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ASSESSING HETEROSIS FOR YIELD AND YIELD COMPONENTS IN OKRA (*Abelmoschus esculentus*)

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ABSTRACT

This study evaluates heterosis, heterobeltiosis, and standard heterosis for yield and key agronomic traits in okra (Abelmoschus esculentus L. Moench) using hybrids from a line × tester mating design to identify superior hybrid combinations for breeding programs. Twenty-one F1 hybrids were developed from seven diverse okra lines and three testers. The hybrids and their parental lines were evaluated in a randomized complete block design (RCBD) with three replications at the experimental farm of Al Zaeim Al Azhari University, Sudan. Data on pod length, number of pods per plant, pod fresh weight, pod dry weight, dry-to-fresh weight ratio, hundred-seed weight, and yield per plant were collected and analyzed for heterotic effects using standard statistical procedures, including ANOVA and t-tests. Significant variation ($p \leq 0.05$) was observed among hybrids and parents for several yield-related traits, confirming the presence of genetic diversity. HSD2543 × Sinnar exhibited the highest heterosis for pod length (+18.77%), while HSD2550 × Sinnar recorded the highest number of pods per plant (+33.33%). HSD1840 × Sinnar showed maximum heterosis for pod dry weight (+57.50%), and HSD1835 × Sinnar demonstrated superior yield per plant (+27.36%). Standard heterosis results reinforced the superiority of these hybrids, particularly those involving the tester Sinnar, suggesting its potential as a dominant genetic contributor in hybrid development. The study highlights the potential of heterosis in enhancing okra yield and yield-related traits. Hybrids involving Sinnar as a parent consistently exhibited superior performance, making them promising candidates for further evaluation and commercialization.

Keywords: Okra, heterosis, line × tester analysis, hybrid vigour, yield improvement, Sudan

1. INTRODUCTION

Okra (Abelmoschus esculentus (L.) Moench), commonly known as lady's finger or gumbo, is a nutrient-rich vegetable crop widely cultivated in tropical, subtropical, and warm temperate regions, playing a vital role in food security and nutrition. Originating in Africa, with Ethiopia, Sudan, and West Africa as centres of genetic diversity, okra belongs to the Malvaceae family and thrives in diverse climatic conditions, from humid tropics to arid regions. It is a staple in African agroecological zones, particularly in Nigeria, the largest global producer, and in Sudan, Ghana, Egypt, and Côte d'Ivoire (FAO, 2023). In Sudan, okra is cultivated under rain-fed and irrigated systems, with landraces adapted to local conditions, underscoring its potential for genetic improvement and climate resilience (Abdalla et al., 2023). Okra is highly valued for its nutrient-rich pods, which are a source of vitamins, minerals, and dietary fibre, contributing significantly to food security and nutrition. In Sudan, it is often dried and ground into powder for use in traditional dishes, while its protein- and oil-rich seeds have potential applications in oil extraction and animal feed production (Abdalla et al., 2023).

Heterosis is more commonly observed in naturally cross-pollinated species due to greater genetic diversity. This phenomenon supports the survival of heterozygotes and preserves recessive alleles under natural conditions, contributing to species adaptation and resilience. Despite its agricultural and nutritional significance, okra production faces challenges in achieving optimal yield and resilience. A critical gap exists in understanding heterosis in okra as an often-pollinated crop. It also offers a promising avenue for genetic improvement. Several reports showed that heterosis enhances yield and other desirable traits in okra (Kishor et al., 2013; Reddy et al., 2013; Shwetha et al., 2021a). However, the extent and direction of heterosis vary across crosses and traits, with both positive and negative effects reported (Kumar & Reddy, 2016). The performance of F1 hybrids relative to their parental lines for specific yield components, particularly under diverse agro-ecological conditions is essential for developing high-yielding, climate-resilient okra varieties. This study aims to estimate heterosis, heterobeltiosis, and standard heterosis for yield and yield-related components in 21 F1 hybrids developed through a line × tester mating design involving seven genetically diverse okra lines and three testers (Sinnar, Hejerat, and Clemson Spineless). The research seeks to identify superior hybrid combinations, assess the genetic diversity of parental lines, and provide insights into the potential of heterosis in okra breeding. By addressing these objectives, the study contributes to the development of high-yielding, climate-resilient okra varieties suitable for commercial cultivation and breeding programs.

2. MATERIALS AND METHODS

The study utilized ten genetically divergent parental lines namely; HSD 1835, HSD1834, HSD1839, HSD 2543, HSD 2482, HSD 1840 and HSD 2550 as lines; Sinnar, Hejerat and Clemson

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spineless as testers, to develop 21 F1 hybrids through a line × tester mating design. The parental lines were selected based on their contrasting agronomic traits, such as yield potential, pod characteristics, and adaptability to different agroecological conditions. The crosses were made at the experimental farm of Al Zaeim Al Azhari University, Khartoum North, Sudan. The resulting F1 hybrids, along with their parental lines were evaluated in the subsequent growing season. The trial was laid out in a Randomized Complete Block Design (RCBD) with three replications. Each replication consisted of 31 treatments (21) F1 hybrids, seven parental lines, and three testers. Each plot measured 3 × 3 meters, with three ridges spaced at 60 cm between rows and 30 cm between plants.

Key yield parameters in okra were measured using randomly sampled mature pods at the harvest stage from five random plants in each plot. Ten pods were selected for measurements of pod length, pod fresh weight, and pod dry weight. Pod length was measured using a ruler from the base to the tip, while pod fresh weight was recorded immediately after harvest using a digital balance. For pod dry weight, the sampled pods were dried in an oven at 70°C for 48 hours until a constant weight was achieved, after which they were weighed. The dry-to-fresh weight ratio was calculated as a percentage using the dry and fresh weights of the same pods. The number of pods per plant was determined by counting all mature pods harvested from each plant at the end of the growing season. The number of seeds per pod was measured using ten mature pods, randomly selected, opened, and the seeds counted. Hundred-seed weight was determined by weighing 100 randomly selected seeds using a digital balance. Yield per plant was calculated as the average of the total fresh weight of all pods harvested from five plants. All measurements were performed in triplicate to ensure accuracy and consistency with the experimental design.

The data were analyzed using Analysis of Variance (ANOVA) as described by Gomez & Gomez (1984) using the online software package OPSTAT developed by Sheoran et al., (1998). The analysis was conducted to test the null hypothesis that there are no significant differences between the various F1 populations and their parental lines. A post-hoc test was used to compare means, setting the significance level at $p \leq 0.05 p \leq 0.05$. The characters showing significant differences were subjected to analysis using heterosis formulas (1), (2) and (3).

2.1 Relative heterosis was computed in terms of per cent increase (+) or decrease (−) of the F_1 hybrids against its mid-parent using the following formula by Powers (1944) and Stern (1948)

$$\text{Relative heterosis (MPH)\%} = \frac{F1 - MP}{MP} \times 100 \ldots\ldots\ldots\ldots (1)$$

Where:

F_1 = Mean of the F_1 cross;

MP = Mid-parent.

2.2 Commercial heterosis addresses the economic utility of hybrids, describing their performance relative to a standard commercial check variety. It was emphasized in practical breeding programs aimed at maximizing agricultural productivity (Lamkey & Edwards, 1999). Commercial heterosis is calculated as per the following formula;

$$\text{Standard heterosis (SH)\%} = \frac{F1-SV}{SV} \times 100 \ldots\ldots\ldots (2)$$

Where:

SV = Standard variety value

2.3 Heterobeltiosis was coined by Bitzer et al., (1972) and Fonseca and Patterson (1968). It is estimated in terms of the per cent increase or decrease of the F_1 hybrid over its better parent using the following formula;

$$\text{Heterobeltiosis (BPH)\%} = \frac{F1-BP}{BP} \times 100 \ldots\ldots\ldots..(3)$$

Where:

BP = Better parent value

The significance of relative and standard heterosis was tested with a t-test as suggested by Cochran and Cox (1950) and Wynne et al., (1970), following the formula (4) .

$$t_{ij} = \frac{= F1_{ij} - MP_{ij}/SV}{\sqrt{3/8\,EMS}} \ldots\ldots\ldots.(4)$$

Where:

F_{1ij} = The Mean of the ijth F_1 cross

$M.P_{ij}$ = The mid parent for the ijth cross

SV = The commercial variety value

EMS = Error mean square

The 't_{ij}' value for heterobeltiosis was calculated following the formula suggested by Rasul et al., (2002) formula (5).

$$t_{ij} = \frac{= F1_{ij} - BP_{ij}}{\sqrt{1/2\,EMS}} \ldots\ldots\ldots (5)$$

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Where:

BP_{ij} = Better parent value for the ij^{th} cross;

3. RESULTS AND DISCUSSION

The methodology adopted in this research involves a line × tester mating design with seven lines and three testers, resulting in 21 F1 hybrids. This design is consistent with other studies in okra heterosis breeding, such as Singh et al., (2010); Sharma & Singh (2012); Singh, et al., (2016); Kumar and Reddy (2016), Chaitanya, et al., (2021), who also used a line × tester approach to evaluate heterosis. The use of genetically divergent parental lines is a common strategy to maximize heterosis, as seen in Shwetha et al., (2021a), where diverse parental lines were used to create hybrids with superior traits. However, Kishor et al., (2013) recommended incorporating molecular markers to assess genetic diversity among parental lines to complement phenotypic data in heterosis studies.

Table 1: Mean squares for yield and yield components with parents and hybrids

Source of Variation	Pod length (cm)	Number of Pods per plant	Pod Dry weight (g)	Pod Fresh weight (g)	Dry to Fresh weight ratio (%)	Number of Seeds per Pod	Hundred-seed weight (g)	Yield per Plant (g)
Replication	0.293^{NS}	1.839^{NS}	0.014^{NS}	0.265^{NS}	2.501^{NS}	704.333^{**}	0.323^{NS}	24.795^{NS}
Treatments	1.063^{**}	2.212^{**}	0.012^{**}	0.352^{NS}	5.701^{*}	150.400^{NS}	1.007^{**}	55.563^{**}
Parents	0.290^{NS}	2.444^{**}	0.005^{NS}	0.585^{*}	2.549^{NS}	191.293^{NS}	1.668^{**}	56.015^{**}
Parents vs. Hybrids	0.814^{NS}	2.048^{NS}	0.004^{NS}	0.054^{NS}	0.875^{NS}	127.986^{NS}	3.028^{**}	11.081^{NS}
Hybrids	1.424^{**}	2.116^{**}	0.016^{NS}	0.262^{NS}	7.361^{**}	133.119^{NS}	0.609^{**}	57.584^{**}
Error	0.473	0.883	0.005	0.269	2.957	94.767	0.254	10.302

*Note: Superscript asterisks on the means indicate statistical significance: * for $p \leq 0.05$, ** for $p \leq 0.01$, and NS for not significant.*

The analysis of variance (ANOVA), (table 1), revealed significant differences among treatments for several yield components, indicating substantial genetic variability among the parental lines and hybrids. Highly significant differences ($p \leq 0.01$) were observed for pod length (cm), number of pods per plant, pod dry weight (g), hundred-seed weight (g), and yield per plant (g). Traits like dry-to-fresh weight ratio (%) exhibited significant differences at ($p \leq 0.05$). The lack of significant differences in pod fresh weight (g) and number of seeds per pod suggests that no variation exists between treatments.

Table 2: Mean performance of okra hybrids and parents for yield and yield components

Genotype	Pod length (cm)	Number of Pods per plant	Pod Dry weight (g)	Dry to Fresh weight ratio (%)	Hundred seed weight (g)	Yield per Plant (g)
HSD1835 × Sinnar	5.33^{abc}	5.67^{ab}	0.60^{ab}	12.97^{ab}	6.00^{ab}	27.00^{a}
HSD1835 × Hjerat	4.30^{cdefg}	4.33^{bcdef}	0.47^{cdef}	9.70^{cde}	5.00^{efgh}	18.17^{ghijk}
HSD1835 × Clemson spineless	4.83^{abcde}	5.00^{abcd}	0.57^{abc}	10.53^{bcde}	4.87^{fgh}	20.50^{defghi}
HSD1834 × Sinnar	5.67^{a}	5.33^{abc}	0.47^{cdef}	9.30^{de}	4.87^{fgh}	25.3^{abcd}
HSD1834 × Hjerat	4.47^{bcdefg}	4.00^{cdef}	047^{cdef}	9.37^{de}	4.87^{fgh}	15.60^{ijkl}
HSD1834 × Clemson spineless	4.27^{cdefg}	5.33^{abc}	0.47^{cdef}	9.53^{cde}	5.50^{bcdefg}	$22.77^{abcdefg}$
HSD1839 × Sinnar	4.70^{abcdef}	5.33^{abc}	0.57^{abc}	11.80^{abcd}	5.03^{efgh}	25.90^{abc}
HSD1839 × Hjerat	5.53^{ab}	4.00^{cdef}	0.40^{ef}	8.00^{e}	4.00^{ij}	12.40^{l}
HSD1839 × Clemson spineless	4.87^{abcde}	4.30^{bcdef}	0.43^{def}	8.67^{e}	4.77^{ghi}	18.23^{ghijk}
HSD2543 × Sinnar	5.87^{a}	5.33^{abc}	0.53^{abcd}	10.67^{bcde}	$5.27^{bcdefgh}$	26.47^{ab}
HSD2543 × Hjerat	4.37^{cdefg}	4.00^{cdef}	0.37^{f}	8.97^{e}	4.70^{ghij}	13.33^{kl}
HSD2543 × Clemson spineless	3.63^{fg}	5.00^{abcd}	0.47^{cdef}	9.83^{cde}	4.70^{ghij}	17.20^{hijkl}
HSD2482 × Sinnar	4.47^{bcdefg}	5.67^{ab}	0.43^{def}	9.30^{de}	5.37^{bcdefg}	26.27^{ab}
HSD2482 × Hjerat	4.90^{abcde}	4.00^{cdef}	0.47^{cdef}	9.30^{de}	4.50^{hij}	$20.83^{cdefghi}$
HSD2482 × Clemson spineless	3.57^{g}	4.33^{bcdef}	0.43^{def}	9.47^{de}	5.77^{abcde}	20.53^{defghi}
HSD1840 × Sinnar	3.87^{efg}	5.33^{abc}	0.63^{a}	13.60^{a}	5.10^{defgh}	25.00^{abcde}
HSD1840 × Hjerat	3.57^{g}	3.00^{f}	0.47^{cdef}	10.47^{bcde}	4.83^{gh}	14.87^{jkl}
HSD1840 × Clemson spineless	4.40^{cdefg}	4.33^{bcdef}	0.50^{bcde}	9.77^{cde}	4.47^{hij}	19.90^{efghij}
HSD2550 × Sinnar	5.10^{abcd}	6.00^{a}	0.63^{a}	13.80^{a}	$5.27^{bcdefgh}$	20.37^{defghi}
HSD2550 × Hjerat	5.57^{ab}	3.00^{f}	0.47^{cdef}	9.47^{de}	4.73^{ghi}	$20.73^{cdefghi}$
HSD2550 × Clemson spineless	4.17^{defg}	4.33^{bcdef}	0.53^{abcd}	10.07^{cde}	5.13^{cdefgh}	19.80^{efghij}
HSD1835	4.33^{cdefg}	3.67^{def}	0.53^{abcd}	12.30^{abc}	6.00^{ab}	16.07^{ijkl}
HSD1834	5.07^{abcd}	4.00^{cdef}	0.50^{bcde}	10.00^{cde}	4.73^{ghi}	20.03^{efghij}
HSD1839	4.90^{abcde}	4.67^{abcde}	0.47^{cdef}	9.50^{cde}	4.87^{fgh}	$20.67^{cdefghi}$
HSD2543	4.50^{bcdefg}	4.33^{bcdef}	0.53^{abcd}	9.77^{cde}	4.93^{fgh}	$21.60^{bcdefgh}$
HSD2482	4.47^{bcdefg}	5.33^{abc}	0.47^{cdef}	9.40^{de}	5.50^{bcdefg}	23.67^{abcdef}
HSD1840	5.07^{abcd}	3.33^{ef}	0.40^{ef}	10.10^{cde}	3.9^{j}	12.13^{l}
HSD2550	5.10^{abcd}	3.00^{f}	0.50^{bcde}	9.87^{cde}	6.33^{a}	14.90^{jkl}
Sinnar	5.27^{abcd}	6.00^{a}	0.47^{cdef}	10.70^{bcde}	5.87^{abcd}	26.33^{ab}
Hjerat	4.87^{abcde}	4.33^{bcdef}	0.47^{cdef}	9.23^{de}	5.67^{abcdef}	19.63^{fghij}
Clemson spineless	4.80^{abcde}	4.67^{abcde}	0.47^{cdef}	9.23^{de}	5.93^{abc}	$22.90^{abcdefg}$
F_1(s) mean	**4.64**	**4.65**	**0.49**	**10.17**	**4.99**	**20.53**
Parents mean	**4.84**	**4.33**	**0.48**	**10.04**	**5.37**	**19.79**
CV	**14.62**	**20.661**	**14.882**	**16.941**	**9.868**	**15.816**
SE(m)	**0.397**	**0.543**	**0.042**	**0.993**	**0.291**	**1.853**
LSD 5%	**1.123**	**1.534**	**0.115**	**2.808**	**0.823**	**5.241**
LSD 1%	**1.494**	**2.041**	**0.154**	**3.735**	**1.095**	**6.971**

*Note: Treatments with different letters are significantly different for $p \leq 0.05$

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Table 3: Crosses showing significant and favorable heterosis for yield and yield components

Trait	Relative Heterosis (%) (Mid parental heterosis)	Heterobeltiosis (%) (Better parent heterosis)	Standard Heterosis (%) (Heterosis over commercial variety)
Pod length (cm)	HSD2543 × Sinnar (+18.77*)	*None of the crosses showed positive and favorable in direction heterosis*	HSD1834 × Sinnar (+18.06*) HSD1839 × Hjerat (+15.28*) HSD2543 × Sinnar (+20.83**) HSD2550 × Hjerat (+15.97*)
Number of Pods per plant	HSD1834 × Clemson spineless (+23.08*) HSD2550 × Sinnar (+33.33**)	HSD2550 × Sinnar (+28.57*)	HSD1835 × Sinnar (+21.43*) HSD2482 × Sinnar (+21.43*) HSD2550 × Sinnar (+28.57*)
Pod Dry weight (g)	HSD1835 × Sinnar (+20.00*) HSD1839 × Sinnar (+21.28*) HSD1840 × Sinnar (+44.83**) HSD2550 × Sinnar (+29.90**)	HSD1835 × Sinnar (+27.66**) HSD1835 × Clemson spineless (+ 21.28*) HSD1839 × Sinnar (+21.28*) HSD1840 × Sinnar (+57.50**) HSD1840 × Clemson spineless (+25.00*) HSD2550 × Sinnar (+34.04**)	HSD1835 × Sinnar (+27.66**) HSD1839 × Sinnar (+21.28*) HSD1840 × Sinnar (+34.04**) HSD2550 × Sinnar (+34.04**)
Dry to Fresh weight ratio (%)	HSD1840 × Sinnar (+25.37**) HSD2550 × Sinnar (+32.44**)	HSD1835 × Sinnar (+19.51*) HSD2550 × Sinnar (+20.52*)	HSD1835 × Sinnar (+35.81**) HSD1839 × Sinnar (+23.75*) HSD1840 × Sinnar (+39.63**) HSD2550 × Sinnar (+45.70**)
Hundred seed weight (g)	*None of the crosses showed positive and favorable in direction heterosis*	*None of the crosses showed positive and favorable in direction heterosis*	*None of the crosses showed positive and favorable in direction heterosis*
Yield per Plant (g)	HSD1835 × Sinnar (+27.36**) HSD1840 × Sinnar (+29.98**) HSD1840 × Clemson spineless (+13.61*) HSD2550 × Hjerat (+20.08*)	*None of the crosses showed positive and favorable in direction heterosis*	HSD1835 × Sinnar (+17.90*) HSD2543 × Sinnar(+15.57*) HSD2482 × Sinnar (+14.70*)

Note: Superscript asterisks * and ** on the means indicate statistical significance for $p \leq 0.05$ and 0.01 respectively.

3.1 Pod Length (cm)

The highest mean performance (Table 2) for pod length (5.87 cm) was observed in the hybrid HSD2543 × Sinnar, while the shortest pods (3.57 cm) were recorded in HSD2482 × Clemson Spineless. Estimates of heterosis, as presented in Table 3, revealed that HSD2543 × Sinnar exhibited the highest positive relative heterosis (+18.77%). Furthermore, estimates of standard heterosis identified HSD2543 × Sinnar (+20.83%) as the best-performing hybrid relative to the commercial check. These results are consistent with recent studies reporting significant heterosis for pod length in okra hybrids. For example, Panchabhaye et al., (2024) documented notable heterosis in specific okra crosses, highlighting the potential for selecting hybrids with improved pod length. Additionally, studies by Thirupathi et al., (2012), Ibrahim et al., (2013), and Bello et al., (2015) suggest that additive gene action plays a key role in controlling this trait, favouring specific optimal allelic combinations. However, as shown in Table 3, none of the crosses outperformed their best parent in terms of heterosis over the better parent.

3.2 Number of Pods per Plant

The highest mean performance (Table 2) for number of pods per plant was observed in HSD2550 x Sinnar (6.00 pods), while the lowest was in HSD1840 x Hjerat and HSD2550 x Hjerat (3.00 pods). Estimates for heterosis in Table 3, showed that cross HSD2550 x Sinnar recorded the highest Mid-parent and heterobeltiosis heterosis, recording (+33.33%) and (+28.57%) respectively. Standard heterosis further supported this hybrid combination as a strong performer at (28.57%), confirming its suitability for commercial production. This trait is crucial as it directly impacts yield potential. These results are consistent with the findings of Ranga et al., (2024) Yohanna, (2023); Shwetha et al., (2021b) and Kerure et al., (2019), who reported significant positive heterosis for the number of pods per plant in okra hybrids.

3.3 Pod Dry Weight

The mean performance data (Table 2) for pod dry weight exhibited significant variation among hybrids and parents. The highest pod dry weight was recorded in HSD2550 x Sinnar and HSD1840 x Sinnar (0.63 g) each. Cross HSD2543 x Hjerat (0.37 g) had the lowest mean performance. Estimates for heterosis in Table 3, showed that the combination of HSD1840 x Sinnar recorded the highest mid-parent and heterobeltiosis heterosis recording (+44.83%) and (+57.50%) respectively. Standard heterosis confirmed HSD1840 x Sinnar (+34.04%) as a superior hybrid for this trait. Similar observations were made by Panchabhaye et al., (2024); Ranga et al., (2024); who found significant heterosis for pod dry weight in certain okra crosses. This trait is particularly important in okra breeding in Sudan, especially for Sudanese cuisine, where dry okra (*waika*) is a staple ingredient in many traditional dishes like *mulaah* and *kisra*-based stews. Selecting for high dry weight ensures that farmers get more usable dried okra per unit of fresh produce. Varieties with naturally low moisture content dry faster and retain better texture and flavour. Higher dry weight usually correlates with better storability, reducing post-harvest losses (Hussein et al., 2018; El-Shaieny et al., 2022).

3.4 Dry-to-Fresh Weight Ratio

Despite the absence of significant differences in fresh weight (g), dry weight (g) exhibited considerable variation among hybrids. Given the relevance of these traits in the context of Sudanese cuisine, the dry-to-fresh weight ratio (%) was further utilized to validate the findings derived from dry weight measurements. The dry-to-fresh weight ratio (%) in Table 2, varied significantly across genotypes (Table 1). Mean performance (Table 2), identifies HSD2550 x Sinnar as the highest performing combination at (13.80%). The hybrid from a combination of

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HSD1839 x Hjerat (8.00%) had the lowest performance. Heterosis estimates in Table 3, identified Mid-parent heterosis and heterobeltiosis as the highest in HSD2550 x Sinnar recording (+32.44%) and (+20.52%) respectively. Standard heterosis supported HSD2550 x Sinnar (+45.70%) as the best performer.

3.5 Hundred-Seed Weight

The mean performance data (Table 2) indicates significant variation in hundred-seed weight was observed. The highest value was recorded in parental line HSD2550 (6.33 g), while the HSD1840 parental line (3.90 g) had the lowest. Among hybrids, HSD1835 x Sinnar recorded the highest value of (6.00g). Estimates for heterosis in Table 3, for Mid-parent, heterobeltiosis and Standard heterosis showed notably negative responses in most hybrid combinations. The results revealed that some parental lines, particularly HSD2550 and HSD1835 likely harbour additive gene effects of favourable allele combinations but failed to produce a heterotic effect due to lack of complementary dominant alleles in testers. Estimates of genetic effects in previous research confirmed the preponderance of additive gene effects for 100 seed weight by Adeniji, et al. (2007); Oyetunde and Ariyo (2014).

3.6 Yield per Plant (g)

The mean performance data (Table 2) indicated that the highest yield per plant was recorded in the hybrid HSD1835 × Sinnar (27.00 g), followed by HSD2543 × Sinnar (26.47 g) and HSD2482 × Sinnar (26.27 g). Conversely, the lowest yield was observed in HSD1839 × Hjerat (12.40 g), HSD2543 × Hjerat (13.33 g) and HSD1840 × Hjerat (14.87 g). These findings suggest that the cross combinations involving Sinnar as a parent generally resulted in higher yields, which could be attributed to favourable genetic interactions or complementary. It is also worth noting that most of the low-yield crosses involved the tester Hjerat as a parent.

Heterosis estimates (Table 3) showed that several hybrids exhibited positive mid-parental heterosis for yield per plant, with HSD1835 × Sinnar (27.36%), HSD1840 × Sinnar (29.98%), and HSD2550 × Hjerat (20.08%) displaying significant heterotic effects at ($p \leq 0.01$ or 0.05). These results confirm the potential of these crosses in enhancing yield performance through hybrid vigour. On the other hand, negative heterosis was recorded in HSD1839 × Hjerat (-38.46%) and HSD2543 × Hjerat (-35.33%), indicating poor hybrid combinations. Standard heterosis further validated these results, with HSD1835 × Sinnar (17.90%), HSD2543 × Sinnar (15.57%), and HSD2482 × Sinnar (14.70%) exhibiting positive heterotic effects relative to the commercial check. This highlights their potential for further evaluation and possible release as superior hybrid cultivars. They are mostly involved in sinner as parents. None of the crosses significantly outperform their parents (heterobeltiosis). Some hybrids, such as HSD1839 × Hjerat (-40.00%), exhibited severe depression in yield, emphasizing the importance of parent selection in hybrid breeding. HSD1835 × Sinnar hybrid should be prioritized for developing high-yielding hybrids.

4. CONCLUSION

This study confirms the potential of heterosis in enhancing okra yield and yield-related traits. Hybrids such as HSD1835 × Sinnar, HSD2543 x Sinnar, HSD2550 x Sinnar, and HSD1839 x Hjerat demonstrated significant heterotic effects and should be considered for further evaluation under different agro-climatic conditions to ensure their stability and commercial viability. The epistatic interactions could be responsible for the exceptional performance of these hybrids. Overall, the findings suggest that hybrid combinations involving Sinnar as a parent generally performed well, reinforcing its role as a strong genetic contributor possessing a unique set of dominance alleles that complement or mask deleterious recessive alleles in the other parent, leading to heterosis in the F1 hybrids. While previous studies have used various testers in okra breeding, few have identified a tester that consistently produces superior hybrids across multiple traits. This study provides novel insights into the role of Sinner as testers in enhancing heterosis. Sinnar's ability to enhance multiple traits suggests that it has a broader genetic base compared to the other testers. This makes Sinnar a more versatile parent for hybrid development. The results also emphasize the importance of heterotic effects in selecting superior hybrid combinations for yield enhancement in breeding programs.

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