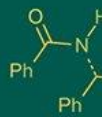


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Diallel analysis of heterosis and combining ability for chlorophyll content across growth stages in okra [*Abelmoschus esculentus* (L.) Moench]

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Abstract

Chlorophyll content governs photosynthetic efficiency and is increasingly recognised as a nutritionally relevant trait in okra yet its genetic architecture has received little attention relative to yield and fruit-quality traits. To address these 9 genetically diverse okra parents were crossed in a full 9×9 diallel excluding self-crosses, producing 36 direct F_1 hybrids and their 36 reciprocals. Along with the parents and 3 commercial checks these were evaluated in a randomized block design with 2 replications during the spring summer season. Leaf chlorophyll content was recorded with a SPAD 502 Plus at 30, 60, 90 and 100 days after sowing and the resulting data were used to estimate heterosis and combining ability. Analysis of variance revealed significant treatment differences at 30 and 100 days after sowing and highly significant F_1 versus reciprocal mean squares at every stage pointing to a significant reciprocal effect, indicating a possible maternal or other parent of origin contribution to chlorophyll expression. Partitioning of hybrid variance by Griffing's diallel model showed that general combining ability mean squares consistently exceeded specific combining ability mean squares establishing the predominance of additive gene action which was most pronounced at the seedling stage and progressively decreases as the crop matures. This confirmed that additive gene action dominates the inheritance of this trait and it dominates most heavily at the seedling stage gradually due to non-additive gene effects as the crop matures. Two parents OL-3 and OL-8 stood out as the best general combiners through the vegetative to flowering period while Okra line-2 emerged as the outstanding combiner for chlorophyll retention at full maturity. Among the 72 hybrids tested OL-3 $\times$ OL-5 recorded the highest chlorophyll content at maturity backed by the strongest positive specific combining ability effect and standard heterosis of 58.5 to 87.4 percent over the commercial checks. The reciprocal cross OL-6 $\times$ OL-1 also produced a significant positive specific combining ability effect further highlighting the importance of maternal inheritance. These findings indicate that recurrent selection exploiting additive variance combined with hybrid development using OL-3, OL-8 and OL-2 as base parents and OL-3 $\times$ OL-5 as a promising hybrid combination offers a practical route to improving chlorophyll content and by extension the photosynthetic and nutritional quality of okra.

Keywords: *Abelmoschus esculentus*, chlorophyll content, combining ability, diallel analysis, heterosis, SPAD meter

Introduction

Okra [*Abelmoschus esculentus* (L.) Moench] is one of the most widely grown warm season vegetables across the tropics and sub tropics and India alone contributes more than 70 percent of the global okra production^[1]. The immature fruits are valued not only as a low-calorie vegetable but as a functional food being a rich source of dietary fibre, mucilage, folate, vitamin C and minerals such as calcium and potassium together with bioactive secondary metabolites including flavonoids and phenolics^[1, 2]. Beyond the fruit the pigment profile of the vegetative tissue itself has attracted growing attention because Chlorophyll, the principal photosynthetic pigment, contributes to photosynthetic carbon assimilation and dry matter accumulation and is also positively associated with several quality attributes of the harvested produce including green colour intensity, ascorbic acid content and overall antioxidant capacity^[3]. Higher chlorophyll levels have been associated with photosynthetic activity and several agronomic and biochemical attributes in okra suggesting that chlorophyll content may have value as a physiological selection criterion^[3, 4].

These observations highlight chlorophyll content as a potentially useful breeding trait rather than solely a physiological indicator; however, its genetic control in okra remains insufficiently characterized.

Despite this relevance, the genetics of chlorophyll content in okra remains poorly characterised. Most reported studies have quantified chlorophyll only as one of several biochemical descriptors used to profile germplasm diversity or to compare genotypes for nutritional quality without examining how the trait is inherited [3, 4, 5, 6, 16]. Systematic genetic insights through mating designs that partition heritable variation into its additive and non-additive components has instead been reserved almost exclusively for fruit yield, earliness and morphological traits [7]. Diallel mating first formalised for combining ability analysis by Sprague and Tatum [8] and later developed statistically by Hayman [9] and Griffing [10] remains the design of choice for such insights because it allows every parent to be crossed with every other parent generating a complete matrix of general combining ability (GCA) which reflects the additive breeding value of a parent averaged across all its crosses and specific combining ability (SCA) which captures the deviation of a particular cross from the sum of its parental GCA values and is attributed largely to dominance and epistatic interaction [8, 10, 11]. When reciprocal crosses are included as in Griffing's Method I the design additionally permits detection of maternal or cytoplasmic effects which are frequently overlooked in half diallel studies but can materially influence pigment traits governed in part by plastid encoded genes. Heterosis the superiority of the F_1 over its parents or over existing commercial standards, complements combining ability analysis by quantifying the immediately exploitable hybrid vigour and its magnitude relative to GCA and SCA variances provides an independent check on the relative importance of additive versus non-additive gene action [12].

This study was undertaken to address this gap by recording chlorophyll content at four growth stages from the seedling phase to harvest across a full diallel set in okra. The specific aims were to work out how much heterosis exists for chlorophyll content relative to the better parent, the best parent and two commercial checks and second to break down the genetic variance among the hybrids into general combining ability, specific combining ability and reciprocal components using Griffing's Method I, Model I and to pick out the parents and cross combinations best suited to recurrent selection or hybrid breeding aimed at lifting both the photosynthetic capacity and the nutritional quality of okra.

Materials and Methods

The trial was carried out at the Department of Vegetable Science, College of Horticulture, Bagalkot during the spring-summer season of 2025. Nine okra genotypes were selected as parents from the working germplasm collection of the University of Horticultural Sciences, Bagalkot including one local landrace collected from Dandipet, Kushalnagar, Karnataka. The nine parents OL-1, OL-2, OL-3, OL-4, OL-5, OL-6, OL-7, OL-8 and OL-9 were crossed in every possible combination excluding selfs, during the earlier season. This full diallel produced 36 direct F_1 combinations ($P_i \times P_j$, $i < j$) and their 36 reciprocals for 72 hybrids in total.

The nine parents, 72 F_1 hybrids (36 direct and 36 reciprocal) and three commercial checks (Arka Nikita from ICAR-IIHR Bengaluru, Mahyco-10 from Mahyco Seeds and Radhika from Advanta Seeds constituting 84 genotypes in all were evaluated in a randomized block design with two replications. Each entry was represented by 30 plants per replication at a spacing 60 cm between rows and 45 cm between plants and standard agronomic and plant protection practices were followed uniformly across the trial.

Chlorophyll content was measured non-destructively with a SPAD 502 Plus meter (Konica Minolta, Osaka, Japan) an instrument that estimates relative chlorophyll from how differently red and infrared light pass through intact leaf tissue [13]. Readings were taken at 30, 60, 90 and 100 days after sowing (DAS) on 5 randomly chosen healthy plants in each plot. On every plant one fully expanded leaf from the middle of the canopy was selected and 3 SPAD readings were taken at different points on the lamina keeping clear of the midrib and major veins and these 3 readings were averaged to give the SPAD value for that leaf. The five plant-wise averages within a plot were then averaged again to arrive at the plot's chlorophyll value. All readings were recorded between 09:00 and 11:00 h to minimise diurnal variation in stomatal and pigment status. Higher SPAD values indicate greater relative leaf chlorophyll content and greener foliage. [13, 14]

Plot means were subjected to analysis of variance appropriate to a randomized block design and the treatment sum of squares was broken down further into parents, hybrids (direct F_1 s and reciprocals) and the parents versus hybrids and F_1 s versus reciprocals contrasts. Combining ability was estimated following Griffing's Method I, Model I, which includes parents, direct F_1 hybrids and reciprocal crosses and partitions the diallel variation into general combining ability, specific combining ability and reciprocal effects. GCA effects (g_i) for each parent and SCA effects (s_{ij}) for each direct and reciprocal cross were calculated and tested for significance against standard errors and critical difference values derived from the pooled error mean square.

Heterosis was calculated in 3 ways as (i) heterosis over the better parent expressed relative to the higher performing of the two parents involved in a given cross (ii) heterosis over the best parent expressed relative to the single highest performing parent in the entire diallel set for the trait concerned and (iii) standard heterosis expressed relative to each of the two commercial hybrid checks (Arka Nikita, designated CC1 and Mahyco-10 designated CC2) that recorded the higher chlorophyll content among the three checks at each growth stage. In every case heterosis was simply the percentage by which the F_1 mean deviated from the relevant reference mean and significance was judged against a critical difference calculated from the pooled error mean square and the tabulated t value at the appropriate error degrees of freedom. All analyses of variance, combining ability calculations and heterosis estimates were carried out in TNAU STAT and R (4.3.3) using the agricolae package for the design analysis and standard Griffing's Method I diallel routines for the genetic partitioning.

Results

Analysis of variance

Mean squares from the analysis of variance for chlorophyll content at each of the four growth stages are presented in

Table 1. Treatment mean squares were significant at 30 DAS and highly significant at 100 DAS but did not attain significance at 60 and 90 DAS indicating that overall genotypic differentiation for chlorophyll content became statistically detectable mainly at the seedling stage and again as the crop approached physiological maturity. Mean squares for parents were significant at 90 and 100 DAS and for hybrids at 100 DAS following the same pattern. The F_1 versus reciprocal contrast, which was significant or highly significant at every single stage (30 DAS: 172.78*; 60 DAS: 766.49**; 90 DAS: 479.20**; 100 DAS: 528.36**) while the parents versus hybrids was significant at 90 and 100 DAS. A consistently significant F_1 versus reciprocal mean square across the entire crop cycle tells us that it mattered which parent was used as the female in a given cross indicating that cross direction influenced chlorophyll expression and that maternal or other reciprocal effects may contribute to its inheritance in how chlorophyll content is passed on.

Combining ability analysis of variance

Partitioning of the hybrid mean square by Griffing's Method I (Table 2) showed that GCA mean squares were considerably larger than the corresponding SCA mean squares at every growth stage. The GCA/SCA ratio worked out to 47.30 at 30 DAS, 3.10 at 60 DAS, 3.47 at 90 DAS and 2.31 at 100 DAS comfortably above one throughout which confirms that additive gene action is the main factor shaping chlorophyll content in this material. The contribution of additive genetic effects was greater at the seedling stage and while it never disappears gradually loses to non-additive effects (dominance and epistasis) as the crop moves toward maturity. Reciprocal mean squares were also significant relative to the SCA mean squares at all four stages validating the significant F_1 versus reciprocal contrast already seen in the overall analysis of variance (Table 1) provided further evidence that cross direction influenced chlorophyll expression.

Per se performance of parents, hybrids and checks

Mean chlorophyll content of the parents ranged from 28.26 (OL-6) to 57.46 SPAD units (OL-2) at 100 DAS, with OL-2, OL-3 (52.06) and OL-8 (47.86) consistently among the highest performing parents across the later growth stages (Table 3). Among the 72 hybrids values at 100 DAS spread from as low as 28.05 (OL-5 $\times$ OL-8) to a high of 56.59 in OL-3 $\times$ OL-5 the best performing hybrid overall. Close behind were the reciprocal cross OL-8 $\times$ OL-3 (55.66) the reciprocal cross OL-2 $\times$ OL-1 (54.62) and OL-1 $\times$ OL-8 (53.83). All of the top-performing hybrids exceeded the chlorophyll content of the commercial checks at 100 DAS. Arka Nikita, Mahyco-10 and Radhika recorded 35.70, 30.20 and 33.80 SPAD units, respectively. These results demonstrated substantial differences between the selected experimental hybrids and the commercial checks for chlorophyll content under the conditions of the present experiment.

Heterosis

The relatively small or negative heterosis observed over the better and best parents, together with the large positive heterosis over the commercial checks, can be explained by the comparatively high chlorophyll content of some parental genotypes, particularly OL-2 and OL-3. (Table 4). When

parental performance is already high, the magnitude of heterotic advantage over the parental value is expected to be limited. In contrast, the substantially lower chlorophyll content of the commercial checks provided greater scope for the experimental hybrids to exhibit positive standard heterosis. This difference emphasizes the importance of defining the reference population when interpreting heterosis estimates.

General combining ability

Table 5 lists the GCA effects of the 9 parents at each growth stage. At 60 DAS only two parents combined significantly in the positive direction *i.e.* OL-3 ($g_i = 3.073$, $p < 0.01$) and OL-8 ($g_i = 2.203$, $p < 0.05$). By 90 DAS, OL-2 ($g_i = 2.479$, $p < 0.01$) and OL-3 ($g_i = 1.809$, $p < 0.05$) combined significantly in the positive direction while OL-7 ($g_i = -2.656$, $p < 0.01$) and OL-6 ($g_i = -1.946$, $p < 0.05$) combined significantly in the negative direction. At 100 DAS, OL-2 emerged as the outstanding general combiner ($g_i = 3.963$, $p < 0.01$) none of the other parents managed a significant positive effect at this stage whereas OL-7 ($g_i = -2.968$, $p < 0.05$), OL-6 ($g_i = -2.771$, $p < 0.05$) and OL-4 ($g_i = -2.495$, $p < 0.05$) were significant in the undesirable negative direction. Taking the four stages together, OL-3 and OL-8 were the most positive combiners through the vegetative to flowering phase while OL-2 was the most favourable general combiner for chlorophyll content at physiological maturity and OL-7 exhibited consistently negative GCA effects across the evaluated growth stages and was therefore an unfavourable general combiner for chlorophyll improvement.

Specific combining ability and promising cross combinations

Specific combining ability effects considered together with *per se* hybrid performance identified a small number of cross combinations of clear breeding value (Table 6). OL-3 $\times$ OL-5 produced the highest and most significant positive SCA effect at 100 DAS ($s_{ij} = 10.00$, $p < 0.01$), matching its status as the top performing hybrid overall. The cross involved one parent with significant positive GCA (OL-3) and another parent with nonsignificant GCA (OL-5), suggesting that favourable non-additive interactions contributed to hybrid performance. OL-6 $\times$ OL-1 exhibited a significant positive SCA effect at 100 DAS, indicating favourable specific combining ability; however, its *per se* performance was comparatively low, suggesting that the cross may be of genetic interest rather than an immediately promising hybrid for high chlorophyll content. Several crosses involving OL-8 most notably OL-8 $\times$ OL-2 and OL-8 $\times$ OL-5 in their reciprocal direction showed significant negative SCA and reciprocal effects at 90 and 100 DAS despite OL-8 itself being a good general combiner during the vegetative phase showing that superior parental GCA does not guarantee a correspondingly superior hybrid and that reciprocal testing is essential to fully exploit this trait.

Discussion

The pattern of significance in the overall analysis of variance, with treatment differences confined largely to the seedling (30 DAS) and near maturity (100 DAS) stages while the F_1 versus reciprocal contrast stayed significant throughout the crop cycle. This suggests that chlorophyll accumulation is kept on a fairly tight genetic and

physiological buffering during the mid vegetative phase (60-90 DAS) when the canopy is expanding rapidly and only becomes more genetically differentiated once the crop nears reproductive maturity and leaves begin to senesce. The F_1 versus reciprocal mean squares stayed significant throughout together with substantial reciprocal effect mean squares in the combining ability analysis are noteworthy because reciprocal effects are rarely examined in okra genetics most published diallel studies having employed half diallel designs that discard reciprocal information altogether [7]. Chloroplasts pass down through the maternal line in most flowering plants and chlorophyll synthesis depends on nuclear and plastid genes working in performance because reciprocal differences can arise from maternal, cytoplasmic or other parent-of-origin effects, the present results demonstrate an effect of cross direction but do not by themselves establish a specific mode of inheritance.

The GCA/SCA mean-square ratio exceeded unity at all four growth stages, ranging from 47.30 at 30 DAS to 2.31 at 100 DAS [10, 11]. The greater magnitude of GCA relative to SCA indicates a predominant contribution of additive genetic effects to variation in chlorophyll content in the evaluated material. The marked reduction in the ratio with crop advancement suggests that the relative contribution of non-additive genetic effects increased toward maturity, although GCA variation remained greater than SCA variation at all stages. This pattern is consistent with reports of both additive and non-additive genetic effects for yield and quality-related traits in okra [7, 15]. The predominance of GCA variation suggests that selection-based breeding approaches may be useful for improving chlorophyll content, while the identification of crosses with favourable SCA effects indicates additional scope for hybrid breeding. OL-3 and OL-8 exhibited favourable GCA effects during the vegetative and flowering stages, whereas OL-2 showed the most favourable GCA effect at 100 DAS. The favourable GCA effects of these parents were accompanied by comparatively high per se chlorophyll values at the corresponding stages, suggesting that these genotypes possess useful genetic potential for chlorophyll improvement. However, the correspondence between per se

performance and GCA was not complete across all stages, indicating that parental phenotypic performance alone may not reliably predict combining ability. Therefore, GCA evaluation remains important for identifying parents with favourable breeding value [7].

From a hybrid-breeding perspective, OL-3 $\times$ OL-5 was particularly promising because it exhibited the highest chlorophyll content at 100 DAS, the highest positive SCA effect and substantial standard heterosis over the commercial checks. The cross involved OL-3, which exhibited a significant positive GCA effect at earlier growth stages and OL-5, which showed a nonsignificant GCA effect, suggesting that favourable non-additive interactions contributed to the superior performance of the hybrid. Such combinations may be useful for exploiting heterosis in the F_1 generation. However, the consistency of hybrid performance should be evaluated across environments and seasons before considering the cross for further breeding or varietal development. The reciprocal combination OL-6 $\times$ OL-1 also exhibited a significant positive SCA effect at 100 DAS, indicating that the direction of crossing may influence hybrid performance for chlorophyll content. The occurrence of small or negative heterosis over the better and best parents, coupled with large and highly significant heterosis over the commercial checks, can be attributed to the relatively high chlorophyll content of some of the parental genotypes, particularly OL-2 and OL-3, which reduced the scope for further improvement over the parental values. Leaf chlorophyll content has already been tied to both dry matter accumulation through photosynthesis and to fruit quality traits such as ascorbic acid and antioxidant capacity in okra [3, 4]. The practical implication of these findings extends beyond agronomic vigour to the nutritional value of the harvested produce. Parents and hybrids exhibiting favourable chlorophyll content together with desirable combining ability may therefore serve as useful genetic resources for breeding programmes aimed at improving physiological efficiency in okra. However, the potential association between enhanced chlorophyll content and nutritional quality should be evaluated through direct assessment of relevant biochemical and nutritional traits [1, 2].

Table 1: Analysis of variance (mean sum of squares) for chlorophyll content at four growth stages in okra

Source of variation	df	Chlorophyll @ 30 DAS	Chlorophyll @ 60 DAS	Chlorophyll @ 90 DAS	Chlorophyll @ 100 DAS
Replications	1	3734.07	8884.46	9264.89	7297.53
Treatments	80	39.86**	64.33	51.49	106.33**
Parents	8	46.01	46.12	87.52*	140.14*
Hybrids	71	41.07	69.57	48.84	101.16*
Parents vs Hybrids	1	6.84	98.02	184.36*	394.42*
F_1 s	35	40.69	84.68*	50.74	110.75*
Reciprocals	35	41.57	51.76	45.41	91.22
F_1 s vs Reciprocals	1	172.78*	766.49**	479.20**	528.36**
Error	80	29.96	53.30	36.31	59.51

*, ** Significant at 5% and 1% levels, respectively (tested against error mean square). DAS = days after sowing.

Table 2: Analysis of variance for combining ability (Griffing's Method I) and GCA/SCA ratio for chlorophyll content

Source of variation	df	Chlorophyll @ 30 DAS	Chlorophyll @ 60 DAS	Chlorophyll @ 90 DAS	Chlorophyll @ 100 DAS
GCA	8	33.58**	57.40**	57.19**	97.55**
SCA	36	0.71	18.53	16.47	42.20*
Reciprocal effects	36	27.41**	42.57*	28.95**	51.97*
Error	80	15.07	24.89	16.83	28.98
GCA/SCA ratio	—	47.30	3.10	3.47	2.31

*, ** Significant at 5% and 1% levels

Table 3: *Per se* performance (SPAD units) of selected parents, top-performing hybrids and commercial checks for chlorophyll content

Genotype	30 DAS	60 DAS	90 DAS	100 DAS
OL-1	48.38	45.76	46.62	43.57
OL-2	46.27	47.13	59.76	57.46
OL-3	44.63	57.16	55.67	52.06
OL-4	35.00	50.15	45.64	40.79
OL-5	40.52	51.97	46.47	40.87
OL-6	39.53	53.62	38.94	28.26
OL-7	36.17	46.22	42.82	38.76
OL-8	43.77	59.60	53.77	47.86
OL-9	36.57	50.79	46.34	41.42
OL-3 × OL-5	40.86	47.31	54.77	56.59
OL-8 × OL-3 (recip.)	47.07	60.47	59.23	55.66
OL-2 × OL-1 (recip.)	50.52	48.33	53.18	54.62
OL-1 × OL-8	47.42	46.45	55.36	53.83
OL-7 × OL-2 (recip.)	39.91	51.22	53.66	52.73
OL-8 × OL-2 (recip.)	43.47	52.75	54.26	52.50
OL-6 × OL-8 (recip.)	48.10	61.57	56.58	50.81
Commercial check 1 (Arka Nikita)	37.93	54.35	48.10	35.70
Commercial check 2 (Mahyco-10)	41.04	54.12	42.10	30.20
Commercial check 3 (Radhika)	41.51	50.90	43.60	33.80
SE ±	3.87	5.16	4.26	5.46
CD @ 5%	10.89	14.52	11.99	15.34
CD @ 1%	14.43	19.25	15.89	20.34

Only the parents and the six highest-performing hybrids at maturity and the checks are presented here.

Table 4: Heterosis (%) over better parent (BP), best parent (BTP) and commercial checks (CC1, CC2) at 90 and 100 DAS for the most promising hybrids

Cross	BP (90 DAS)	BTP (90 DAS)	CC1 (90 DAS)	CC2 (90 DAS)	CC1 (100 DAS)	CC2 (100 DAS)
OL-3 × OL-5	-1.62	-8.35	13.87*	30.10**	58.52**	87.39**
OL-8 × OL-3 (recip.)	6.39	-0.89	23.14**	40.69**	55.90**	84.29**
OL-2 × OL-1 (recip.)	-11.01	-11.01	10.56	26.32**	52.98*	80.84**
OL-1 × OL-8	2.96	-7.36	15.09*	31.50**	50.80*	78.26**
OL-7 × OL-2 (recip.)	-10.21	-10.21	11.56	27.46**	47.71**	74.61**
OL-8 × OL-2 (recip.)	-9.20	-9.20	12.81	28.88**	47.06**	73.84**
OL-3 × OL-2 (recip.)	-14.26*	-14.26*	6.53	21.71**	43.48*	69.61**
OL-6 × OL-8 (recip.)	5.23	-5.32	17.63*	34.39*	42.33**	68.25**
OL-1 × OL-5	13.00	-11.85*	9.52	25.13**	40.58	66.18*
OL-1 × OL-6	16.97*	-8.75	13.37	29.52**	40.29	65.83*

*, ** Significant at 5% and 1% levels, respectively. BP = heterosis over better parent; BTP = heterosis over best parent in the diallel set; CC1 = Arka Nikita; CC2 = Mahyco-10.

Table 5: General combining ability (GCA) effects of parents for chlorophyll content at four growth stages

Parent	30 DAS	60 DAS	90 DAS	100 DAS
OL-1	1.521	-1.174	0.582	0.519
OL-2	0.633	-0.066	2.479**	3.963**
OL-3	0.999	3.073**	1.809*	1.375
OL-4	0.729	1.381	-1.230	-2.495*
OL-5	-0.432	-0.968	-0.276	0.391
OL-6	-1.040	-0.283	-1.946*	-2.771*
OL-7	-1.931*	-1.559	-2.656**	-2.968*
OL-8	1.431	2.203*	1.730	1.567
OL-9	-1.909*	-2.013	-0.493	0.419
SE (gi)	0.44	0.51	0.42	0.55
CD @ 5%	0.86	1.11	0.91	1.20
CD @ 1%	1.29	1.66	1.37	1.79

*, ** Significant at 5% and 1% levels, respectively.

Table 6: Specific combining ability (SCA) effects at 100 DAS and *per se* performance of the most promising hybrids for chlorophyll content

Cross	Direction	SCA effect (100 DAS)	<i>Per se</i> (100 DAS)	Remark
OL-3 × OL-5	Direct	10.00**	56.59	Best specific combiner; good × average GCA parents
OL-6 × OL-1	Reciprocal	8.62*	32.84	Significant positive reciprocal (maternal) effect
OL-2 × OL-4	Direct	-3.15	37.83	Average combination
OL-8 × OL-2	Reciprocal	-12.01**	52.50	High <i>per se</i> despite negative SCA; driven by high mid parent value
OL-8 × OL-5	Reciprocal	-10.45**	48.95	Significant negative reciprocal effect
OL-7 × OL-2	Reciprocal	-10.15**	52.73	High <i>per se</i> despite negative SCA; driven by high mid parent value

*, ** Significant at 5% and 1% levels, respectively. SE(sij) = 2.57, CD @ 5% = 5.14, CD @ 1% = 6.80 for direct crosses; corresponding values for reciprocal effects were SE = 2.57, CD @ 5% = 5.14, CD @ 1% = 6.80 (100 DAS).

Conclusion

The results indicated a predominant contribution of additive genetic effects to chlorophyll content, with a smaller but increasing relative contribution of non-additive effects toward maturity. Significant reciprocal effects across growth stages further indicated that cross direction influenced chlorophyll expression, suggesting possible maternal or other parent of origin contributions. OL-3 and OL-8 could therefore serve as useful genetic resources for population improvement during the vegetative and flowering stages, whereas OL-2 appeared particularly promising for maintaining chlorophyll content at physiological maturity. OL-7 which combined poorly throughout is best left out of crosses where this trait matters. For those looking to develop hybrids now OL-3 × OL-5 is the combination that delivered on every front highest chlorophyll at maturity the strongest positive SCA effect and heterosis of 58 to 87 percent over commercial checks and is recommended for multi-location testing prior to potential commercial release. OL-6 × OL-1 when OL-6 is used as the female parent offers a second viable option where the reciprocal cross direction is applied purposely. Breeding strategies that combine early-generation selection for additive merit among the identified elite general combiners with targeted hybridisation using the specific combinations highlighted here should provide an efficient route to okra genotypes with enhanced chlorophyll content and potentially improved source capacity; associated nutritional traits should be validated independently.

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