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RESEARCH ARTICLE

# Unraveling heterosis and combining ability for enhancing yield and its component traits in cabbage

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## Abstract

The present study explores heterosis, combining ability, gene action and proportional contribution of lines, testers and their interactions for yield and its contributing traits in cabbage (*Brassica oleracea* L. var. *capitata*). Evaluating 30 $F_1$ populations, 11 parents (6 CMS lines and 5 DH testers) and a standard check (Pusa Cabbage Hybrid-81) in RCBD during winter 2018, the results revealed that KTCB-836A, KTCB-50-1 and cross, KTCB-1A × KTCB-50-1 found superior for yield and its component traits based on GCA and SCA estimates respectively. Further, KTCB-836A × KTCB-51-19, KTCB-836A × KTCB-51-2, KTCB-836A × KTCB-50-3 and KTCB-836A × KTCB-51-6 identified as superior hybrids for yield per hectare based on estimates of standard heterosis and heterobeltiosis. The gene action studies indicated that non-additive gene action predominantly controls most quantitative traits, as the dominant variance ($\sigma^2$D) was more than the additive variance ($\sigma^2$A) and the variance ratio was less than one for most of the quantitative traits. While higher contribution of line × tester interactions also highlighted the effective role of testers. Heterosis breeding can thus be commercially exploited to develop superior cabbage hybrids.

**Keywords:** Cabbage, Cytoplasmic male sterility, Doubled haploid (DH), Combining ability, heterosis.

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## Introduction

Cabbage (*Brassica oleracea* L. var. *capitata*) is a major brassica vegetable, traditionally grown in temperate regions but now cultivated throughout the world. Despite its diversity, traditional cultivars often perform poorly in head formation, yield and other traits. These problems can be addressed by developing $F_1$ hybrids, which are early maturing, uniform, higher yielding, and more resistant to pests, diseases, and adverse weather. Heterosis, or hybrid vigor, manifested as the superior performance of $F_1$ hybrid over its parents. In cabbage, $F_1$ hybrid seeds are produced using self-incompatibility (SI) or cytoplasmic male sterility (CMS). While most hybrids have been developed using the SI system, it is less stable at high temperatures and challenging to maintain. The CMS system, being more stable, is a better alternative for producing $F_1$ hybrids. As cabbage is highly heterozygous in nature, producing 100% pure homozygous parental lines through conventional breeding is impossible. Therefore, doubled haploid (DH) lines, created via isolated microspore culture, are completely homozygous in nature. Similarly, both general combining ability (GCA), linked with additive gene action, and specific combining ability (SCA), associated with non-additive effects, are crucial for the development of breeding populations. The knowledge on the nature and magnitude of gene action controlling the inheritance of yield and other quantitative traits would facilitate to exploit the materials for heterotic effect and assessing the proportional contributions of lines, testers, and their interactions is useful for selecting parents effectively to improve quantitative traits (Kumar and Kumar, 2017).

## Materials and Methods

### *Experimental site and layout plan*

The present research was carried out at Naggar Experimental Farm of ICAR-IARI, Regional Station, Katrain, Himachal Pradesh, India. The most divergent cabbage genotypes consisting of 6 CMS lines and 5 DH testers selected based on molecular characterization (Table 1), were crossed in a line × tester mating design during April-June, 2018, producing 30 $F_1$ hybrids. In September 2018, these hybrids, along with their 11 parents and a standard check (Pusa Cabbage Hybrid-81), were planted in a randomized complete block design with three replications. Each plot, measuring 3.0 x 1.5 $m^2$, maintained 18 plants with 45 x 45 $cm^2$ spacing.

### *Sampling and statistical analysis*

Observations were recorded on five randomly selected plants from three replications of each genotype/hybrid for all the 14 quantitative traits under study *viz.,* plant height (cm), plant spread (cm), number of non-wrapper leaves, head polar diameter (cm), head equatorial diameter (cm), head size (cm2), stalk length (cm), days to head maturity, head core length (cm), gross plant weight (kg), net head weight (kg), head compactness (%), harvest index (%) and yield (t/ha). Data recorded from thirty crosses, eleven parents, and standard checks were analyzed using the Line × Tester model (Kempthorne, 1957) with MS-Excel and the OPSTAT package (Sheoran, 2006).

Combining ability analysis was carried out using Kempthorne's (1957) method. The additive and dominance components of variances were estimated using the following formulae (Singh and Chaudhary, 2012).

## Results and Discussion

### *Combining ability studies*

Combining ability plays a crucial role in selecting desirable parents in breeding programs and understanding gene effects on quantitative traits. It is evaluated using various mating designs, including line × tester, North Carolina designs I, II, and III, and diallel (Fasahat *et al*., 2016) and we employed Line × Tester mating design (Kempthorne, 1957), an extension of top cross analysis. The experimental results concerning to significant desirable general combining ability (GCA) effects of 11 parental lines have been presented in Table 2, which revealed mean sum of squares for lines and testers were significant for all studied characters. A perusal of GCA effects relating to good plant stature (plant height, plant spread and number of non-wrapper leaves) revealed that lines viz., KTCB-836A, KTCB-831A and tester KTCB-50-1 were best combiners for plant height due to their significant positive GCA effects (Table 2), whereas the lines KTCB-5A (-3.16; -1.03) and KTCB-1A (-3.04; -0.49) and tester KTCB-51-19 (-2.37; -0.82) were good general combiners for plant spread and number of non-wrapper leaves due to their significant negative GCA effects. KTCB-836A exhibits significantly negative GCA for days to head maturity (-3.69), indicating it matures earlier. Different cabbage genotypes with early maturity have been reported by Nieuwhof and Garretsen (1975), Parkash et al. (2015), Li et al. (2011) and also More and Wallace (1984). The two parents, KTCB-836A and KTCB-50-1, were excellent general combiners for yield and related traits *viz*., head polar and equatorial diameter, gross and net head weight (Table 2). This implies the genetic worthiness of KTCB-836A line for developing high-yielding, early hybrids. Verma *et al*. (1989) also found Pride of Asia to be a good general combiner for gross weight, net weight and head size index. Similar desirable GCA effects for yield traits in cabbage have been reported by Gill *et al*. (1975), Fang and Sun (1982), More and Wallace (1987), and Liu *et al*. (1996).SCA effects, which help to identify the best cross combinations for various traits, have also been studied and presented in Table 3. Among the 30 crosses, six were good combiners for plant height as they exhibited significant positive SCA effects, whereas four hybrids for plant spread and six hybrids for a number of non-wrapper leaves were good specific combiners due to their significant negative SCA effects (Table 3). Whereas, two crosses, including KTCB-1A × KTCB-50-1 and KTCB-1A × KTCB-50-3, showed significantly negative SCA effects for earliness traits (Table 3). Verma *et al*. (2016) also reported two earliest cabbage hybrids through SCA analysis.. For commercial traits *viz.* head polar and equatorial diameter, gross and net head weight, head size, and yield per hectare, several crosses exhibited significantly high SCA effects. Notably, KTCB-1A × KTCB-50-1 showed the highest positive SCA effects for all these traits (Table 3). These findings align with previous studies of Gill et al. (1975), Nieuwhof and Garretsen (1975), Parkash et al. (2015), Thakur (2016), Fang and Sun (1982), Verma et al. (2016) as well as More and Wallace (1987) who reported significant SCA effects for yield and its components.

**Table 1:** List of cabbage parental genotypes and a standard check

| *S. No.* | *Genotype* | *Sr No.* | *Genotype* |
|---|---|---|---|
| | Lines (CMS lines) = 6 | | Testers (DH) = 5 |
| 1. | KTCB-1A (L1) | | KTCB-50-1 (T1) |
| 2. | KTCB-5A (L2) | | KTCB-50-3 (T2) |
| 3. | KTCB-6A (L3) | | KTCB-51-2 (T3) |
| 4. | KTCB-208A (L4) | | KTCB-51-6 (T4) |
| 5. | KTCB-831A (L5) | | KTCB-51-19 (T5) |
| 6. | KTCB-836A (L6) | | |
| | Standard check: Pusa Cabbage Hybrid-81 | | |

**Table 2:** Estimates of general combining ability (GCA) effects of parents for different quantitative traits in cabbage

| S. No. | Parent(s) | Plant height (cm) | Plant spread (cm) | Number of non-wrapper leaves | Head polar diameter (cm) | Head equatorial diameter (cm) | Head size ($cm^2$) | Head compact ness (%) | Head core length (cm) | Stalk length (cm) | Days to head maturity | Gross head weight (kg) | Net head weight (kg) | Harvest Index (%) | Yield per hectare (q) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Lines* | | | | | | | | | | | | | | |
| 1. | KTCB 1A | -1.17* | -3.04* | -0.49* | -0.10 | -0.58 | -8.41 | 2.5* | -0.08 | -0.10* | 6.18* | -0.08* | 0.00 | 2.38* | 0.12 |
| 2. | KTCB 5A | -0.65* | -3.16* | -1.03* | -0.46* | -1.35* | -25.28* | 4.3* | 0.23 | -0.20* | -2.62 | -0.23* | -0.07* | 3.71* | -28.61* |
| 3. | KTCB 6A | -1.00* | -0.29 | 0.79* | -0.86* | -0.99* | -27.46* | 0.0 | -0.71* | 0.08* | -1.62 | -0.23* | -0.17* | -3.23* | -66.04* |
| 4. | KTCB 208A | -0.26 | 1.55* | 0.42* | -1.05* | -0.19 | -20.14* | -0.2 | 0.09 | 0.18* | 1.38 | -0.17* | -0.12* | -2.10* | -48.79* |
| 5. | KTCB 831A | 1.04* | 1.12 | 0.42* | -0.22* | -0.10 | -7.28 | -1.3 | -0.02 | 0.08* | 0.38 | -0.07 | -0.07* | -1.97* | -27.37* |
| 6. | KTCB 836A | 2.04* | 3.81* | -0.10 | 2.70* | 3.20* | 88.58* | -5.4 | 0.49* | -0.04 | -3.69* | 0.78* | 0.43* | 1.20 | 170.69* |
| | Testers | | | | | | | | | | | | | | |
| 7. | KTCB 50-1 | 1.10* | 2.07* | 0.27 | 1.02* | 0.95* | 28.28* | -3.12* | 0.20 | -0.01 | -2.78 | 0.23* | 0.11* | -0.88 | 43.05* |
| 8. | KTCB 50-3 | 0.03 | 1.45* | 1.35* | -0.14 | 0.40 | 3.51 | -3.51* | 0.30* | 0.09* | -2.17 | 0.03 | -0.07* | -5.11* | -28.30* |
| 9. | KTCB 51-2 | -0.31 | -0.91 | -0.41* | -0.23* | -0.31 | -7.24 | 2.01* | -0.41* | 0.10* | 4.61* | -0.07* | 0.00 | 2.05* | -0.59 |
| 10 | KTCB 51-6 | 0.05 | -0.23 | -0.39* | -0.51* | -0.26 | -13.04* | 1.88* | -0.12 | -0.08* | 1.00 | -0.08* | -0.02 | 1.06 | -8.27 |
| 11. | KTCB 51-19 | -0.87* | -2.37* | -0.82* | -0.13 | -0.78* | -11.51* | 2.74* | 0.03 | -0.10* | -0.67 | -0.11* | -0.02 | 2.89* | -5.88 |
| | S.E. (gi) Lines | 0.19 | 0.75 | 0.21 | 0.11 | 0.32 | 4.56 | 0.84 | 0.15 | 0.04 | 1.64 | 0.04 | 0.03 | 0.96 | 9.92 |
| | S.E. (gj) Testers | 0.17 | 0.67 | 0.19 | 0.10 | 0.28 | 4.08 | 0.75 | 0.13 | 0.04 | 1.46 | 0.03 | 0.02 | 0.86 | 8.87 |
| | C.D.$_{(0.05)}$ (gi) Lines | 0.38 | 1.47 | 0.42 | 0.22 | 0.62 | 8.94 | 1.64 | 0.29 | 0.09 | 3.20 | 0.07 | 0.05 | 1.88 | 19.43 |
| | C.D$_{(0.05)}$ (gi) Testers | 0.34 | 1.31 | 0.37 | 0.20 | 0.55 | 8.00 | 1.46 | 0.26 | 0.08 | 2.87 | 0.07 | 0.04 | 1.68 | 17.38 |

*Significant at 5% level of significance

**Table 3:** Estimates of specific combining ability (SCA) effects of crosses for different quantitative traits in cabbage

| *S. No.* | *Cross combination(s)* | *Plant height (cm)* | *Plant spread (cm)* | *Number of non-wrapper leaves* | *Head polar diameter (cm)* | *Head equatorial diameter (cm)* | *Head size (cm²)* | *Head compactness (%)* | *Head core length (cm)* | *Stalk length (cm)* | *Days to head maturity* | *Gross head weight (kg)* | *Net head weight (kg)* | *Harvest Index (%)* | *Yield per hectare (q)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | KTCB-1A × KTCB-50-1 | 1.73* | 1.19 | -0.92* | 3.08* | 2.56* | 86.06* | -5.28* | 1.26* | 0.14 | -7.96* | 0.72* | 0.45* | 2.47 | 177.50* |
| 2. | KTCB-1A × KTCB-50-3 | -1.14* | -0.59 | 1.10* | -1.40* | -1.40* | -40.38* | 0.50 | -0.45 | -0.11 | -7.23* | -0.32* | -0.22* | -4.47* | -88.18* |
| 3. | KTCB-1A × KTCB-51-2 | 0.20 | 1.03 | -1.67* | -0.37 | -0.69 | -17.62 | 7.55* | -0.26 | -0.16 | 6.32 | -0.15* | 0.03 | 9.57* | 14.05 |
| 4. | KTCB-1A × KTCB-51-6 | -0.49 | -0.42 | 0.34 | -0.73* | -0.11 | -12.12 | -0.75 | 0.15 | -0.06 | -0.07 | -0.13 | -0.12* | -2.16 | -45.54* |
| 5. | KTCB-1A × KTCB-51-19 | -0.30 | -1.21 | 1.15* | -0.57* | -0.37 | -15.94 | -2.02 | -0.69* | 0.18* | 8.93* | -0.12 | -0.15* | -5.41* | -57.83* |
| 6. | KTCB-5A × KTCB-50-1 | 0.28 | 3.41* | 0.26 | -0.43 | 0.66 | -0.52 | -1.35 | 0.25 | 0.02 | 0.18 | 0.01 | 0.00 | -1.31 | -1.89 |
| 7. | KTCB-5A × KTCB-50-3 | 0.91* | 0.53 | -0.93* | 0.50* | 0.91 | 17.18 | 0.01 | 0.58 | -0.01 | 2.23 | 0.14 | 0.14* | 3.04 | 55.84* |
| 8. | KTCB-5A × KTCB-51-2 | 0.85* | 0.85 | 0.60 | 0.32 | 1.35* | 20.51* | -4.26* | 0.20 | 0.02 | -4.21 | 0.19* | 0.06 | -3.16 | 22.52 |
| 9. | KTCB-5A × KTCB-51-6 | -1.17* | -3.17* | 0.25 | 0.36 | 0.00 | 6.03 | -0.67 | -0.94* | -0.03 | 1.73 | 0.02 | 0.00 | -0.66 | 0.85 |
| 10. | KTCB-5A × KTCB-51-19 | -0.86* | -1.62 | -0.18 | -0.75* | -2.91* | -43.20* | 6.27* | -0.09 | 0.00 | 0.07 | -0.36* | -0.20* | 2.10 | -77.32* |
| 11. | KTCB-6A × KTCB-50-1 | -1.21* | -1.23 | -0.40 | -1.14* | -0.67 | -26.59* | 2.77 | -0.40 | -0.04 | 1.18 | -0.22* | -0.11* | 0.72 | -42.92* |
| 12. | KTCB-6A × KTCB-50-3 | -0.45 | 0.36 | 0.71 | -0.54* | 0.21 | -5.66 | -0.97 | -0.84* | 0.05 | 4.90 | -0.03 | -0.04 | -1.80 | -15.14 |
| 13. | KTCB-6A × KTCB-51-2 | 0.09 | -2.69 | 1.61* | -0.22 | -1.31* | -18.76* | -1.35 | 0.34 | -0.14 | -3.88 | -0.14 | -0.16* | -6.09* | -62.28* |
| 14. | KTCB-6A × KTCB-51-6 | 0.84* | 1.23 | -1.14* | 1.69* | 0.84 | 36.78* | -1.03 | -0.11 | -0.04 | 0.40 | 0.27* | 0.20* | 4.34* | 79.60* |
| 15. | KTCB-6A × KTCB-51-19 | 0.72 | 2.34 | -0.78 | 0.21 | 0.93 | 14.22 | 0.58 | 1.00* | 0.17 | -2.60 | 0.12 | 0.10* | 2.83 | 40.74 |
| 16. | KTCB-208A × KTCB-50-1 | 0.16 | 0.03 | -1.20* | -0.48* | -0.57 | -15.90 | 4.14* | -0.59* | -0.07 | 4.51 | -0.13 | 0.00 | 4.61* | -0.99 |
| 17. | KTCB-208A × KTCB-50-3 | 0.92* | 2.25 | -0.66 | -0.15 | -0.05 | -3.85 | 1.53 | -0.05 | -0.03 | -3.77 | -0.03 | 0.03 | 2.37 | 11.35 |
| 18. | KTCB-208A × KTCB-51-2 | -0.78* | 0.21 | 0.96* | -0.49* | -0.98 | -18.44* | 0.11 | 0.01 | -0.04 | -3.21 | -0.14 | -0.13* | -3.70 | -51.21* |
| 19. | KTCB-208A × KTCB-51-6 | 0.68 | 1.09 | 0.46 | 0.42 | 0.37 | 12.94 | -2.39 | 0.56 | 0.10 | 5.07 | 0.08 | 0.01 | -1.71 | 3.92 |
| 20. | KTCB-208A × KTCB-51-19 | -0.98* | -3.57* | 0.43 | 0.71* | 1.23 | 25.25* | -3.40* | 0.07 | 0.04 | -2.60 | 0.22* | 0.10 | -1.57 | 36.93 |
| 21. | KTCB-831A × KTCB-50-1 | -0.02 | 0.66 | 1.27* | -0.41 | -0.92 | -19.17* | -1.05 | -0.44 | -0.12 | -0.82 | -0.14 | -0.16* | -4.77* | -64.86* |
| 22. | KTCB-831A × KTCB-50-3 | -0.20 | -3.34* | -0.41 | 0.42 | -0.12 | 4.26 | 0.51 | -0.05 | 0.01 | -0.10 | 0.04 | 0.04 | 1.32 | 16.77 |
| 23. | KTCB-831A × KTCB-51-2 | -0.85* | 3.24* | -1.39* | 0.11 | 0.90 | 13.25 | 1.44 | -0.02 | 0.08 | 9.46* | 0.10 | 0.14* | 5.00* | 55.91* |
| 24. | KTCB-831A × KTCB-51-6 | 0.40 | -0.62 | 0.90* | -0.08 | -0.11 | -0.11 | -2.06 | 0.46 | 0.22* | -4.93 | -0.02 | -0.07 | -3.43 | -27.34 |
| 25. | KTCB-831A × KTCB-51-19 | 0.66 | 0.05 | -0.37 | -0.05 | 0.25 | 1.77 | 1.15 | 0.04 | -0.19* | -3.60 | 0.02 | 0.05 | 1.88 | 19.52 |
| 26. | KTCB-836A × KTCB-50-1 | -0.94* | -4.06* | 0.99* | -0.62* | -1.07 | -23.89* | 0.76 | -0.09 | 0.06 | 2.91 | -0.23* | -0.17* | -1.73 | -66.84* |
| 27. | KTCB-836A × KTCB-50-3 | -0.05 | 0.80 | 0.19 | 1.17* | 0.45 | 28.45* | -1.58 | 0.81* | 0.09 | 3.97 | 0.20* | 0.05 | -0.45 | 19.35 |
| 28. | KTCB-836A × KTCB-51-2 | 0.49 | -2.65 | -0.12 | 0.66* | 0.73 | 21.05* | -3.50* | -0.28 | 0.24* | -4.48 | 0.14 | 0.05 | -1.61 | 21.01 |
| 29. | KTCB-836A × KTCB-51-6 | -0.26 | 1.90 | -0.82 | -1.66* | -0.99 | -43.52* | 6.89* | -0.11 | -0.18* | -2.20 | -0.22* | -0.03 | 3.62 | -11.49 |
| 30. | KTCB-836A × KTCB-51-19 | 0.75* | 4.01* | -0.25 | 0.46* | 0.87 | 17.91* | -2.58 | -0.33 | -0.20* | -0.20 | 0.11 | 0.10 | 0.17 | 37.97 |
| | S.E. (Sij) | 0.39 | 1.50 | 0.43 | 0.23 | 0.63 | 9.12 | 1.67 | 0.29 | 0.09 | 3.27 | 0.08 | 0.05 | 1.92 | 19.83 |
| | C.D.$_{(0.05)}$(Sij) | 0.75 | 2.94 | 0.83 | 0.44 | 1.24 | 17.88 | 3.27 | 0.58 | 0.17 | 6.41 | 0.15 | 0.10 | 3.76 | 38.87 |

*Significant at 5% level of significance

**Table 4:** Estimates of standard heterosis (%) for different quantitative traits in cabbage

| S. No. | Cross combination(s) | Plant height (cm) | Plant spread (cm) | Number of non-wrapper leaves | Head polar diameter (cm) | Head equatorial diameter (cm) | Head size ($cm^2$) | Head compactness | Head core length (cm) | Stalk length (cm) | Days to head maturity | Gross head weight (kg) | Net head weight (kg) | Harvest Index (%) | Yield per hectare (q) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | KTCB-1A × KTCB-50-1 | 10.12* | -10.25* | -17.03* | 22.59* | 13.67* | 39.12* | -12.51 | 10.72 | -4.29 | -12.50* | 35.44* | 44.21* | 6.12 | 44.56* |
| 2. | KTCB-1A × KTCB-50-3 | -10.12* | -14.46* | 4.37 | -17.18* | -15.62* | -30.24* | 4.24 | -20.72* | -17.18 | -10.83 | -28.18* | -38.61* | -14.85* | -38.46* |
| 3. | KTCB-1A × KTCB-51-2 | -4.97 | -15.74* | -26.90* | -10.59* | -15.62* | -24.73* | 43.37* | -30.98* | -21.47 | 14.58* | -24.97* | -6.68 | 24.94* | -6.45 |
| 4. | KTCB-1A × KTCB-51-6 | -6.69 | -17.08* | -12.87* | -15.06* | -11.50 | -24.87* | 17.18 | -17.32* | -29.45* | 2.08 | -24.22* | -23.21* | 1.09 | -23.03* |
| 5. | KTCB-1A × KTCB-51-19 | -10.39* | -22.22* | -10.31 | -11.29* | -16.59* | -25.92* | 15.88 | -30.72* | -7.98 | 11.25 | -25.05* | -25.65* | -1.59 | -25.47* |
| 6. | KTCB-5A × KTCB-50-1 | 5.32 | -6.59 | -12.64* | -4.71 | -3.69 | -8.33 | 5.07 | -2.88 | -25.15 | -13.33* | -8.73 | -6.93 | 1.52 | -6.71 |
| 7. | KTCB-5A × KTCB-50-3 | 3.09 | -12.71* | -13.33* | -6.35 | -5.64 | -11.58 | 8.07 | 5.56 | -18.40 | -10.00 | -11.81 | -10.28 | 1.73 | -10.06 |
| 8. | KTCB-5A × KTCB-51-2 | 1.03 | -16.27* | -14.94* | -8.24* | -7.38 | -14.98* | 11.98 | -15.69 | -15.34 | -9.58 | -15.09* | -11.66 | 3.54 | -11.44 |
| 9. | KTCB-5A × KTCB-51-6 | -7.55 | -22.10* | -17.24* | -9.88* | -15.84* | -24.28* | 22.77* | -32.48* | -36.20* | -6.67 | -23.94* | -18.87* | 6.39 | -18.68* |
| 10. | KTCB-5A × KTCB-51-19 | -10.63* | -23.15* | -23.22* | -15.06* | -38.18* | -46.17* | 47.00* | -12.68 | -35.28* | -10.83 | -44.81* | -37.49* | 14.99* | -37.34* |
| 11. | KTCB-6A × KTCB-50-1 | -4.12 | -9.68* | -4.60 | -12.47* | -9.98 | -21.29* | 4.76 | -33.99* | -4.29 | -10.83 | -20.36* | -26.21* | -7.70 | -26.03* |
| 12. | KTCB-6A × KTCB-50-3 | -5.66 | -7.99 | 10.57 | -16.42* | -7.81 | -23.05* | -8.08 | -40.52* | 13.50 | -5.42 | -21.06* | -36.92* | -20.38* | -36.77* |
| 13. | KTCB-6A × KTCB-51-2 | -4.63 | -17.43* | 4.60 | -14.82* | -22.34* | -33.99* | 7.93 | -31.37* | -3.07 | -7.92 | -31.68* | -41.70* | -14.99* | -41.56* |
| 14. | KTCB-6A × KTCB-51-6 | 1.03 | -9.39* | -14.25* | -3.29 | -8.03 | -11.17 | 8.49 | -34.64* | -11.04 | -7.08 | -11.48 | -8.72 | 2.74 | -8.50 |
| 15. | KTCB-6A × KTCB-51-19 | -4.29 | -11.20* | -14.71* | -11.06* | -10.85 | -20.82* | 16.17 | -9.80 | 6.75 | -12.92* | -20.55* | -17.68* | 3.34 | -17.48* |
| 16. | KTCB-208A × KTCB-50-1 | 6.69 | -4.26 | -12.64* | -9.18* | -4.12 | -13.03 | 8.34 | -22.22 | 1.23 | -2.92 | -13.12* | -11.67 | 1.72 | -11.46 |
| 17. | KTCB-208A × KTCB-50-3 | 5.15 | -1.46 | -1.49 | -15.06* | -4.34 | -18.87* | -0.98 | -9.47 | 15.34 | -12.50* | -17.89* | -26.17* | -10.42 | -26.00* |
| 18. | KTCB-208A × KTCB-51-2 | -5.32 | -9.15* | -2.41 | -18.12* | -14.97* | -30.49* | 11.77 | -22.22* | 14.11 | -3.33 | -28.83* | -34.74* | -8.37 | -34.58* |
| 19. | KTCB-208A × KTCB-51-6 | 3.95 | -6.41 | -5.75 | -13.65* | -5.86 | -18.75* | 3.58 | -5.88 | 10.43 | 2.50 | -18.05* | -23.08* | -6.49 | -22.89* |
| 20. | KTCB-208A × KTCB-51-19 | -9.26* | -18.31* | -8.97 | -8.94* | -3.69 | -12.41 | 3.09 | -12.42 | 4.29 | -9.17 | -12.31 | -14.38 | -2.80 | -14.17 |
| 21. | KTCB-831A × KTCB-50-1 | 12.52* | -3.91 | 4.37 | -2.82 | -5.86 | -8.63 | -11.18 | -21.24* | -11.66 | -10.83 | -7.95 | -22.10* | -15.63* | -21.91* |
| 22. | KTCB-831A × KTCB-50-3 | 6.09 | -11.98* | 0.23 | -5.18 | -4.23 | -9.25 | -7.55 | -11.44 | 9.51 | -9.17 | -8.78 | -19.58* | -12.15 | -19.38* |
| 23. | KTCB-831A × KTCB-51-2 | 1.03 | -4.61 | -18.62* | -8.00* | -2.17 | -10.05 | 12.52 | -24.84* | 16.56 | 11.25 | -10.71 | -3.15 | 8.21 | -2.91 |
| 24. | KTCB-831A × KTCB-51-6 | 9.26* | -10.15* | -2.76 | -11.29* | -8.46 | -18.84* | 1.25 | -9.80 | 12.58 | -11.25 | -17.95* | -25.49* | -9.47 | -25.31* |
| 25. | KTCB-831A × KTCB-51-19 | 5.92 | -12.74* | -14.48* | -8.47* | -9.54 | -17.28* | 13.87 | -15.03 | -25.77 | -11.67 | -17.22* | -13.39 | 3.92 | -13.18 |
| 26. | KTCB-836A × KTCB-50-1 | 12.86* | -7.46 | -1.15 | 16.28* | 14.69* | 33.18* | -18.42* | -4.58 | -6.75 | -11.25 | 30.86* | 26.08* | -3.97 | 26.39* |
| 27. | KTCB-836A × KTCB-50-3 | 12.01* | -0.06 | 0.80 | 20.71* | 20.98* | 45.82* | -26.90* | 15.03 | 5.21 | -9.17 | 42.82* | 29.73* | -9.51 | 30.05* |
| 28. | KTCB-836A × KTCB-51-2 | 13.04* | -10.20* | -13.45* | 16.47* | 18.22* | 37.50* | -15.71 | -20.26* | 19.63 | -11.25 | 34.14* | 36.95* | 1.74 | 37.28* |
| 29. | KTCB-836A × KTCB-51-6 | 10.98* | -1.05 | -18.16* | -1.88 | 7.38 | 5.22 | 16.23 | -11.11 | -35.58* | -12.92* | 15.46* | 27.07* | 9.71 | 27.38* |
| 30. | KTCB-836A × KTCB-51-19 | 11.49* | -1.11 | -17.24* | 15.76* | 16.05* | 34.10* | -10.57 | -12.42 | -38.65* | -12.50* | 30.72* | 39.82* | 6.66 | 40.15* |

*Significant at 5% level of significance

**Table 5:** Estimates of heterosis (%) over better parent for different quantitative traits in cabbage

| *Sr. No.* | *Cross combination(s)* | *Plant height (cm)* | *Plant spread (cm)* | *Number of non-wrapper leaves* | *Head polar diameter (cm)* | *Head equatorial diameter (cm)* | *Head size ($cm^2$)* | *Head compactness* | *Head core length (cm)* | *Stalk length (cm)* | *Days to head maturity* | *Gross head weight (kg)* | *Net head weight (kg)* | *Harvest Index (%)* | *Yield per hectare (q)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | KTCB-1A × KTCB-50-1 | 6.47 | 0.60 | -8.86 | 35.32* | 24.76* | 89.31* | -23.22* | 34.44* | -9.57 | -8.30 | 81.83* | 99.75* | 9.72 | 99.75* |
| 2. | KTCB-1A × KTCB-50-3 | -21.79* | -4.12 | 8.10 | -8.57* | -0.26 | -3.96 | -8.52 | -3.73 | 7.14 | -13.01* | -4.10 | -6.41 | -6.93 | -6.41 |
| 3. | KTCB-1A × KTCB-51-2 | -9.92* | -5.56 | -24.29* | -1.30 | -9.53 | -10.68 | 25.81* | -16.19 | -17.68 | 12.24* | -12.09 | 26.64* | 36.57* | 26.64* |
| 4. | KTCB-1A × KTCB-51-6 | -4.56 | -7.06 | -2.57 | -6.23 | 11.78 | 8.22 | -10.61 | 0.40 | -36.64* | -0.41 | 6.70 | 17.07 | 2.11 | 17.07 |
| 5. | KTCB-1A × KTCB-51-19 | -1.43 | -12.81* | -4.85 | -2.08 | -0.39 | 2.31 | 1.69 | -15.87 | -12.54 | 9.88 | 1.74 | 7.08 | 4.45 | 7.08 |
| 6. | KTCB-5A × KTCB-50-1 | 1.49 | 6.80 | -4.04 | 6.86 | 5.71 | 12.40 | -7.36 | 13.87 | -29.28* | -9.17 | 10.60 | 26.67* | 4.97 | 26.67* |
| 7. | KTCB-5A × KTCB-50-3 | -10.30* | -0.20 | -12.33* | 5.01 | 3.57 | 8.42 | 6.36 | 23.75* | 5.56 | -10.00 | 6.87 | 22.11* | 13.39 | 22.11* |
| 8. | KTCB-5A × KTCB-51-2 | -4.23 | -4.27 | -13.95* | 1.43 | -0.70 | 0.89 | 10.20 | -1.15 | -11.25 | -9.58 | -0.52 | 19.89 | 15.41* | 19.89 |
| 9. | KTCB-5A × KTCB-51-6 | -10.91* | -10.93* | -7.46 | 1.06 | -7.62 | -7.16 | -6.35 | -20.84* | -39.71* | -6.67 | -7.84 | 10.42 | 7.46 | 10.42 |
| 10. | KTCB-5A × KTCB-51-19 | -13.88* | -12.13* | -18.54* | -4.75 | -32.14* | -33.99* | 33.25* | 2.38 | -38.48* | -10.83 | -33.12* | -14.93 | 22.06* | -14.93 |
| 11. | KTCB-6A × KTCB-50-1 | -7.30 | -0.06 | 4.80 | 2.76 | -1.19 | 5.05 | -7.64 | 1.00 | -0.95 | -6.55 | 4.76 | 2.20 | -4.56 | 2.20 |
| 12. | KTCB-6A × KTCB-50-3 | -17.91* | 1.81 | 17.32* | -2.68 | 4.68 | 2.70 | -16.27* | -9.00 | 46.83* | -7.72 | 3.83 | -12.18 | -15.49* | -12.18 |
| 13. | KTCB-6A × KTCB-51-2 | -9.59* | -8.65 | 10.98 | -5.85 | -16.74* | -21.68* | -1.69 | 5.00 | 1.61 | -9.80 | -19.96* | -20.88 | -9.77 | -20.88 |
| 14. | KTCB-6A × KTCB-51-6 | 3.33 | 0.26 | -4.11 | 13.54* | 4.43 | 18.56 | -17.24* | 0.00 | -7.94 | -9.35 | 16.43 | 27.09* | 3.77 | 27.09* |
| 15. | KTCB-6A × KTCB-51-19 | 13.41* | -1.10 | -9.51 | 1.34 | 1.23 | 5.68 | 5.31 | 38.00* | 10.48 | -13.99* | 4.50 | 14.61 | 9.68 | 14.61 |
| 16. | KTCB-208A × KTCB-50-1 | 3.15 | 1.61 | -4.04 | 12.87* | 5.24 | 18.34 | -4.48 | -20.67* | -4.35 | 1.75 | 16.64 | 22.34* | 5.18 | 22.34* |
| 17. | KTCB-208A × KTCB-50-3 | -8.51* | 4.97 | -10.73* | -1.10 | 13.08 | 11.70 | 2.37 | -10.64 | 49.21* | -9.87 | 9.64 | 22.89 | 11.99 | 22.89 |
| 18. | KTCB-208A × KTCB-51-2 | -10.24* | -2.93 | -5.67 | -9.49* | -8.84 | -17.51* | 18.29 | -18.49* | 19.61 | -0.43 | -16.62* | -11.43 | 6.39 | -11.43 |
| 19. | KTCB-208A × KTCB-51-6 | 6.32 | -1.53 | 5.40 | 9.55* | 12.73 | 23.28* | -20.98* | 7.46 | -0.83 | 5.58 | 17.52 | 26.06 | -5.55 | 26.06 |
| 20. | KTCB-208A × KTCB-51-19 | -3.82 | -9.03 | -3.41 | 3.75 | 15.03 | 20.97* | -6.55 | -13.55 | -0.87 | -6.44 | 19.03* | 23.31* | 3.17 | 23.31* |
| 21. | KTCB-831A × KTCB-50-1 | 8.79* | 17.71* | 14.65* | 20.76* | 3.33 | 24.33* | -21.69* | -19.13* | -16.52 | -6.55 | 23.59* | 7.90 | -12.76* | 7.90 |
| 22. | KTCB-831A × KTCB-50-3 | -7.69* | 7.82 | -9.17 | 10.41* | 13.21 | 24.94* | -4.43 | -9.06 | 41.67* | -11.38 | 21.81* | 33.87* | 9.83 | 33.87* |
| 23. | KTCB-831A × KTCB-51-2 | -4.23 | 16.86* | -21.33* | 1.69 | 4.88 | 6.73 | 17.60 | -21.23* | 22.19 | 8.98 | 4.61 | 31.44* | 25.65* | 31.44* |
| 24. | KTCB-831A × KTCB-51-6 | 11.75* | 10.07 | 8.74 | 13.90* | 14.36 | 30.32* | -22.76* | 2.99 | 1.10 | -13.41* | 24.34* | 22.10 | -8.56 | 22.10 |
| 25. | KTCB-831A × KTCB-51-19 | 8.33 | 6.89 | -9.27 | 4.29 | 8.03 | 14.24 | 3.22 | -12.75 | -29.45* | -12.76* | 12.36 | 24.72* | 10.31 | 24.72* |
| 26. | KTCB-836A × KTCB-50-1 | 7.17 | -1.79 | 8.59 | 18.80* | 25.88* | 77.02* | -28.07 | 6.57 | -11.88 | -6.99 | 67.97* | 74.64* | -0.71 | 74.64* |
| 27. | KTCB-836A × KTCB-50-3 | -2.54 | 6.46 | -8.65 | 23.32* | 43.00* | 93.82* | -24.43* | 28.47* | 36.11* | -11.38 | 83.32* | 115.95* | 13.13 | 115.95* |
| 28. | KTCB-836A × KTCB-51-2 | 7.15 | -4.05 | -16.33* | 18.99* | 26.74* | 63.16* | -10.80 | -10.95 | 25.40 | -13.06* | 57.16* | 85.85* | 18.14* | 85.85* |
| 29. | KTCB-836A × KTCB-51-6 | 5.37 | 4.11 | -8.48 | 0.24 | 35.62* | 39.85* | -11.33 | 1.49 | -42.15* | -15.04* | 48.20* | 108.24* | 10.81 | 108.24* |
| 30. | KTCB-836A × KTCB-51-19 | 5.86 | 10.13* | -12.20* | 18.27* | 38.60* | 78.24* | -18.94* | -2.19 | -41.69* | -13.58* | 67.79* | 101.35* | 13.21* | 101.35* |

*Significant at 5% level of significance

**Table 6:** Estimates of genetic components of variance and proportional contribution of lines, testers and their interactions to sum of squares of the hybrids for quantitative traits in cabbage

| *Traits* | *$\sigma^2g$* | *$\sigma^2s$* | *$\sigma^2A$* | *$\sigma^2D$* | *$(\sigma^2g)/(\sigma^2s)$* | *Per cent contribution of* | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | *Lines* | *Testers* | *Lines × Testers* |
| Plant height | 0.86 | 0.64 | 3.43 | 2.57 | 1.34 | 57.75 | 17.54 | 24.71 |
| Plant spread | 3.97 | 3.18 | 15.87 | 12.70 | 1.25 | 47.37 | 19.52 | 33.11 |
| Number of non-wrapper leaves | 0.40 | 0.85 | 1.60 | 3.40 | 0.47 | 22.42 | 33.90 | 43.68 |
| Head polar diameter | 0.82 | 1.17 | 3.27 | 4.67 | 0.70 | 58.57 | 10.41 | 31.02 |
| Head equatorial diameter | 1.17 | 1.04 | 4.69 | 4.15 | 1.13 | 60.57 | 9.90 | 29.53 |
| Head size | 856.05 | 926.51 | 3424.20 | 3706.05 | 0.92 | 63.54 | 9.11 | 27.35 |
| Head compactness | 7.59 | 9.63 | 30.34 | 38.54 | 0.79 | 35.67 | 28.72 | 35.61 |
| Head core length | 0.05 | 0.25 | 0.19 | 1.00 | 0.20 | 29.81 | 13.89 | 56.30 |
| Stalk length | 0.01 | 0.01 | 0.04 | 0.03 | 1.00 | 44.28 | 18.67 | 37.05 |
| Days to head maturity | 5.43 | 12.07 | 21.73 | 48.27 | 0.45 | 29.06 | 19.34 | 51.61 |
| Gross head weight | 0.07 | 0.06 | 0.27 | 0.22 | 1.17 | 67.86 | 8.44 | 23.69 |
| Net head weight | 0.02 | 0.02 | 0.08 | 0.10 | 0.99 | 63.93 | 5.71 | 30.36 |
| Harvest index | 5.73 | 13.2 | 22.93 | 52.82 | 0.43 | 24.27 | 29.85 | 45.88 |
| Yield per hectare | 2978.44 | 3819.13 | 11913.74 | 15276.53 | 0.78 | 64.13 | 5.67 | 30.20 |

Where, $\sigma^2g$= General combining ability (GCA) variance, $\sigma^2s$= Specific combining ability variance, $\sigma^2A$= Additive variance, $\sigma^2D$= Dominance variance and $(\sigma^2g)/(\sigma^2s)$ = Variance ratio.

### *Heterosis studies*

The estimates of heterosis for 30 hybrids, compared to the standard check and better parent, revealed significant heterosis in both directions for all quantitative traits except plant spread, which showed standard heterosis in only one direction (Tables 4 and 5). The highest significant positive standard heterosis was observed in the crosses KTCB-836A × KTCB-51-2 (13.04) for plant height, KTCB-1A × KTCB-50-1 (22.59) for head polar diameter, KTCB-836A × KTCB-50-3 (20.98) for head equatorial diameter, KTCB-836A × KTCB 50-3 (45.82) for head size, KTCB-1A × KTCB-50-1 (24.05) for head compactness, KTCB-836A × KTCB-50-3 (42.82) for gross head weight, KTCB-1A × KTCB-50-1 (44.21) for net head weight, KTCB-1A × KTCB-51-2 (24.94) for harvest index and KTCB-1A × KTCB-50-1 (44.56) for yield per hectare (Table 4), while high significant negative heterosis was observed in the crosses KTCB-5A × KTCB-51-19 (-23.15) for plant spread, KTCB-1A × KTCB-51-2 (-26.90) for number of non-wrapper leaves, KTCB-6A × KTCB-50-3 (-40.52) for head core length, KTCB-836A × KTCB-51-19 (-38.65) for stalk length, KTCB-5A × KTCB-50-1 (-13.33) for days to head maturity (Table 4) implies that these crosses were most desirable for the respective traits and cross combinations *viz.* KTCB-836A × KTCB-50-1 (44.56), KTCB-836A × KTCB-51-19 (40.15), KTCB-836A × KTCB-51-2 (37.18), KTCB-836A × KTCB-50-3 (30.05) and KTCB-836A × KTCB-51-6 (27.38) were regarded as top five hybrids for yield per hectare based on standard heterosis (Table 4).

The highest significant positive heterobeltiosis observed in the crosses KTCB-6A × KTCB-51-19 (13.41) for plant height, KTCB-1A × KTCB-50-1 (35.32) for head polar diameter, KTCB-836A × KTCB-50-3 (43.00) for head equatorial diameter, KTCB-836A × KTCB-50-3 (93.82) for head size, KTCB-5A × KTCB-51-19 (33.25) for head compactness, KTCB-836A × KTCB-50-3 (83.32) for gross head weight, KTCB-836A × KTCB-50-3 (115.95) for net head weight, KTCB-1A × KTCB-51-2 (36.57) and KTCB-836A × KTCB-50-3 (115.95) for yield per hectare (Table 5). Whereas cross combinations viz., KTCB-1A × KTCB-51-19 (-12.81), KTCB-1A × KTCB-51-2 (-24.29), KTCB-831A × KTCB-51-2 (-21.23), KTCB-836A × KTCB-51-6 (-42.15) and KTCB-836A × KTCB-51-6 (-15.04) exhibited highest significant negative heterobeltiosis for plant spread, number of non-wrapper leaves, head core length, stalk length and days to head maturity respectively (Table 5). Previously, Singh *et al.* (2009) also observed significant negative heterosis over a standard check and better parent for 48 and 16 cabbage hybrids, respectively for various traits. The cross combinations viz., KTCB-836A × KTCB-50-3 (115.95), KTCB-836A × KTCB-51-6 (108.24), KTCB-836A × KTCB-51-19 (101.35), KTCB-1A × KTCB-50-1 (99.75) and KTCB-836A × KTCB-51-2 (85.85) were identified as top five hybrids for yield per hectare based on estimates of better parent heterosis (Table 5). Similarly, significant standard and better parent heterosis was also observed for net head weight in the past by Singh *et al.* (2009), indicating the potentiality for increasing cabbage yield.

### *Gene action*

The presently used line × tester (Kempthorne, 1957) mating design not only assists in the evaluation of combining ability but also reveals the nature of gene action controlling the traits under consideration. Analysis showed that SCA variance ($\sigma^2s$) was greater than GCA variance ($\sigma^2g$) for most of the studied traits indicating they were governed by non-additive gene action. Conversely, traits viz., plant height, plant spread, head equatorial diameter, stalk length, and gross head weight had higher $\sigma^2$g, suggesting role of additive gene action in governing them (Table 6). These findings were further confirmed by the higher dominant variance ($\sigma^2$D) compared to additive variance ($\sigma^2$A) and variance ratios less than one for most traits, demonstrating their non-additive gene action. Therefore, heterosis breeding can be effectively used to improve yield and its components. These results were in conformity with past studies by Gill *et al*. (1975), More and Wallace (1984), and Verma *et al*. (1989), who reported non-additive gene action for yield and its components.

### *Proportional contribution of lines, testers and their interactions (%)*

The proportional contribution of lines was higher than that of testers and line × tester interactions for plant height (57.75%), plant spread (47.37%), head polar diameter (58.57%), head equatorial diameter (60.57%), head size (63.54%), head compactness (35.67%), stalk length (44.28%), gross head weight (67.86%), net head weight (63.93%), and yield per hectare (64.13%) (Table 6). Although testers had a negligible contribution to all traits, the contribution of line × tester interactions was higher for the number of non-wrapper leaves (43.68%), head core length (56.30%), days to head maturity (51.61%), and harvest index (45.38%), indicating the effective role of testers in heterosis breeding programs (Table 6) (Kumar and Kumar, 2017).

## Conclusion

The study concluded that KTCB-836A and KTCB-50-1 are superior for yield per hectare and traits like head polar and equatorial diameter, gross and net head weight, based on general combining ability. These can be used for future heterosis breeding in cabbage. Further, crosses KTCB-836A × KTCB-51-19, KTCB-836A × KTCB-51-2, KTCB-836A × KTCB-50-3, and KTCB-836A × KTCB-51-6 were top hybrids for yield per hectare, based on standard heterosis and heterobeltiosis, and can be further evaluated at multiplications for release. Gene action studies revealed that non-additive gene action controls most traits, highlighting the role of heterosis breeding in improving quantitative traits.

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## सारांश

वर्तमान अध्ययन 30 एफ1 जनसंख्या, 11 माता-पिता (6 सीएमएस लाइनें) का मूल्यांकन करके हेटेरोसिस, संयोजन क्षमता, जीन क्रिया और लाइनों के आनुपातिक योगदान, परीक्षकों और उपज के लिए उनकी बातचीत और गोभी (ब्रैसिका ओलेरासिया एल. वेर. कैपिटाटा) में इसके योगदान देने वाले लक्षणों का पता लगाता है। और 5 डीएच परीक्षक) और सर्दियों, 2018 के दौरान आरसीबीडी में एक मानक जांच (पूसा हाइब्रिड-81)। परिणामों से पता चला कि माता-पिता के बीच, केटीसीबी-836ए, केटीसीबी-50-1 और एफ1 के भीतर, केटीसीबी-1ए × केटीसीबी-50 -1 को क्रमशः जीसीए और एससीए अनुमानों के आधार पर उपज और उसके घटक गुणों के लिए बेहतर पाया गया। इसके अलावा, KTCB-836A × KTCB-51-19, KTCB-836A × KTCB-51-2, KTCB-836A × KTCB-50-3 और KTCB-836A × KTCB-51-6 जैसे क्रॉस संयोजनों को बेहतर संकर के रूप में पहचाना गया। मानक हेटेरोसिस और हेटेरोबेल्टिओसिस के अनुमान के आधार पर प्रति हेक्टेयर उपज के लिए। जीन क्रिया अध्ययनों ने अधिकांश मात्रात्मक लक्षणों को नियंत्रित करने में गैर-योज्य जीन क्रिया की प्रमुख भूमिका का संकेत दिया क्योंकि विचरण के प्रमुख घटक ($\sigma^2$D) योगात्मक घटकों ($\sigma^2$A) से अधिक थे और अधिकांश के लिए विचरण अनुपात का अनुमान एक से कम पाया गया। अध्ययन किए गए अधिकांश लक्षणों के लिए लाइन्स × टेस्टर इंटरैक्शन के मात्रात्मक लक्षण और आनुपातिक योगदान को लाइन्स और परीक्षकों के व्यक्तिगत योगदान से अधिक पाया गया और इन लक्षणों को सुधारने में परीक्षकों की प्रभावी भूमिका को भी रेखांकित किया गया। इसलिए गोभी की संकर किस्मों के विकास के लिए हेटेरोसिस प्रजनन का व्यावसायिक रूप से उपयोग किया जा सकता है जो उपज और उससे संबंधित लक्षणों के लिए बेहतर हैं।