2.57	1.44	2.36	2.36	2.36	2.36
	CD (1%)	2.08	3.40	3.40	3.40	3.40	1.91	3.12	3.12	3.12	3.12

Note: * Significant at 5% level of significance
** Significant at 1% level of significance

Sr. No.	Hybrids	1. Plant height					2. Head diameter				
		MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)	MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)
1	CMS-248A × AKSF-5R	18.35*	17.89*	2.04	-16.29*	-24.69**	-12.63	-13.69	-16.04	-24.38	-30.95
2	CMS-248A × AKSF-11R	11.06	8.00	-1.83	-19.47*	-27.54**	-16.72	-18.06	-20.29	-28.21	-34.44
3	CMS-248A × AKSF-14R	46.08**	44.96**	24.50*	2.13	-8.11	1.53	0.00	0.29	-9.67	-17.52
4	CMS-248A × 3/147R	45.79**	40.61**	30.02**	6.65	-4.05	-27.73	-29.60	-27.78	-34.96	-40.61
5	CMS-248A × 3/148R	47.17**	46.04**	25.43*	2.89	-7.43	-26.82	-27.10	-29.08	-36.13	-41.68
6	CMS-248A × RHA-138-2R	17.21	6.91	11.40	-8.62	-17.78*	-20.93	-25.95	-17.49	-25.69	-32.14
7	CMS-248A × 189/1R	34.28**	20.97**	29.58*	6.29	-4.37	-11.77	-15.00	-10.78	-19.65	-26.63
8	CMS-248A × PKV-105R	48.03**	38.26**	36.81**	12.22**	0.97	17.13**	16.69**	14.37**	3.01	-5.94
9	CMS-302A × AKSF-5R	-15.73**	-26.72**	-14.18**	-29.60**	-36.66**	-14.27	-14.98	-19.31	-27.32	-33.64
10	CMS-302A × AKSF-11R	-4.93*	-15.57*	-1.12	-18.89*	-27.02**	-22.23	-22.57	-27.09	-34.34	-40.04
11	CMS-302A × AKSF-14R	-6.10*	-19.14*	-5.31*	-22.33**	-30.11**	-14.50	-17.46	-17.22	-25.44	-31.92

12	CMS-302A × 3/147R	-3.12*	-13.32*	1.52	-16.73*	-25.08**	9.25**	4.33	7.03**	-3.61	-11.98
13	CMS-302A × 3/148R	4.89	-9.68*	5.77	-13.24*	-21.94**	-11.51	-12.98	-15.99	-24.34	-30.91
14	CMS-302A × RHA-138-2R	-3.05*	-8.39*	7.28	-12.00*	-20.82**	7.70*	-1.04	10.27**	-0.69	-9.31
15	CMS-302A × 189/1R	1.27	-3.05	13.54	-6.87	-16.21*	-14.46	-19.19	-15.18	-23.61	-30.24
16	CMS-302A × PKV-105R	3.46	-4.56	11.77	-8.32	-17.51*	-18.49	-20.43	-22.01	-29.76	-35.86
17	CMS-138A × AKSF-5R	22.57**	16.33*	12.11	-8.04	-17.26*	-13.01	-13.41	-17.05	-25.29	-31.78
18	CMS-138A × AKSF-11R	13.00	16.40*	5.81	-13.21*	-21.91**	-23.29	-23.95	-27.14	-34.38	-40.08
19	CMS-138A × AKSF-14R	14.48	7.47	3.57	-15.04*	-23.56**	11.34**	8.84**	9.16**	-1.68	-10.22
20	CMS-138A × 3/147R	-4.34*	-6.27	-9.68*	-25.91**	-33.34**	-18.65	-21.34	-19.31	-27.32	-33.64
21	CMS-138A × 3/148R	17.50	10.31	6.30	-12.80*	-21.54**	-3.32	-3.69	-7.03	-16.26	-23.54
22	CMS-138A × RHA-138-2R	8.55	4.47	8.86	-10.71	-19.66*	-3.53	-10.30	-0.05	-9.98	-17.80
23	CMS-138A × 189/1R	3.26	-1.92	5.06	-13.82*	-22.46**	-19.56	-23.08	-19.26	-27.28	-33.60
24	CMS-138A × PKV-105R	11.82	10.36	9.20	-10.42	-19.40*	-25.96	-26.79	-28.25	-35.38	-40.99
25	CMS-108A × AKSF-5R	37.26**	19.57*	39.45**	14.39**	2.92	20.09**	15.55**	18.64**	6.86**	-2.42
26	CMS-108A × AKSF-11R	25.76**	11.89	30.50**	7.04	-3.69	20.43**	15.43**	18.52**	6.75**	-2.53
27	CMS-108A × AKSF-14R	20.03**	3.53	20.75	-0.95	-10.89*	-22.43	-23.33	-21.27	-29.09	-35.25
28	CMS-108A × 3/147R	30.31**	16.81*	36.24**	11.75*	0.55	-8.21	-8.25	-5.80	-15.15	-22.53
29	CMS-108A × 3/148R	30.28**	12.37	31.06*	7.51	-3.27	-17.78	-20.24	-18.10	-26.24	-32.65
30	CMS-108A × RHA-138-2R	21.11**	14.65*	33.72**	9.69	-1.31	-4.68	-8.42	2.04	-8.10	-16.08
31	CMS-108A × 189/1R	16.08*	11.35	29.87**	6.53	-4.15	-28.97	-29.74	-26.26	-33.58	-39.35
32	CMS-108A × PKV-105R	15.20	-15.87*	-1.88	-19.51**	-27.58**	-5.97	-8.11	-5.65	-15.02	-22.40
33	CMS-102A × AKSF-5R	12.67	4.46	5.84	-13.18*	-21.89**	-12.81	-13.44	-16.63	-24.91	-31.43
34	CMS-102A × AKSF-11R	16.02*	10.05	11.51	-8.53	-17.71*	8.56**	7.35**	3.39	-6.88	-14.97
35	CMS-102A × AKSF-14R	10.58	1.44	2.78	-15.69*	-24.15**	-23.99	-25.50	-25.28	-32.70	-38.55
36	CMS-102A × 3/147R	38.31**	32.26**	34.01**	9.92	-1.10	3.89*	0.72	3.32	-6.95	-15.03
37	CMS-102A × 3/148R	43.61**	31.74**	33.48**	9.49	-1.49	0.98	0.87	-2.63	-12.30	-19.92
38	CMS-102A × RHA-138-2R	17.40	15.78*	20.64*	-1.04	-10.96*	13.80**	6.08**	18.20**	6.46**	-2.79
39	CMS-102A × 189/1R	-5.41*	-7.97	-1.42	-19.14**	-27.25**	-19.14	-22.47	-18.62	-26.70	-33.07
40	CMS-102A × PKV-105R	10.31	9.02	10.46	-9.39	-18.48*	-28.28	-28.90	-30.31	-37.23	-42.69
	Range	-15.73 to 48.03	-26.72 to 46.04	-14.18 to 39.45	-29.6 to 14.39	-36.66 to 2.92	-28.97 to 20.43	-29.74 to 16.69	-30.31 to 18.64	-37.23 to 6.86	-42.69 to -2.42
	SE(d)±	0.42	0.68	0.68	0.68	0.68	0.21	0.34	0.34	0.34	0.34
	CD (5%)	0.83	1.36	1.36	1.36	1.36	0.41	0.67	0.67	0.67	0.67
	CD (1%)	1.10	1.80	1.80	1.80	1.80	0.54	0.88	0.88	0.88	0.88

Note: * Significant at 5% level of significance
** Significant at 1% level of significance

Sr. No.	Hybrids	1. 100 seed weight					2. Volume weight				
		MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)	MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)
1	CMS-248A × AKSF-5R	-6.86	-2.79	9.10	-1.32	1.63	2.07	-1.33	-11.40	1.73	3.41
2	CMS-248A × AKSF-11R	-5.03**	12.07*	25.78	13.77	17.16	7.72**	2.92	-5.32	8.71**	10.51**
3	CMS-248A × AKSF-14R	0.60**	20.70**	35.47*	22.53*	26.19*	9.64**	6.94*	-10.38	2.90	4.60
4	CMS-248A × 3/147R	-2.06	-0.84	11.29	0.66	3.66	-1.97	-7.91	-12.19	0.83	2.49
5	CMS-248A × 3/148R	-11.57	-25.98	-3.50	-12.71	-10.11	5.36**	3.09	-9.71	3.67	5.39
6	CMS-248A × RHA-138-2R	1.08**	-9.21	1.89	-7.84	-5.09	4.28*	1.82	-14.67	-2.03	-0.41
7	CMS-248A × 189/1R	-6.92	-9.47	1.60	-8.10	-5.36	11.97**	5.20	0.28	15.14**	17.04**
8	CMS-248A × PKV-105R	-4.13	-24.99	-3.35	-12.58	-9.97	-3.83	-9.23	-14.31	-1.61	0.02
9	CMS-302A × AKSF-5R	-12.78**	25.14**	33.79*	21.01*	24.63*	12.91**	11.58**	0.19	15.03**	16.93**
10	CMS-302A × AKSF-11R	-10.37**	22.76**	27.68*	15.48*	18.93	15.00**	12.31**	3.31	18.62**	20.58**
11	CMS-302A × AKSF-14R	-13.45**	1.05	5.10	-4.94	-2.10	-0.98	-5.49	-17.14	-4.86	-3.29
12	CMS-302A × 3/147R	-10.60	-6.27	0.22	-9.35	-6.65	2.57	-1.56	-6.13	7.78*	9.56**
13	CMS-302A × 3/148R	-11.82	-17.82	7.14	-3.10	-0.20	10.01**	9.95**	-3.59	10.69**	12.52**
14	CMS-302A × RHA-138-2R	1.05**	1.17	13.33	2.50	5.56	1.50	-3.03	-14.98	-2.39	-0.77
15	CMS-302A × 189/1R	-6.71	1.07	10.12	-0.40	2.58	8.53**	4.18	-0.70	14.02**	15.90**
16	CMS-302A × PKV-105R	-0.92	-21.93	0.58	-9.03	-6.31	6.36**	2.57	-3.16	11.18**	13.02**
17	CMS-138A × AKSF-5R	-11.43**	30.86**	39.91**	26.55**	30.33*	13.60**	10.12**	-1.12	13.53**	15.41**
18	CMS-138A × AKSF-11R	-6.92**	6.01	7.94*	-2.37	0.54	-2.72	-6.79	-14.26	-1.55	0.08
19	CMS-138A × AKSF-14R	-10.24**	70.86**	34.52*	21.67*	25.31*	15.33**	12.17**	-5.45	8.56*	10.35**
20	CMS-138A × 3/147R	-14.45**	-4.29	2.33	-7.44	-4.68	12.43**	5.90	0.98	15.95**	17.86**
21	CMS-138A × 3/148R	-9.79**	-10.45	16.75	5.60	8.75	9.84**	7.77*	-5.60	8.39*	10.18**
22	CMS-138A × RHA-138-2R	-2.15**	12.81*	26.37	14.30*	17.71	16.21**	13.15**	-4.62	9.51**	11.32**
23	CMS-138A × 189/1R	-10.69**	-3.28	5.39	-4.68	-1.83	11.38**	4.94	0.03	14.85**	16.75**
24	CMS-138A × PKV-105R	-9.21	-41.44	-24.54	-31.75	-29.72	-0.92	-6.23	-11.47	1.64	3.32
25	CMS-108A × AKSF-5R	-11.83**	23.77**	32.34*	19.70*	23.27*	-0.60	-7.17	-16.64	-4.29	-2.71
26	CMS-108A × AKSF-11R	-3.92**	38.77**	41.30**	27.80**	31.61*	11.87**	3.31	-4.96	9.12**	10.92**
27	CMS-108A × AKSF-14R	-3.75**	41.81**	11.65	0.99	4.00	16.05**	14.77**	-8.55	4.99	6.73*

28	CMS-108A × 3/147R	-5.81**	-0.34	6.55	-3.62	-0.75	9.89**	-0.16	-4.80	9.31**	11.12**
29	CMS-108A × 3/148R	0.31**	7.60	40.28**	26.88**	30.66**	11.06**	4.93	-8.09	5.53	7.27*
30	CMS-108A × RHA-138-2R	-5.00**	18.01**	32.19**	19.57**	23.13**	16.19**	14.78**	-8.35	5.23	6.97*
31	CMS-108A × 189/1R	-3.27**	16.38*	26.80**	14.69*	18.11**	8.15**	-1.72	-6.32	7.56*	9.34**
32	CMS-108A × PKV-105R	4.29**	-6.33	20.68**	9.16	12.42	-6.90	-5.64	-10.91	2.29	3.98
33	CMS-102A × AKSF-5R	-8.78**	41.28**	51.06**	36.63**	40.71**	2.97	-3.11	-13.01	-0.12	1.54
34	CMS-102A × AKSF-11R	-0.31**	23.81**	31.03**	18.51**	22.05**	-6.73	-13.22	-20.17	-8.35	-6.83
35	CMS-102A × AKSF-14R	-8.66	2.27	8.23	-2.11	0.81	18.20**	17.83**	-6.12	7.79*	9.57**
36	CMS-102A × 3/147R	-7.60**	20.37**	28.70**	16.40*	19.88**	6.35**	-2.67	-7.19	6.56*	8.32*
37	CMS-102A × 3/148R	-11.18	-9.05	18.57**	7.25	10.45	10.29**	5.00	-8.03	5.60	7.34*
38	CMS-102A × RHA-138-2R	-4.53**	28.87**	44.36**	30.57**	34.46**	12.49**	12.02**	-10.55	2.70	4.40
39	CMS-102A × 189/1R	-7.79	-3.21	5.46	-4.61	-1.76	5.28**	-3.64	-8.15	5.46	7.21*
40	CMS-102A × PKV-105R	-9.43	-15.09	9.40	-1.05	1.90	14.53**	5.29	-0.60	14.13**	16.02**
	Range	-14.45 to 4.29	-41.44 to 70.86	-24.54 to 51.06	-31.75 to 36.63	-29.72 to 40.71	-6.9 to 18.2	-13.22 to 17.83	-20.17 to 3.31	-8.35 to 18.62	-6.83 to 20.58
	SE(d)±	0.20	0.32	0.32	0.32	0.32	0.81	1.32	1.32	1.32	1.32
	CD (5%)	0.39	0.64	0.64	0.64	0.64	1.60	2.62	2.62	2.62	2.62
	CD (1%)	0.52	0.85	0.85	0.85	0.85	2.12	3.47	3.47	3.47	3.47

Note: * Significant at 5% level of significance
** Significant at 1% level of significance

Sr. No.	Hybrids	1. Seed filling percentage					2. Hull content				
		MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)	MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)
1	CMS-248A × AKSF-5R	23.79**	21.86**	-6.71	9.16*	3.54	-14.57**	-14.66**	7.73	-9.61	-4.22
2	CMS-248A × AKSF-11R	38.42**	37.08**	1.67	18.97**	12.85**	-15.05**	-16.12**	8.40	-9.05	-3.62
3	CMS-248A × AKSF-14R	20.71**	14.21**	-5.07	11.08**	5.36	-10.87*	-19.23**	1.74	-14.64**	-9.54*
4	CMS-248A × 3/147R	13.31**	3.13	-6.74	9.13*	3.51	-18.25**	-20.02**	5.30	-11.65*	-6.38
5	CMS-248A × 3/148R	11.86**	-2.37	-2.89	13.64**	7.79*	-0.29	-11.28*	11.75	-6.24	-0.64
6	CMS-248A × RHA-138-2R	26.16**	24.70**	-7.51	8.23*	2.66	-5.30	-9.87*	13.53	-4.75	0.94
7	CMS-248A × 189/1R	14.52**	6.27	-7.90	7.77*	2.22	-11.62*	-13.27**	9.24	-8.34	-2.87
8	CMS-248A × PKV-105R	8.23**	-3.35	-8.80	6.72	1.23	-17.59**	-18.64**	5.15	-11.77*	-6.51
9	CMS-302A × AKSF-5R	20.21**	13.42**	-2.13	14.53**	8.64*	-18.49**	-18.53**	2.85	-13.70**	-8.55*
10	CMS-302A × AKSF-11R	21.76**	12.20**	-3.18	13.30**	7.47*	-18.73**	-19.71**	3.76	-12.94*	-7.74
11	CMS-302A × AKSF-14R	7.92**	5.94	-8.58	6.97*	1.47	-2.02	-11.27*	11.92	-6.10	-0.49
12	CMS-302A × 3/147R	7.31**	4.85	-5.18	10.95**	5.24	-23.64**	-25.24**	-1.58*	-17.42**	-12.49**
13	CMS-302A × 3/148R	-6.47	-12.66	-13.13	1.65	-3.58	-8.18*	-18.35**	2.99	-13.59**	-8.43*
14	CMS-302A × RHA-138-2R	21.41**	11.67**	-3.64	12.77**	6.96*	-8.20*	-12.68**	10.13	-7.59	-2.08
15	CMS-302A × 189/1R	9.70**	9.46**	-5.13	11.01**	5.30	4.32	2.30	29.03**	8.26	14.73
16	CMS-302A × PKV-105R	7.44**	2.84	-2.95	13.56**	7.72*	6.14	4.87*	35.53**	13.71	20.50*
17	CMS-138A × AKSF-5R	23.68**	22.45**	-4.36	11.91**	6.15	-23.24**	-25.37**	-5.78**	-20.95**	-16.23**
18	CMS-138A × AKSF-11R	14.76**	10.82**	-13.45	1.28	-3.93	-16.98**	-20.20**	3.14	-13.46*	-8.30*
19	CMS-138A × AKSF-14R	11.25**	7.90*	-10.32	4.94	-0.46	-2.21	-9.15*	8.33	-9.10	-3.68
20	CMS-138A × 3/147R	9.94**	2.45	-7.35	8.42*	2.83	-12.10**	-16.24**	10.27	-7.48	-1.96
21	CMS-138A × 3/148R	9.87**	-1.92	-2.45	14.15**	8.28*	13.73	3.70*	23.65*	3.75	9.94
22	CMS-138A × RHA-138-2R	28.01**	23.38**	-3.63	12.77**	6.96*	-16.91**	-18.80**	-3.17*	-18.76**	-13.91**
23	CMS-138A × 189/1R	16.74**	10.97**	-3.83	12.54**	6.75*	-10.03*	-10.77*	8.19	-9.22	-3.81
24	CMS-138A × PKV-105R	3.09	-5.79	-11.10	4.03	-1.33	-16.98**	-20.19**	3.14	-13.46*	-8.29*
25	CMS-108A × AKSF-5R	26.70**	18.68**	4.01	21.71**	15.45**	-14.28**	-14.98**	9.11	-8.45	-2.99
26	CMS-108A × AKSF-11R	18.11**	8.07*	-5.29	10.83**	5.13	10.45	10.06**	42.25**	19.35*	26.47**
27	CMS-108A × AKSF-14R	2.62	-0.03	-12.39	2.52	-2.75	-17.46**	-25.82**	-4.80**	-20.13**	-15.36**
28	CMS-108A × 3/147R	13.94**	12.19**	1.45	18.72**	12.60**	-22.94**	-23.91**	0.17	-15.95**	-10.94*
29	CMS-108A × 3/148R	1.79	-4.26	-4.77	11.44**	5.70	5.27	-7.09	19.23	0.04	6.01
30	CMS-108A × RHA-138-2R	26.81**	15.82**	1.51	18.79**	12.67**	7.24	1.17	29.83**	8.94	15.44*
31	CMS-108A × 189/1R	13.24**	12.61**	-1.30	15.49**	9.55**	-25.19**	-27.26**	-6.65**	-21.67**	-17.00**
32	CMS-108A × PKV-105R	12.04**	2.02	-3.73	12.66**	6.86*	-26.16**	-6.32	21.07*	1.59	7.65
33	CMS-102A × AKSF-5R	6.39**	-0.61	-12.38	2.53	-2.75	-12.46**	-14.31**	8.17	-9.24	-3.82
34	CMS-102A × AKSF-11R	17.71**	7.42*	-5.31	10.81**	5.11	-3.11	-6.24	21.18*	1.67	7.74
35	CMS-102A × AKSF-14R	10.87**	7.70*	-5.05	11.11**	5.39	13.88*	5.13**	27.10**	6.64	13.00
36	CMS-102A × 3/147R	6.40**	5.06	-4.99	11.18**	5.45	-16.59**	-19.99**	5.33	-11.62*	-6.35
37	CMS-102A × 3/148R	-14.76	-19.60	-20.03	-6.42	-11.24	18.04**	6.96	29.31**	8.50	14.97
38	CMS-102A × RHA-138-2R	22.54**	11.63**	-1.59	15.16**	9.23**	0.57	-2.37	18.02	-0.97	4.94
39	CMS-102A × 189/1R	10.77**	9.83**	-3.18	13.30**	7.47*	-15.25**	-15.37**	2.61	-13.90**	-8.77*
40	CMS-102A × PKV-105R	8.96**	5.38	-0.56	16.36**	10.37**	-8.75*	-11.70*	14.12	-4.25	1.46
	Range	-14.76 to 38.42	-19.60 to 37.08	-20.03 to 4.01	-6.42 to 21.71	-11.24 to 15.45	-26.16 to 18.04	-27.26 to 10.06	-6.65 to 42.25	-21.67 to 19.35	-17.00 to 26.47
	SE(d)±	1.15	1.88	1.88	1.88	1.88	0.27	0.44	0.44	0.44	0.44

	CD (5%)	2.28	3.73	3.73	3.73	3.73	0.54	0.88	0.88	0.88	0.88
	CD (1%)	3.02	4.93	4.93	4.93	4.93	0.71	1.16	1.16	1.16	1.16

Note: * Significant at 5% level of significance
** Significant at 1% level of significance

Sr. No.	Hybrids	1. Oil content					2. Seed yield plant^{-1}				
		MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)	MP (H_1)	BP (H_2)	Check (H_3)	Check (H_4)	Check (H_5)
1	CMS-248A × AKSF-5R	1.63**	-0.09	-14.15	7.18**	-5.53	59.54**	50.87**	29.29*	23.68	18.99
2	CMS-248A × AKSF-11R	18.87**	9.96**	-5.51	17.96**	3.97**	40.54**	29.46	17.40	12.30	8.04
3	CMS-248A × AKSF-14R	12.12**	4.85**	-9.90	12.48**	-0.86	26.94**	21.78	1.26	-3.14	-6.81
4	CMS-248A × 3/147R	3.68**	2.25**	-9.65	12.79**	-0.59	36.80**	23.76	16.81	11.74	7.50
5	CMS-248A × 3/148R	10.81**	10.58**	-4.58	19.13**	5.00**	31.04**	21.30	8.84	4.11	0.17
6	CMS-248A × RHA-138-2R	-0.56	-6.09	-19.31	0.74	-11.21	54.21**	44.92**	25.87	20.40	15.84
7	CMS-248A × 189/1R	6.31**	3.75**	-6.34	16.92**	3.05**	68.19**	60.03**	35.38*	29.50*	24.59
8	CMS-248A × PKV-105R	-10.61	-15.67	-18.28	2.02**	-10.08	25.85**	11.56	10.26	5.46	1.47
9	CMS-302A × AKSF-5R	15.83**	15.57**	-3.62	20.32**	6.05**	11.74	0.16	8.27	3.57	-0.36
10	CMS-302A × AKSF-11R	19.31**	11.92**	-6.67	16.52**	2.70**	22.79**	12.90	22.05	16.74	12.32
11	CMS-302A × AKSF-14R	3.28**	-2.05	-18.31	1.98**	-10.12	-0.44	-11.93	-4.80	-8.94	-12.39
12	CMS-302A × 3/147R	10.65**	7.55**	-4.98	18.63**	4.56**	45.97**	36.71**	47.78**	41.36**	36.01**
13	CMS-302A × 3/148R	9.82**	7.97**	-6.83	16.32**	2.52**	23.06**	12.61	21.73	16.44	12.03
14	CMS-302A × RHA-138-2R	11.03**	6.36**	-11.30	10.73**	-2.40	21.26*	9.35	18.20	13.07	8.78
15	CMS-302A × 189/1R	4.69**	0.70	-9.09	13.49**	0.03	30.28**	16.12	25.52	20.07	15.52
16	CMS-302A × PKV-105R	3.26**	-3.94	-6.92	16.20**	2.42**	27.76**	22.28	32.19*	26.45*	21.66
17	CMS-138A × AKSF-5R	10.21**	7.09**	-11.10	10.99**	-2.17	0.25	-11.62	-0.76	-5.08	-8.67
18	CMS-138A × AKSF-11R	30.72**	26.33**	-1.06	23.52**	8.87**	3.97	-6.03	5.52	0.93	-2.89
19	CMS-138A × AKSF-14R	11.70**	9.19**	-14.49	6.75**	-5.91	2.06	-11.18	-0.26	-4.60	-8.21
20	CMS-138A × 3/147R	7.52**	1.42*	-10.40	11.86**	-1.40	22.51**	12.75	26.60	21.10	16.51
21	CMS-138A × 3/148R	9.68**	4.61**	-9.73	12.70**	-0.67	-3.87	-13.52	-2.90	-7.12	-10.64
22	CMS-138A × RHA-138-2R	19.87**	18.38**	-7.29	15.75**	2.02**	17.61*	4.29	17.11	12.02	7.77
23	CMS-138A × 189/1R	17.37**	9.59**	-1.07	23.51**	8.86**	18.79*	4.15	16.94	11.86	7.62
24	CMS-138A × PKV-105R	12.21**	1.45**	-1.69	22.73**	8.17**	17.04*	10.03	23.55	18.18	13.70
25	CMS-108A × AKSF-5R	6.99**	0.60	-16.48	4.27**	-8.10	52.33**	44.05**	38.51**	32.49*	27.47*
26	CMS-108A × AKSF-11R	13.06**	13.02**	-17.38	3.14**	-9.09	47.07**	42.89**	37.40**	31.42*	26.45*
27	CMS-108A × AKSF-14R	19.76**	18.40**	-11.45	10.55**	-2.56	34.56**	25.45	20.63	15.39	11.02
28	CMS-108A × 3/147R	11.17**	1.58**	-10.25	12.04**	-1.25	32.32**	31.10*	26.06	20.58	16.01
29	CMS-108A × 3/148R	4.63**	-3.37	-16.61	4.10**	-8.25	58.08**	52.80**	46.93**	40.54**	35.22**
30	CMS-108A × RHA-138-2R	5.88**	3.61**	-20.87	-1.21	-12.92	27.49**	21.32	16.66	11.59	7.36
31	CMS-108A × 189/1R	9.83**	-0.62	-10.29	12.00**	-1.28	51.09**	42.01**	36.55**	30.62*	25.67*
32	CMS-108A × PKV-105R	-14.72**	-8.09	-10.94	11.19**	-2.00	-18.20	10.91	9.62	4.85	0.88
33	CMS-102A × AKSF-5R	-4.21	-5.41	-19.45	0.56	-11.36	64.89**	56.57**	49.25**	42.76**	37.35**
34	CMS-102A × AKSF-11R	14.72**	6.57**	-9.24	13.30**	-0.14	19.50*	16.59	11.14	6.31	2.28
35	CMS-102A × AKSF-14R	22.75**	15.28**	-1.83	22.56**	8.03**	14.96	7.61	2.58	-1.88	-5.59
36	CMS-102A × 3/147R	2.21**	0.36	-11.33	10.70**	-2.43	46.19**	45.47**	38.67**	32.64*	27.61*
37	CMS-102A × 3/148R	3.53**	2.85**	-11.25	10.80**	-2.34	-22.26	-24.54	-28.06	-31.19	-33.80
38	CMS-102A × RHA-138-2R	2.32**	-2.96	-17.36	3.17**	-9.06	31.83**	25.98	20.09	14.87	10.51
39	CMS-102A × 189/1R	8.30**	5.24**	-5.00	18.60**	4.53**	47.01**	38.74**	32.25*	26.50*	21.71
40	CMS-102A × PKV-105R	7.09**	0.60	-2.52	21.70**	7.26**	33.58**	31.21*	29.68*	24.04	19.35
	Range	-14.72 to 30.72	-15.67 to 26.33	-20.87 to -1.06	-1.21 to 23.52	-12.92 to 8.87	-22.26 to 68.19	-24.54 to 60.03	-28.06 to 49.25	-31.19 to 42.76	-33.8 to 37.35
	SE(d)±	0.12	0.19	0.19	0.19	0.19	0.89	1.45	1.45	1.45	1.45
	CD (5%)	0.24	0.39	0.39	0.39	0.39	1.76	2.87	2.87	2.87	2.87
	CD (1%)	0.31	0.51	0.51	0.51	0.51	2.33	3.80	3.80	3.80	3.80

Note: * Significant at 5% level of significance
** Significant at 1% level of significance

CMS-102A × AKSF-5R (56.57%) and CMS-108A × 3/148R (52.80%). The hybrid CMS-302A × AKSF-11R (-18.78%) followed by CMS-302A × AKSF-14R (-18.23%) and CMS-138A × 189/1R (-16.96%) recorded highest significant negative heterobeltiosis for days to 50% flowering. The hybrid CMS-248A× PKV-105 R (16.69%) exhibited highest positive heterobeltiosis for head diameter followed by CMS-108A × AKSF-5R (15.55%) and CMS-108A × AKSF-11R (15.43%). The hybrids CMS-138A × AKSF-14R (70.86%) exhibited significant maximum positive heterobeltiosis for 100 seed weight followed by CMS-108A × AKSF-14R (41.81%) and CMS-102A × AKSF-5R (41.28%) respectively. Highest heterobeltiosis for volume weight was exhibited by the hybrid CMS-102A × AKSF-14R (17.83%) followed by CMS-108A × RHA-138-2R (14.78%) and CMS-108A × AKSF-14R (14.77%). The hybrid CMS-108A × 189/1R (-27.26%), exhibited highest significant negative heterosis for hull content followed by CMS-108A × AKSF-14R (-25.82%) and CMS-138A × AKSF-5R (-25.37%).

In case of standard heterosis, 12 hybrids recorded significantly superior standard heterosis over the best check LSFH-171 for seed yield plant^{-1}. The hybrid CMS-102A × AKSF-5R (49.25%), CMS-302A × 3/147R (47.78%), CMS-108A × 3/148R (46.93%) and CMS-102A × 3/147R (38.67%) recorded significant positive useful heterosis over the best check LSFH-171 for seed yield plant^{-1}. The sunflower hybrids, CMS-138A × 189/1R (-14.46%), CMS-138A × PKV-105R (-13.86%) and CMS-102A × PKV-105R (-13.25%) recorded significantly lowest days to 50% flowering over the best check DRSH-1. The hybrid, CMS-108A × AKSF-5R (18.64%) exhibited maximum positive standard heterosis for head diameter followed by CMS-108A × AKSF-11R (18.52%) and CMS-102A × RHA-138-2R (18.20%). The hybrids CMS-102A × AKSF-5R (51.06%), CMS-102A × RHA-138-2R (44.36%), CMS-108A × AKSF-11R (41.30%) and CMS-108A × 3/148R (40.28%) recorded significant maximum standard heterosis for 100 seed weight over the best check LSFH-171. Maximum standard heterosis in negative direction for hull content showed by the hybrids, CMS-108A × 189/1R (-21.67) followed by CMS-138A × AKSF-5R (-20.95%) and CMS-108A × AKSF-14R (-20.13%) over the best check PDKVSH-952.

The hybrid CMS-102A × AKSF-5R recorded highest heterosis and found to be statistically at par with the hybrids CMS-108A × 3/148R and CMS-102A × 3/147R over all the three checks. This hybrid CMS-102A × AKSF-5R also displayed the highest standard heterosis for 100 seed weight over all the three checks. This indicated that the highest standard heterosis for seed yield in this hybrid may be due the standard heterosis for 100 seed weight.

Conclusions

The hybrids CMS-102A × AKSF-5R and CMS-108A × AKSF-11R having high seed yield also recorded high mean values for 100 seed weight and head diameter. However, out of these hybrids, the hybrid CMS-102A × AKSF-5R was found to be more promising as it showed highest standard heterosis over all the three checks and may be commercially exploited after confirmation of its performance in large multilocation trials.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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