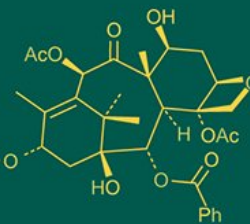
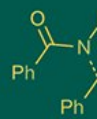
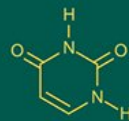
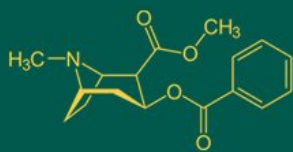


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Genetic analysis of heterosis and inbreeding depression for fruit quality attributes in cucumber (*Cucumis sativus* L.)

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Abstract

Cucumber (*Cucumis sativus* L.) is an economically and nutritionally important vegetable crop belonging to the family Cucurbitaceae. The present investigation was carried out at the Vegetable Research Farm, Department of Vegetable Science, C.S. Azad University of Agriculture and Technology, Kanpur, to assess the heterosis and inbreeding depression for key fruit quality traits. The experimental material comprised ten lines and three testers crossed in a Line $\times$ Tester mating design, producing thirty F_1 hybrids and their corresponding F_2 populations, evaluated along with parents and a standard check ('Malini') in a randomized block design with three replications. Observations were recorded on fruit flesh thickness, total soluble solids, ascorbic acid content, total sugar, dry matter and shelf life using standard analytical methods. Significant positive heterosis was observed in several crosses, notably VRCU-27 $\times$ Pant Khira-1 and VRCU-2210 $\times$ Pusa Uday for fruit flesh thickness, TSS and ascorbic acid content, while dry matter and total sugar also exhibited moderate heterotic response. Inbreeding depression was negligible for most traits, suggesting additive and partial dominance gene actions. No significant standard heterosis over the check variety was detected, indicating limited scope for commercial exploitation of heterosis in these specific crosses. Study identified promising hybrids with superior fruit quality traits that can be effectively utilized in selection breeding programs aimed at developing nutritionally rich and longer-shelf-life cucumber varieties.

Keywords: Heterosis, inbreeding depression, fruit flesh thickness, total soluble solids, ascorbic acid, total sugar, dry matter and shelf life

Introduction

Cucumber (*Cucumis sativus* L.) is one of the most important vegetables in Cucurbitaceae family. It has a chromosome number $2n = 2X = 14$. It is ranked as the second most widely grown cucurbit after watermelon and the fourth most important vegetable crop after tomato, cabbage, and onion at the global level. India is regarded as the primary centre of origin of cucumber because its wild progenitor, *Cucumis sativus* var. *hardwickii*, is naturally distributed in the Himalayan foothills. From this region, cucumber spread eastward to China and westward to Asia Minor, North Africa and Southern Europe well before documented history. China is also considered a secondary centre of genetic diversification for cucumber (De Candolle, 1882) [8]. The cucumber plant is typically a monoecious, trailing or climbing vine with angled, rough stems. Cucumber is cultivated worldwide to consume fresh relished mostly as salad and processed as pickled cucumber. In addition, it has medicinal properties such as anti-inflammatory, antioxidant and anti-cancer benefits. Also, cucumber is used for digestive benefits and mood stability by modulating stress. Furthermore, cucumber may slow age-related cellular deteriorations by fortifying cells (Akhtar *et al.*, 2020) [1]. One hundred gram of edible cucumber fruits contain 96 gm water, 0.6 gm protein, 0.1gm fat, 2.2 gm carbohydrate, 45 IU Vitamin A, 0.03 mg Vitamin B₁, 0.02 mg Vitamin B₂, 0.3 mg Niacin, 12 mg Vitamin C, 12 mg Calcium, 0.3 mg Iron, 15 mg Magnesium and 24 mg phosphorus (Alcazar and Gulick, 1983) [2]. China is the highest producer country which accounts for nearly half of the total world production. The other main producers are Iran, Turkey and USA. Cucumber is commercially grown throughout India ranging from north western

Himalayan region to southern peninsular region including riverbeds and floating gardens in Dal lake of Kashmir valley. In India the area under cucumber cultivation is 138.54 thousand hectares and produces 1989.88 thousand metric tons annually. The major cucumber producing states in India are West Bengal, Madhya Pradesh, Haryana, Gujarat, Karnataka, Punjab and Uttar Pradesh. West Bengal is the leading cucumber producing state with the production of 349.95 thousand metric tons from an area of 24.81 thousand hectares followed by Madhya Pradesh which produced 323.79 thousand metric tons from an area of 19.71 thousand hectares. Uttar Pradesh covers 4.60 thousand hectares area under cucumber cultivation with an annual production of 121.03 thousand metric tons production (Anonymous, 2024-25)^[3].

Heterosis refers to the superiority of F_1 hybrid in one or more characters over its parents. In other words, heterosis refers to increase of F_1 in fitness and vigour over the parental values. Heterosis leads to superiority in adaptation, yield, quality, maturity and general vigour over its parents. Inbreeding depression, the reduction in fitness of inbred progeny relative to outcrossed progeny, has long been considered an important factor in the evolution of plant mating systems (Darwin, 1876)^[6]. Because each plant donates two sets of chromosomes to selfed seeds and only one set to outcrossed seeds, alleles that increase the selfing rate will increase in frequency unless the magnitude of inbreeding depression is severe enough to overcome the transmission advantage of selfing (Fisher, 1941)^[10]. Cucumber fruit quality depends on a number of traits including fruit color, spines, flavor, texture, firmness, maturity stage, fruit flesh thickness, total soluble solids, ascorbic acid content, total sugar content, dry matter content and shelf life. Cucumber fruit color and fruit spine traits are considered as the most important external quality traits, which affect consumer's choice and have been interest of breeders to enhance product quality (Tang *et al.*, 2018; Xue *et al.*, 2019)^[23, 24].

Materials and Methods

The experiment was conducted at the Vegetable Research Farm, Department of Vegetable Science, C.S. Azad University of Agriculture and Technology, Kanpur (26°49' N, 80°30' E; 113 m above mean sea level) situated in a subtropical climatic region with sandy loam soil of moderate fertility. The experimental material comprised 10 female

parents (lines) namely, Kalyanpur Green, Swarna Sheetal, VRCU-2210, Punjab Naveen, Swarna Ageti, VRCU-2244, Phule Shubhangi, VRCU-27, Pusa Long Green, Arka Veera and 3 male parents (testers) namely, Azad Ageta, Pant Khira-1, Pusa Uday and one standard check (Malini) collected from different reputed agricultural research institutions. The study was conducted on Genetic Analysis of Heterosis and Inbreeding Depression for Fruit Quality Attributes in Cucumber (*Cucumis sativus* L.). The crosses were made by following the Line $\times$ Tester mating design as per Kempthorne (1957)^[13], resulting in 30 F_1 hybrids, which were selfed to produce 30 F_2 populations. In total, 74 genotypes (13 parents, 30 F_1 s, 30 F_2 s, and 1 check) were evaluated for their performance in a Randomized Complete Block Design (RCBD) with three replications. Each plant was spaced at 2.0 m $\times$ 0.5 m, and standard agronomic practices were followed, including land preparation and fertilization with 100:50:50 kg ha⁻¹ NPK and 20 t ha⁻¹ of well-decomposed farmyard manure. Regular irrigation, weeding and plant protection measures were undertaken to ensure optimal growth and development.

The observations were recorded on randomly selected plants for a comprehensive set of quality traits, namely fruit flesh thickness, total soluble solids, ascorbic acid content, total sugar, dry matter, and shelf life. These were measured by using standard analytical methods like refractometric determination for TSS, AOAC (1970)^[4] titrimetric estimation for ascorbic acid, Anthrone method for total sugars (Dubois *et al.*, 1956)^[9], oven-drying for dry matter, and ambient storage observation for shelf life.

The recorded data were subjected to analysis of variance (ANOVA) under the RCBD model to test the significance of variation among genotypes. Concurrent meteorological data, including weekly maximum and minimum temperatures, rainfall, relative humidity and evaporation rates, were recorded throughout the cropping seasons to facilitate interpretation of genotype-environment interactions.

Statistical Analysis

Estimation of Heterosis and Inbreeding depression

Heterosis was calculated for each trait and the significance of F_1 heterosis values was tested by comparing it with separately obtained significant difference (CD) values for MP and BP employing the formulas below.

1a. Relative heterosis

Mid-parental value (MP) was calculated following the formula = $\frac{\bar{P}_1 - \bar{P}_2}{2}$

Per cent heterosis over relative heterosis (MP) = $\frac{\bar{F}_1 - \bar{MP}}{\bar{MP}} \times 100$

Where,

$\bar{F}_1$ = Mean value of F_1 hybrid

$\bar{MP}$ = Average of two parents involved in the hybrid

C.D for relative heterosis = S.E.(d) $\times$ 't' value at error d.f (P = 0.05 and 0.01 levels of significance)

$$S.E.(d) = \sqrt{\frac{3EMS}{2r}}$$

Where,

EMS = Error mean of square from analysis of variance

r = Number of replication

t = Table value at error degree of freedom

Significance of relative heterosis values was tested using 't' test:

$$t = \frac{\bar{F}_1 - \bar{MP}}{S.E.(d)}$$

The calculated 't' value was compared to the table value at the error degrees of freedom for significance.

1b. Better parent heterosis (Heterobeltiosis)

Per cent heterosis over better parent (BP) = $\frac{\bar{F}_1 - \bar{BP}}{\bar{BP}} \times 100$

Where,

$\bar{F}_1$ = Mean value of F1 hybrid

$\bar{BP}$ = Mean value of better parent

C.D value for better parent heterosis = $S.E(d) \times t(0.05)$
value at error of d.f

$$S.E(d) = \sqrt{\frac{2EMS}{r}}$$

Significance of better parent heterosis values was tested using 't' test:

$$t = \frac{\bar{F}_1 - \bar{BP}}{S.E.(d)}$$

The calculated 't' value was compared to the table value at the error degrees of freedom for significance.

1c. Standard parent heterosis

$$\text{Per cent heterosis over standard heterosis (SC)} = \frac{F_1 - \bar{SC}}{\bar{SC}} \times 100$$

Where,

$\bar{F}_1$ = Mean value of F1 hybrid

$\bar{SC}$ = Mean value of standard parent

C.D value for standard parent heterosis = $S.E(d) \times t(0.05)$
value at error of d.f

$$S.E(d) = \sqrt{\frac{2EMS}{r}}$$

Significance of standard parent heterosis values was tested using 't' test:

$$t = \frac{\bar{F}_1 - \bar{SC}}{S.E.(d)}$$

The calculated 't' value was compared to the table value at the error degrees of freedom for significance.

2. Inbreeding Depression

The coefficient of inbreeding depression was calculated by the following formula:

$$\text{Inbreeding depression (\%)} = \frac{\bar{F}_1 - \bar{F}_2}{\bar{F}_1} \times 100$$

Where,

$\bar{F}_1$ and $\bar{F}_2$ = Mean of F_1 and F_2 generations, respectively.

Test of significance

Significance of the estimate was tested as:

$$SE (\text{Inbreeding depression}) = \frac{\sqrt{2Me_2}}{r}$$

Where,

Me_2 = Error variance obtained from Parents + F_1 's + F_2 's combinations

r = number of replications.

Results and Discussion

Analysis of variance for the experimental design

The analysis of variance (Table:1) revealed highly significant ($p < 0.01$) differences among genotypes for all the quality traits, indicating substantial genetic variability for fruit flesh thickness, TSS, ascorbic acid, total sugars, dry matter and shelf life. Both parents and hybrids showed significant variation with lines contributing more to trait expression than testers, suggesting wider genetic divergence among lines. Significant Line $\times$ Tester interaction for dry matter and shelf life indicates the importance of non-additive gene action. The significant Hybrids vs. Parents contrast for most traits confirms the presence of heterosis, highlighting the potential of hybrid breeding to enhance cucumber quality. Low error variance indicates high experimental precision. Similar results were also reported by Singh *et al.* (2011) [22], Kumari *et al.* (2018) [16] and Sawant *et al.* (2020) [19].

Table 1: Analysis of variance (ANOVA) for different Quality traits in Cucumber

Source	DF	Fruit flesh thickness (mm)	Total Soluble Solids (°Brix)	Ascorbic Acid (mg/100 gm fresh fruit)	Total Sugar (%)	Dry Matter (%)	Shelf life (days)
Replication	2	0.001	0.001	0.001	0.002	0.008	0.004
Genotypes	42	0.051**	0.094**	0.105**	0.025**	0.288**	0.305**
Hybrids (H)	29	0.055**	0.076**	0.102**	0.029**	0.277**	0.284**
Parent (P)	12	0.044**	0.128**	0.100**	0.015**	0.333**	0.321**
Line (L)	9	0.056**	0.164**	0.128**	0.020**	0.424**	0.249**
Tester (T)	2	0.005*	0.031**	0.025*	0.003	0.093**	0.146**
Line vs Tester	1	0.015**	0.002	0.001	0.002	0.002	1.313**
Hybrids vs Parent	1	0.026**	0.214**	0.237**	0.030	0.067	0.696**
Error	84	0.001	0.004	0.009	0.004	0.010	0.023
Total	128	0.018	0.034	0.040	0.011	0.102	0.115

*, ** significant at 5% and 1% level, respectively

Estimation of Heterosis and Inbreeding Depression

Heterosis, or hybrid vigor, refers to the increased performance of F_1 hybrids over their parental means, which can be assessed as mid-parent (relative heterosis), better-parent (heterobeltiosis), and standard heterosis (economic heterosis). Economic heterosis was calculated over the standard commercial variety Malini. In contrast, inbreeding depression measures the decline in performance from F_1 to F_2 generations due to the breakdown of heterozygosity.

Estimation of these parameters provides insight into the nature and magnitude of genetic effects governing the quality attributes in cucumber. The results of heterosis and inbreeding depression for different quality traits are presented in Table-2a, 2b and discussed below.

1. Fruit Flesh Thickness (mm)

The significant and positive heterosis was considered desirable for the fruit flesh thickness as it enhances fruit

quality and consumer preference. The magnitude of heterosis over the mid-parent ranged from 3.70% (Swarna Sheetal × Pant Khira-1) to 14.51% (VRCU-27 × Pant Khira-1). Out of 30 cross combinations, 18 exhibited positive heterosis with 11 being significant. The best-performing crosses were VRCU-27 × Pant Khira-1 (14.51%), Kalyanpur Green × Pant Khira-1 (11.44%), Phule Shubhangi × Pant Khira-1 (11.32%), Swarna Ageti × Pant Khira-1 (11.23%), and Kalyanpur Green × Pusa Uday (8.10%). The Better-parent heterosis ranged from -9.11% (Arka Veera × Pant Khira-1) to 14.00% (VRCU-27 × Pant Khira-1) with 12 crosses showing positive heterosis, out of which the crosses VRCU-27 × Pant Khira-1 (14.00%) followed by Phule Shubhangi × Pant Khira-1 (7.20%), Swarna Ageti × Pant Khira-1 (6.28%) and Kalyanpur Green × Pant Khira-1 (5.57%) were significant in positive direction. No cross exhibited significant heterosis over the standard check and inbreeding depression was negligible. These results suggest that the inheritance of fruit flesh thickness is mainly governed by additive and partial dominance gene effects. Similar findings were reported by Kumar *et al.* (2010) ^[14] and Simi *et al.* (2017) ^[20] in cucumber.

2. Total Soluble Solids (°Brix)

Total soluble solids (TSS) are an important indicator of sweetness and overall fruit quality. The Mid-parent heterosis ranged from 3.59% (Kalyanpur Green × Pusa Uday) to 6.95% (VRCU-2210 × Pusa Uday). Among 30 crosses, 29 exhibited positive heterosis with 14 being significant. The best five highly significant and positive heterosis were observed for VRCU-2210 × Pusa Uday (6.95%) followed by Swarna Ageti × Pusa Uday (6.38%), Punjab Naveen × Pusa Uday (6.05%), VRCU-27 × Pusa Uday (5.97%) and Pusa Long Green × Pusa Uday (5.66%), respectively. The Better-parent heterosis ranged from -6.68% (Arka Veera × Azad Ageta) to 4.19% (VRCU-2210 × Pusa Uday) and only three crosses VRCU-2210 × Pusa Uday (4.19%), followed by VRCU-27 × Pusa Uday (4.17%), and Pusa Long Green × Pusa Uday (4.17%) recorded significant positive heterosis. None of the crosses showed significant standard heterosis over Malini, and inbreeding depression was statistically non-significant. The results indicate a predominance of additive gene effects for TSS, corroborating the findings of Kaur *et al.* (2016) ^[12], Kumari *et al.* (2017) ^[15] and Rajaguru *et al.* (2020) ^[18], who also observed similar trends of heterosis for TSS in cucurbits.

3. Ascorbic Acid (mg/100 g fresh fruit)

The crosses with positive significant heterosis were considered as desirable for Ascorbic Acid. The magnitude of the mid-parent heterosis ranged from 3.80% (Pusa Long Green × Pant Khira-1) to 7.09% (VRCU-27 × Pusa Uday). Among 30 crosses, 26 recorded positive heterosis, 11 of which were significant. The top-performing crosses included VRCU-27 × Pusa Uday (7.09%), VRCU-2210 ×

Pusa Uday (6.64%), Pusa Long Green × Pusa Uday (6.22%), Swarna Sheetal × Pusa Uday (5.75%) and Swarna Ageti × Pusa Uday (5.73%). The Better-parent heterosis ranged from -6.73% (Arka Veera × Pant Khira-1) to 5.80% (VRCU-27 × Pusa Uday). Out of 30 cross combinations, total number of crosses with positive heterosis was 16, out of which VRCU-27 × Pusa Uday (5.80%), followed by Pusa Long Green × Pusa Uday (5.21%), VRCU-27 × Pant Khira-1 (4.68%) and VRCU-2210 × Pusa Uday (4.65%) were significant in positive direction. No significant positive heterosis was observed over the standard check. The absence of inbreeding depression in F₂ suggests stable transmission of ascorbic acid content. The results align with those reported by Kaur *et al.* (2016) ^[12] and Bisht *et al.* (2023) ^[5], indicating a preponderance of additive genetic effects for this trait.

4. Total Sugar (%)

The crosses with positive significant heterosis were considered as desirable for Total Sugar. For total sugar content, the mid-parent heterosis ranged from 4.15% (Swarna Ageti × Pant Khira-1) to 6.02% (VRCU-2210 × Pusa Uday). Seventeen crosses exhibited positive heterosis with six being significant. The most promising hybrids were VRCU-2210 × Pusa Uday (6.02%), Swarna Ageti × Pusa Uday (5.83%), Pusa Long Green × Pusa Uday (5.54%), and Swarna Sheetal × Pusa Uday (5.36%). The Better-parent heterosis ranged from -5.48% (Arka Veera × Pusa Uday) to 5.47% (Pusa Long Green × Pusa Uday). Out of 30 cross combinations, 14 crosses showed positive heterosis, out of which Pusa Long Green × Pusa Uday (5.47%), VRCU-2210 × Pusa Uday (5.41%), Swarna Sheetal × Pusa Uday (4.54%) and Swarna Ageti × Pusa Uday (4.49%) were significant in a positive direction. Economic heterosis was generally negative and no significant inbreeding depression was observed. These findings are consistent with Das *et al.* (2020) ^[7] and Singh *et al.* (2019) ^[21], who also reported partial dominance for sugar accumulation.

5. Dry Matter (%)

The crosses with positive significant heterosis were considered as desirable for Dry Matter. Dry matter is an important determinant of texture and post-harvest shelf life. The Mid-parent heterosis ranged from -4.32% (Punjab Naveen × Pant Khira-1) to 8.74% (VRCU-2210 × Pusa Uday). Out of 30 crosses, 17 exhibited positive heterosis, with six being significant. The best-performing crosses were VRCU-2210 × Pusa Uday (8.74%), VRCU-27 × Pusa Uday (8.05%), Swarna Sheetal × Pusa Uday (7.15%), Swarna Ageti × Pusa Uday (7.11%) and Pusa Long Green × Pusa Uday (5.98%). The Better-parent heterosis ranged from -12.29% (Swarna Ageti × Azad Ageta) to 6.22% (VRCU-27 × Pusa Uday). Only three crosses VRCU-27 × Pusa Uday (6.22%), VRCU-2210 × Pusa Uday (5.99%) and Pusa Long Green × Pusa Uday (4.78%) showed

Table 2a: Heterosis and Inbreeding depression for different Quality traits in Cucumber

S.N.	Hybrids	FFT				TSS				AA			
		MP (%)	BP (%)	SC (%)	ID (%)	MP (%)	BP (%)	SC (%)	ID (%)	MP (%)	BP (%)	SC (%)	ID (%)
1	Kalyanpur Green x Azad Ageta	5.27 **	-2.78	-4.12	6.13	1.93	0.54	-13.99	3.25	1.07	0.61	-11.29	2.42
2	Kalyanpur Green x Pant Khira-1	11.44 **	5.57 **	4.12	1.69	2.41	-1.92	-10.84	2.75	1.45	-1.07	-9.06	2.16
3	Kalyanpur Green x Pusa Uday	8.10 **	0.80	-0.59	2.96	3.59 *	-1.52	-9.09	2.19	2.09	-0.87	-8.06	1.75
4	Swarna Sheetal x Azad Ageta	-2.24	-6.62 **	-14.29	3.91	1.01	-5.67 **	-6.99	3.01	3.43	-1.47	-4.03	2.24
5	Swarna Sheetal x Pant Khira-1	3.70 *	1.71	-6.65	1.70	3.81 *	-0.24	-1.64	1.28	3.93 *	1.01	-1.61	1.17
6	Swarna Sheetal x Pusa Uday	1.88	-1.71	-9.82	3.46	5.13 **	1.77	0.35	0.70	5.75 **	3.22	0.54	0.53
7	VRCU-2210 x Azad Ageta	0.58	-1.13	-14.53	5.71	2.49	-3.71	-6.29	1.98	3.16	-1.21	-4.84	0.48
8	VRCU-2210 x Pant Khira-1	1.68	0.67	-11.18	3.97	4.02 *	0.60	-2.10	1.07	4.90 *	2.51	-1.26	0.90
9	VRCU-2210 x Pusa Uday	1.37	0.68	-12.94	4.05	6.95 **	4.19 *	1.40	0.45	6.64 **	4.65 *	0.81	0.35
10	Punjab Naveen x Azad Ageta	-0.67	-5.70 **	-12.35	7.38	0.70	-1.91	-16.08	3.75	1.39	0.30	-11.56	2.83
11	Punjab Naveen x Pant Khira-1	3.90 *	1.27	-5.88	5.63	3.25	-2.31	-11.19	3.15	1.06	-2.05	-9.95	2.39
12	Punjab Naveen x Pusa Uday	2.97	-1.27	-8.24	6.41	6.05 **	-0.38	-8.04	2.28	2.10	-1.45	-8.60	2.06
13	Swarna Ageti x Azad Ageta	5.00 **	-2.23	-5.29	3.73	2.20	-5.03 **	-5.35	1.74	3.72	-2.16	-2.69	1.38
14	Swarna Ageti x Pant Khira-1	11.23 **	6.28 **	2.94	1.14	4.22 *	-0.35	-0.70	1.51	4.21 *	0.27	-0.27	1.08
15	Swarna Ageti x Pusa Uday	7.21 **	0.81	-2.35	2.41	6.38 **	2.46	2.10	0.68	5.73 **	2.16	1.61	0.79
16	VRCU-2244 x Azad Ageta	-0.95	-2.35	-18.41	6.49	2.36	1.47	-11.64	3.05	1.46	0.50	-9.68	2.38
17	VRCU-2244 x Pant Khira-1	-0.69	-4.67 *	-15.88	5.59	1.38	-0.77	-9.79	2.71	1.92	0.78	-7.34	1.86
18	VRCU-2244 x Pusa Uday	-0.35	-2.76	-17.06	7.09	2.14	-0.76	-8.39	2.29	3.63	2.03	-5.38	1.70
19	Phule Shubhangi x Azad Ageta	1.75	-4.53 *	-9.00	4.78	5.29 **	1.77	-12.94	3.61	0.83	-1.02	-12.72	2.68
20	Phule Shubhangi x Pant Khira-1	11.32 **	7.20 **	2.18	1.55	5.26 **	-1.15	-10.14	3.11	-0.61	-4.39	-12.10	2.54
21	Phule Shubhangi x Pusa Uday	6.84 **	1.23	-3.53	4.09	5.35 **	-1.77	-9.34	2.70	0.45	-3.77	-10.75	2.20
22	VRCU-27 x Azad Ageta	-1.15	-3.36	-15.47	1.67	2.47	0.39	-10.49	2.23	4.11 *	2.77	-6.99	1.73
23	VRCU-27 x Pant Khira-1	14.51 **	14.00 **	0.59	0.76	3.04	2.05	-7.24	1.13	5.50 **	4.68 *	-3.76	0.84
24	VRCU-27 x Pusa Uday	3.52	2.24	-10.59	1.97	5.97 **	4.17 *	-3.85	0.84	7.09 **	5.80 *	-1.88	0.55
25	Pusa Long Green x Azad Ageta	-2.17	-4.93 *	-20.59	8.15	1.10	-3.93 *	-8.74	2.30	2.70	-0.76	-6.18	1.72
26	Pusa Long Green x Pant Khira-1	-1.41	-6.67 **	-17.65	5.71	4.58 **	2.33	-2.80	1.91	3.80 *	2.37	-3.23	1.67
27	Pusa Long Green x Pusa Uday	-1.79	-5.52 *	-19.41	8.03	5.66 **	4.17 *	-1.05	0.35	6.22 **	5.21 *	-0.54	0.54
28	Arka Veera x Azad Ageta	-3.34	-8.22 **	-23.35	8.67	-2.77	-6.68 **	-20.17	4.51	-1.72	-4.07	-15.40	2.67
29	Arka Veera x Pant Khira-1	-1.80	-9.11 **	-19.82	6.82	0.21	-6.54 **	-15.03	3.58	-2.50	-6.73 **	-14.25	2.82
30	Arka Veera x Pusa Uday	-3.18	-8.97 **	-22.35	7.80	1.02	-6.44 **	-13.64	3.24	-1.72	-6.38 **	-13.17	2.48
	SE(sca effects)	0.027	0.032			0.045	0.052			0.066	0.077		
	SE(best sca effects)	0.054	0.062			0.089	0.102			0.130	0.150		

*, ** significant at 5% and 1% level, respectively

FFT - Fruit flesh thickness (mm) TSS - Total Soluble Solids (⁰Brix) AA - Ascorbic Acid (mg/100 gm fresh fruit)**Table 2b:** Heterosis and Inbreeding depression for different Quality traits in Cucumber

S.N.	Hybrids	TS				DM				SL			
		MP (%)	BP (%)	SC (%)	ID (%)	MP (%)	BP (%)	SC (%)	ID (%)	MP (%)	BP (%)	SC (%)	ID (%)
1	Kalyanpur Green x Azad Ageta	-0.45	-1.04	-9.10**	3.01	2.36	1.37	-16.55**	2.19	0.60	0.30	-5.73**	1.04
2	Kalyanpur Green x Pant Khira-1	-0.81	-2.19	-8.69**	2.55	3.75	-0.91	-12.12**	2.19	1.24	-0.43	-3.22*	0.91
3	Kalyanpur Green x Pusa Uday	-0.81	-2.74	-8.16**	2.22	4.23 *	-1.33	-10.84**	1.89	4.12 **	1.22	0.74	0.46
4	Swarna Sheetal x Azad Ageta	0.00	-2.13	-6.12*	3.04	-4.16 *	-11.49 **	-13.98**	2.61	0.69	-1.85	-8.29**	1.74
5	Swarna Sheetal x Pant Khira-1	2.66	1.28	-2.86	2.23	3.54	-0.99	-3.78	1.33	-0.75	-5.08 **	-7.73**	1.42
6	Swarna Sheetal x Pusa Uday	5.36 **	4.54 *	0.29	0.81	7.15 **	3.39	0.48	0.72	1.19	-4.31 *	-4.76*	1.32
7	VRCU-2210 x Azad Ageta	1.23	-0.71	-5.18*	1.98	-3.80	-10.30 **	-14.63**	2.06	0.07	-1.31	-5.17**	0.69
8	VRCU-2210 x Pant Khira-1	3.75	2.56	-2.04	2.08	2.84	-0.68	-5.47*	1.02	0.96	0.38	-2.42	0.53
9	VRCU-2210 x Pusa Uday	6.02 **	5.41 *	0.69	0.41	8.74 **	5.99 **	0.89	0.33	4.10 **	2.30	1.82	0.14
10	Punjab Naveen x Azad Ageta	-0.75	-1.78	-9.80**	3.76	-1.48	-5.95 *	-22.58**	3.21	-1.40	-5.39 **	-11.61**	2.10
11	Punjab Naveen x Pant Khira-1	-1.11	-2.92	-9.39**	3.29	-4.32 *	-11.78 **	-21.76**	2.68	-1.45	-7.19 **	-9.79**	1.86
12	Punjab Naveen x Pusa Uday	0.96	-1.44	-6.94**	2.50	-3.84	-12.09 **	-20.55**	2.34	-1.48	-8.24 **	-8.67**	1.84
13	Swarna Ageti x Azad Ageta	1.08	-1.54	-4.61*	2.01	-4.07 *	-12.29 **	-12.84**	1.85	0.41	-2.59	-8.99**	1.95
14	Swarna Ageti x Pant Khira-1	4.15 *	2.25	-0.94	1.94	1.50	-3.96	-4.58*	1.59	-1.13	-5.90 **	-8.53**	1.68
15	Swarna Ageti x Pusa Uday	5.83 **	4.49 *	1.22	1.09	7.11 **	2.26	1.61	0.95	-1.77	-7.54 **	-7.97**	1.32
16	VRCU-2244 x Azad Ageta	0.67	0.44	-7.35**	3.52	2.87	1.03	-13.73**	2.51	0.65	0.35	-6.25**	1.19
17	VRCU-2244 x Pant Khira-1	1.61	1.02	-5.71*	2.47	3.00	1.09	-10.36**	2.07	1.35	-0.91	-3.68*	0.97
18	VRCU-2244 x Pusa Uday	2.62	1.44	-4.20	2.00	3.38	0.53	-9.16**	1.94	4.39 **	0.89	0.42	0.60
19	Phule Shubhangi x Azad Ageta	-1.81	-3.70	-11.55**	3.55	1.50	-1.07	-18.55**	2.96	0.35	-0.85	-7.37**	1.71
20	Phule Shubhangi x Pant Khira-1	-1.87	-4.52 *	-10.90**	3.34	-1.78	-7.61 **	-18.07**	2.65	1.46	-1.68	-4.43**	1.17
21	Phule Shubhangi x Pusa Uday	-1.71	-4.90 *	-10.20**	2.73	-1.24	-7.91 **	-16.80**	2.40	2.52	-1.78	-2.24	1.29
22	VRCU-27 x Azad Ageta	1.03	0.29	-6.53*	2.18	-0.57	-3.40	-15.66**	2.09	0.69	0.10	-5.36**	0.84
23	VRCU-27 x Pant Khira-1	1.97	1.90	-4.90*	2.70	2.97	2.17	-9.40**	1.06	2.70	1.29	-1.54	0.67
24	VRCU-27 x Pusa Uday	5.00 *	4.32	-1.51	1.91	8.05 **	6.22 **	-4.02	0.83	4.16 **	1.55	1.08	0.19
25	Pusa Long Green x Azad Ageta	-0.88	-2.30	-7.63**	2.47	-2.94	-8.25 **	-15.18**	2.07	0.53	-0.45	-6.99**	1.31
26	Pusa Long Green x Pant Khira-1	2.97	2.30	-3.27	1.98	2.79	0.70	-6.92**	1.63	1.63	-1.29	-4.06*	1.17
27	Pusa Long Green x Pusa Uday	5.54 **	5.47 *	-0.29	1.76	5.98 **	4.78 *	-3.13	1.00	3.61 *	-0.52	-0.98	0.99
28	Arka Veera x Azad Ageta	-1.90	-4.30	-12.12**	4.32	-3.29	-6.93 **	-23.37**	3.46	-3.24	-8.33 **	-14.36**	2.45
29	Arka Veera x Pant Khira-1	-2.26	-5.39 *	-11.71**	3.84	-3.22	-10.05 **	-20.24**	3.02	-4.07 *	-10.79 **	-13.29**	2.26
30	Arka Veera x Pusa Uday	-1.80	-5.48 *	-10.73**	3.06	-3.42	-11.02 **	-19.59**	2.70	-4.38 **	-12.04 **	-12.45**	2.08
	SE(sca effects)	0.045	0.052			0.072	0.084			0.107	0.123		
	SE(best sca effects)	0.089	0.102			0.142	0.164			0.209	0.241		

*, ** significant at 5% and 1% level, respectively

TS - Total Sugar (%) DM - Dry Matter (%) SL - Shelf life (days)

significant positive heterosis, while most were negative. No cross showed significant economic heterosis. Inbreeding depression was non-significant for all crosses. These results suggest the predominance of additive $\times$ additive gene interaction, agreeing with findings by Kaur *et al.* (2016)^[12] and Bisht *et al.* (2023)^[15] in cucumber.

6. Shelf Life (days)

The positive heterosis for shelf life indicates enhanced storage and market potential. The Mid-parent heterosis ranged from -4.38% (Arka Veera $\times$ Pusa Uday) to 4.39% (VRCU-2244 $\times$ Pusa Uday). Among the crosses, 21 showed positive heterosis, five of which VRCU-2244 $\times$ Pusa Uday (4.39%), VRCU-27 $\times$ Pusa Uday (4.16%), Kalyanpur Green $\times$ Pusa Uday (4.12%), VRCU-2210 $\times$ Pusa Uday (4.10%) and Pusa Long Green $\times$ Pusa Uday (3.61%) were significant in positive direction. However, better-parent heterosis and economic heterosis were predominantly negative, suggesting limited dominance for this trait. No significant inbreeding depression was recorded, indicating genetic stability of shelf life in the F₂ generation. Similar results were reported by Preethi *et al.* (2019)^[17] and Kalgudi *et al.* (2021)^[11] in cucumber and another cucurbit.

Conclusion

The study revealed considerable variability among the crosses for fruit quality traits in cucumber, with several exhibiting positive and significant heterosis for desirable attributes. Crosses such as VRCU-27 $\times$ Pant Khira-1 and VRCU-2210 $\times$ Pusa Uday consistently performed well across multiple traits including fruit flesh thickness, total soluble solids, ascorbic acid content, total sugar, and dry matter percentage. The predominance of additive and partial dominance gene actions was evident for most traits, as indicated by negligible inbreeding depression and the non-significance of standard heterosis. These results suggest that simple selection procedures could be effective for improving these quality traits in subsequent generations. Overall, the identified superior hybrids and their segregating generations may serve as valuable genetic material for developing high-quality cucumber cultivars with improved nutritional and post-harvest characteristics.

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Disclaimer (artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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