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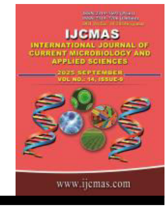

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Phenotypic and PCA-Based Evaluation of Tomato Genotypes for Growth and Fusarium Wilt Resistance under Pot Conditions

Kumari Sarika[1]*, Snehashish Chakravarty[1], Satish Kumar Yadav[2], Smita Kumari[3]* and Kishan Singh[4]

[1]*Department of Horticulture & Post-Harvest Technology, Palli Shiksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, India*
[2]*ARS, Principal Scientist, ICAR-NBPGR, New Delhi-110012, India*
[3]*Horticulture Development Officer, Sabji Mandi Dabua, Faridabad, Haryana, India*
[4]*Department of Horticulture, Institute of Agricultural Sciences, BHU, Varanasi, India*

**Corresponding author*

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ABSTRACT

Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *lycopersici*, is one of the most destructive diseases affecting tomato production worldwide. The present study evaluated 60 tomato genotypes under controlled pot culture to assess variation in growth, yield, biochemical traits, and disease response. Data were analyzed using one-way ANOVA, pooled ANOVA, correlation, and principal component analysis (PCA). Significant differences were observed among genotypes for number of leaves per plant, number of branches per plant, total soluble solids, phenolic content, and fresh weight of fruit per plant. Disease severity ranged from 46.8% to 77.2%, with genotypes such as D1, D2, and Arka Rakshak exhibiting reduced wilt incidence, while H30 and D16 were highly susceptible. Biochemical analysis indicated that higher phenolic accumulation was associated with reduced disease severity, suggesting a role in defense mechanisms. Correlation analysis revealed a negative relationship between disease severity and yield as well as quality traits, whereas phenolic content showed a positive association with total soluble solids. PCA grouped genotypes based on trait performance, with tolerant and high-yielding entries (e.g., D1, Arka Rakshak, Arka Alok) clustering together, distinct from susceptible lines. These results highlight the genetic variability among tomato genotypes and demonstrate the utility of combining morphological, biochemical, and multivariate analyses in identifying resistance sources. The identified promising genotypes may serve as valuable candidates in breeding programs for developing wilt-tolerant tomato cultivars with stable yield and superior fruit quality.

Introduction

Tomato (*Solanum lycopersicum L.*) is a globally significant crop, both nutritionally and economically. However, its cultivation is severely impacted by *Fusarium oxysporum* f. sp. *lycopersici* (Fol), the causal agent of Fusarium wilt, leading to substantial yield losses worldwide (Chitwood-Brown *et al.,* 2021; Heikal, 2025).

Traditional control methods, such as chemical treatments and crop rotation, have proven ineffective due to the pathogen's persistence in soil and rapid evolution of resistance. Consequently, breeding tomato genotypes with inherent resistance to Fol has become a pivotal strategy in sustainable agriculture. Over the past century, breeders have focused on developing tomato cultivars resistant to Fusarium wilt, primarily by introgressing resistance genes (R genes) from wild tomato species, including I, I-2, I-3, and I-7, which combat the three known races of Fol (Heikal, 2025).

Evaluating tomato genotypes under controlled conditions is essential for identifying resistant varieties. Pot culture experiments provide a controlled environment that minimizes external variables, allowing precise assessment of genotype performance.

Recent studies have employed multivariate statistical techniques, such as Principal Component Analysis (PCA), to analyze complex datasets from such experiments. PCA facilitates the reduction of dimensionality, enabling identification of key traits contributing to disease resistance and overall plant performance (García-Barrera *et al.,* 2024; Heikal, 2025).

This study aims to evaluate sixty tomato genotypes for their growth, yield components, and resistance to Fol under controlled pot conditions. By employing PCA, we seek to elucidate the relationships between various phenotypic traits and disease resistance, thereby identifying promising genotypes for future breeding programs.

Experimental Details

Experimental Material and Pot Screening

Seeds of sixty tomato genotypes (Table.1) were obtained from NBPGR, IIHR, BAU, PAU, Himachal Pradesh, and local cultivars from Punjab. A pot screening experiment was conducted in the greenhouse of the Department of Plant Pathology, Lovely Professional University, Phagwara, during the *rabi* seasons of 2019–20 and 2020–21. The experiment was arranged in a Completely Randomized Design (CRD) with three replications. Wilt incidence was recorded 55 days after transplanting, and genotypes were classified as Immune, Highly Resistant, Moderately Resistant, Moderately Susceptible, Susceptible, or Highly Susceptible based on percentage wilt incidence.

Pathogen Isolation, Maintenance, and Inoculation

Fusarium oxysporum f. sp. *lycopersici* (FOL) was isolated from infected tomato stems showing vascular discoloration, surface-sterilized (0.1% $HgCl_2$ for 30 s), and cultured on Potato Dextrose Agar (PDA) at 28 ± 1°C. Pure cultures were maintained at 5 ± 1°C. Pathogenicity was confirmed by transplanting seedlings into inoculated soil (1:3 ratio of pathogen to soil) and monitoring symptom development.

The pathogen was re-isolated from wilted plants and identified based on colony morphology and microscopic characteristics, with verification at PAU Ludhiana and MTCC Chandigarh. For inoculum production, fungal cultures were mass-multiplied on substrates including wheat meal, sorghum, bajra grains with 0.5% glucose, wheat bran + sawdust (1:1), and peat soil, and incubated at 28 ± 1°C for 15 days.

Trait Evaluation and Data Analysis

The tomato genotypes were evaluated for a range of physiological, yield, and biochemical traits. Vegetative growth was assessed through the number of leaves per plant (NLPP), while canopy development and fruiting potential were measured by the number of branches per plant (NBPP).

Disease severity (DS) was recorded as the percentage of plant tissue affected by Fusarium wilt. Fruit quality was determined using total soluble solids (TSS, °Brix), and biochemical attributes were assessed through phenolic content, reflecting antioxidant capacity and stress tolerance. Yield potential was measured as the fresh weight of fruit per plant (FWPF).

Data were analyzed using Agrianalyze software, and one-way ANOVA along with pooled ANOVA was performed to detect significant differences among genotypes. Mean separation was carried out using the LSD test at $P \leq 0.05$.

Results and Discussion

Mean Performance

Growth and Yield Components (NLPP and NBPP)

The evaluated tomato genotypes exhibited significant variability in growth, disease severity, biochemical composition and yield potential under Fusarium wilt pressure. The pooled values for the number of leaves per plant ranged from 6.2 in Pusa Ruby to 15.2 in H7, while the number of branches per plant varied from 3.0 in North West Hybrid to 5.1 in D13. Genotypes such as Arka Rakshak, Channaya, and D4 produced relatively higher leaf numbers, suggesting better vegetative growth potential, whereas D13, H10, and D3 exhibited greater branching ability, which could contribute to enhanced fruiting and yield. Previous reports have also highlighted that higher vegetative vigor and branching patterns are positively associated with yield potential in tomato under stress conditions (Singh *et al.,* 2017; Kumar *et al.,* 2020).

Substantial differences were also observed in the response to Fusarium wilt. Disease severity values ranged from 46.8% in D2 to 77.2% in H30, with D1, D2, and P4 demonstrating moderate to low susceptibility, while H30, D16, and Arka Vikas appeared more vulnerable. Such variation in wilt incidence has been widely documented and is critical for identifying resistant donors in breeding programs (Agrios, 2005; McGovern, 2015). Interestingly, several genotypes that showed reduced disease severity also exhibited higher phenolic content, including Arka Alok, D1, and Arka Rakshak (>50 mg/100 g). Phenolic compounds are known to play a pivotal role in plant defense by strengthening cell walls and limiting pathogen colonization, consistent with earlier studies linking phenolics with Fusarium wilt resistance (Mandal *et al.,* 2010).

Fruit quality parameters further highlighted genetic diversity among the genotypes. Total soluble solids varied from 3.7 °Brix in H6 to 6.3 °Brix in Jaya Hybrid, with D3 and D4 recording higher values desirable for market preference. Notably, the presence of Fusarium stress did not appear to compromise quality traits in these lines, which aligns with previous observations that resistant genotypes can maintain both productivity and quality under pathogen pressure (Hibar *et al.,* 2007). Yield performance followed a similar trend, with fresh fruit weight per plant ranging from 66.1 g in Pusa Ruby to 117.4 g in D1. High-yielding genotypes such as D1, Arka Rakshak, and Arka Vikas demonstrated the capacity to sustain production under disease pressure, supporting earlier findings that yield stability is a reliable indicator of resistance (Garibaldi *et al.,* 2018).

Figur … **t Stress**

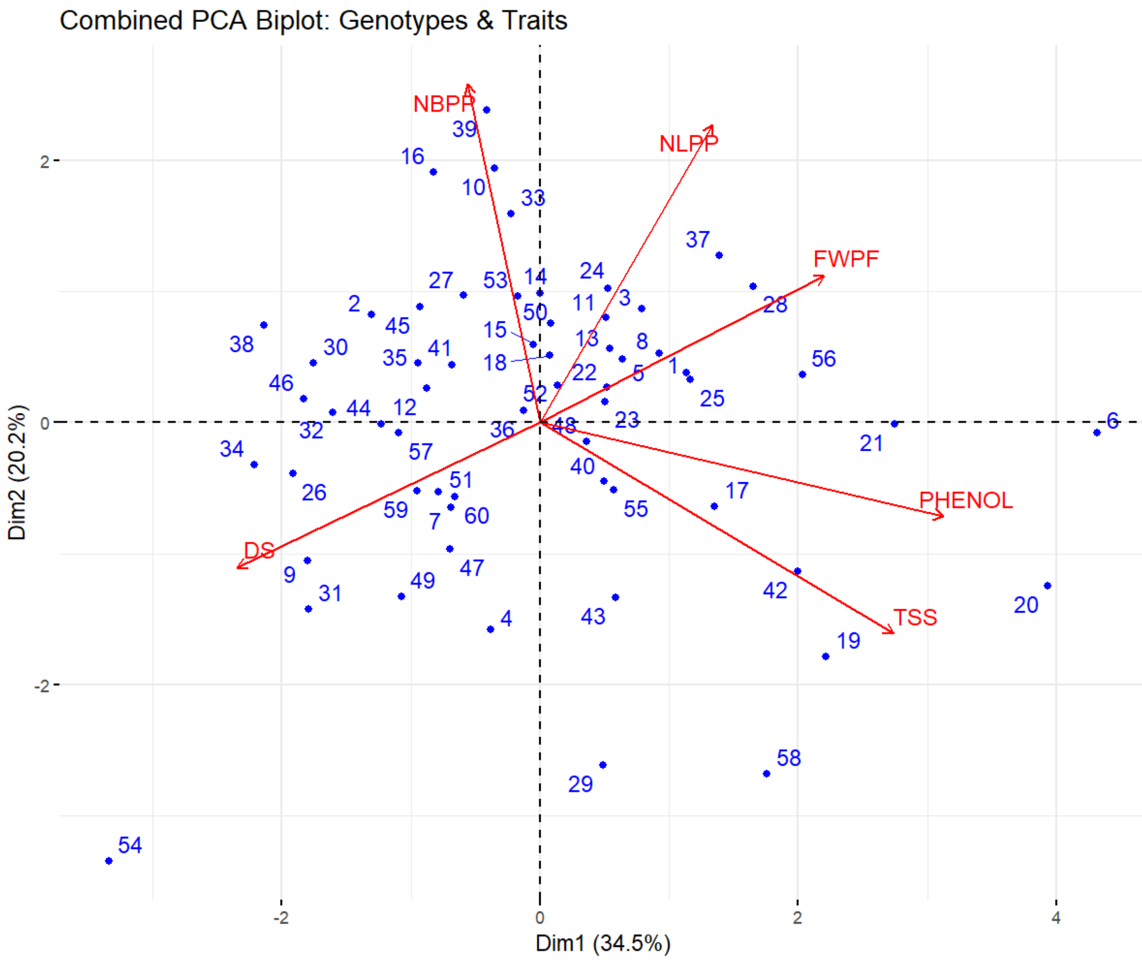
Table.1

S. No.	Entry	NLPP			NBPP			DS			TSS			PHENOL			FWPF		
		Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled	Y1	Y2	Pooled
1.	Arka Alok	13.5	14.3	13.9	3.5	5.1	4.3	68.7	53.3	61.0	5.3	4.5	4.9	46.9	52.4	49.6	94.1	94.7	94.4
2.	Arka Meghna	9.2	11.3	10.3	4.8	4.7	4.8	68.7	52.0	60.3	4.2	3.9	4.1	40.0	39.1	39.6	95.1	97.6	96.3
3.	Arka Rakshak	15.3	11.7	13.5	3.9	5.1	4.5	74.0	69.3	71.7	4.9	4.6	4.7	52.3	41.9	47.1	112.1	113.7	112.9
4.	Arka Vikas	9.3	10.0	9.7	2.7	3.9	3.3	79.7	74.0	76.8	4.4	4.6	4.5	50.4	41.2	45.8	110.6	103.1	106.8
5.	Channaya	15.3	14.3	14.8	3.3	3.7	3.5	67.7	54.0	60.8	5.5	3.9	4.7	42.8	41.6	42.2	111.2	95.0	103.1
6.	D1	13.3	14.0	13.7	2.5	3.7	3.1	46.3	35.7	41.0	5.1	5.2	5.2	57.7	53.8	55.7	119.0	115.8	117.4
7.	D10	11.5	12.0	11.8	3.1	3.3	3.2	58.0	65.0	61.5	4.1	4.4	4.3	44.1	36.8	40.5	105.7	83.4	94.5
8.	D11	13.4	12.3	12.8	4.4	3.8	4.1	51.0	48.7	49.8	5.0	4.2	4.6	44.9	47.2	46.0	97.9	91.7	94.8
9.	D12	9.7	5.0	7.3	4.4	3.9	4.2	67.0	60.3	63.7	4.3	4.0	4.2	43.1	38.6	40.8	82.9	95.1	89.0
10.	D13	12.0	13.7	12.8	5.0	5.2	5.1	54.7	63.0	58.8	4.0	4.7	4.3	43.7	37.2	40.5	110.5	94.8	102.7
11.	D14	15.0	14.0	14.5	3.7	5.2	4.4	70.7	54.7	62.7	4.7	4.7	4.7	48.7	45.6	47.2	82.1	101.6	91.9
12.	D15	12.0	12.8	12.4	4.8	3.5	4.2	83.7	53.0	68.3	3.9	3.9	3.9	50.0	43.0	46.5	88.8	91.7	90.3
13.	D16	10.7	13.0	11.8	4.9	5.2	5.1	80.0	51.3	65.7	4.5	4.9	4.7	50.3	52.2	51.3	99.2	92.0	95.6
14.	D17	14.0	13.3	13.6	4.8	4.4	4.6	69.3	50.3	59.8	4.6	4.0	4.3	50.0	44.4	47.2	96.1	80.5	88.3
15.	D18	14.0	15.3	14.7	3.3	3.6	3.5	70.7	42.3	56.5	4.2	4.3	4.2	40.9	41.7	41.3	98.4	89.2	93.8
16.	D19	14.7	12.0	13.3	5.1	5.1	5.1	61.0	60.7	60.8	4.1	3.9	4.0	44.1	40.1	42.1	91.6	96.8	94.2
17.	D2	13.0	12.0	12.5	3.5	3.3	3.4	42.0	51.7	46.8	4.3	4.8	4.6	54.3	49.0	51.7	84.3	83.5	83.9
18.	D20	15.0	14.3	14.7	3.8	3.0	3.4	55.0	61.7	58.3	4.0	4.6	4.3	40.6	42.8	41.7	101.5	92.2	96.8
19.	D3	11.0	8.7	9.8	2.6	5.2	3.9	64.7	58.0	61.3	6.0	6.2	6.1	54.8	45.1	50.0	108.3	100.8	104.6
20.	D4	16.7	13.5	15.1	2.6	3.5	3.0	58.7	55.3	57.0	6.6	5.6	6.1	60.5	50.0	55.2	108.7	100.6	104.7

21.	D5	14.9	13.1	14.0	3.6	3.3	3.5	42.0	49.0	45.5	4.8	5.6	5.2	51.4	48.8	50.1	104.4	99.2	101.8
22.	D6	10.5	11.7	11.1	4.9	4.1	4.5	59.7	63.0	61.3	4.4	4.3	4.3	51.6	49.8	50.7	98.7	99.0	98.8
23.	D7	14.3	13.3	13.8	3.5	4.7	4.1	76.7	69.7	73.2	4.6	4.7	4.6	48.9	48.4	48.7	107.9	96.0	101.9
24.	D8	16.7	12.5	14.6	3.7	3.0	3.4	43.0	51.0	47.0	4.5	3.7	4.1	39.8	42.7	41.3	97.7	100.2	98.9
25.	D9	15.2	11.8	13.5	3.9	3.3	3.6	58.3	47.0	52.7	4.6	4.8	4.7	42.5	47.1	44.8	94.4	110.6	102.5
26.	H1	11.7	13.7	12.7	3.0	3.7	3.4	65.0	74.7	69.8	4.0	3.8	3.9	38.8	39.1	39.0	92.3	78.8	85.5
27.	H10	13.3	12.0	12.7	5.3	4.1	4.7	63.0	50.3	56.7	5.3	4.0	4.7	39.4	39.4	39.4	90.3	88.0	89.1
28.	H11	15.7	10.7	13.2	4.7	4.0	4.4	62.7	34.3	48.5	4.5	4.6	4.5	48.0	52.0	50.0	106.8	94.4	100.6
29.	H12	13.0	12.3	12.7	1.6	3.7	2.6	79.0	50.7	64.8	5.5	4.9	5.2	50.5	48.9	49.7	79.3	68.9	74.1
30.	H13	11.0	12.3	11.7	4.8	4.4	4.6	73.0	60.7	66.8	4.3	4.1	4.2	40.4	39.6	40.0	83.0	86.9	85.0
31.	H2	8.3	11.0	9.7	3.6	3.1	3.3	77.3	71.0	74.2	4.3	4.8	4.5	36.0	36.4	36.2	103.8	92.2	98.0
32.	H28	11.0	15.0	13.0	3.6	4.8	4.2	77.0	65.3	71.2	4.2	4.2	4.2	38.1	47.9	43.0	77.2	82.8	80.0
33.	H29	15.3	14.3	14.8	4.5	4.9	4.7	76.7	60.3	68.5	4.3	4.4	4.4	40.5	45.9	43.2	97.8	103.9	100.8
34.	H3	13.0	13.3	13.2	4.1	3.1	3.6	83.0	68.0	75.5	4.3	3.9	4.1	35.6	40.9	38.2	91.8	75.3	83.5
35.	H30	10.7	14.7	12.7	2.6	5.2	3.9	83.3	71.0	77.2	3.5	4.4	3.9	37.5	46.9	42.2	111.2	108.1	109.7
36.	H4	8.5	13.3	10.9	3.9	4.7	4.3	61.0	52.3	56.7	4.3	4.2	4.3	50.5	43.1	46.8	95.3	85.8	90.6
37.	H5	12.9	13.7	13.3	4.7	5.2	4.9	58.7	51.0	54.8	4.2	5.9	5.0	50.5	43.3	46.9	100.3	105.1	102.7
38.	H6	10.7	15.3	13.0	4.6	4.1	4.3	72.0	59.3	65.7	3.5	4.0	3.7	41.1	38.7	39.9	82.5	76.1	79.3
39.	H7	13.3	17.0	15.2	4.5	5.1	4.8	68.0	55.3	61.7	3.8	3.9	3.8	43.5	42.0	42.7	104.2	96.9	100.5
40.	H8	16.0	10.7	13.3	2.6	3.6	3.1	57.0	56.0	56.5	5.5	3.9	4.7	47.0	38.4	42.7	90.4	100.7	95.5
41.	H9	14.7	13.7	14.2	4.1	4.1	4.1	75.7	60.7	68.2	4.3	3.9	4.1	49.9	43.0	46.4	82.6	88.5	85.6
42.	Jaya Hybrid	14.0	15.0	14.5	3.4	4.7	4.1	77.0	64.0	70.5	6.8	5.7	6.3	50.4	51.3	50.9	95.1	85.6	90.4
43.	North West	11.0	10.6	10.8	2.9	3.2	3.0	70.7	52.7	61.7	4.3	4.3	4.3	48.2	51.1	49.7	96.5	101.9	99.2

	Hybrid																		
44.	P1	15.3	14.7	15.0	2.8	4.6	3.7	68.7	79.7	74.2	4.4	4.4	4.4	43.4	39.1	41.2	84.3	83.4	83.8
45.	P2	15.3	13.3	14.3	3.7	4.7	4.2	70.0	66.7	68.3	3.8	4.8	4.3	40.4	40.5	40.5	96.5	89.4	92.9
46.	P3	16.0	13.7	14.8	2.5	4.0	3.2	78.7	77.7	78.2	3.8	3.4	3.6	43.5	36.5	40.0	95.1	92.1	93.6
47.	P4	11.0	15.3	13.2	3.5	4.7	4.1	72.3	69.0	70.7	4.4	5.7	5.0	47.5	45.6	46.5	78.9	62.0	70.4
48.	P5	14.3	12.7	13.5	2.5	3.7	3.2	61.0	63.7	62.3	3.8	4.2	4.0	49.6	45.9	47.7	99.5	97.7	98.6
49.	P6	8.3	11.3	9.8	3.0	3.4	3.2	57.3	72.7	65.0	4.8	4.0	4.4	38.9	39.5	39.2	95.1	97.1	96.1
50.	Punj Gaurav	14.7	14.3	14.5	4.0	3.6	3.8	70.3	62.7	66.5	4.4	3.9	4.2	48.7	41.0	44.9	102.8	101.4	102.1
51.	Punj local	10.7	11.7	11.2	4.2	3.5	3.9	68.7	63.0	65.8	4.9	4.5	4.7	41.7	38.5	40.1	89.4	99.0	94.2
52.	Punj sartaj	13.3	15.3	14.3	3.8	4.5	4.1	55.0	71.7	63.3	5.5	4.5	5.0	39.8	45.5	42.7	89.4	89.7	89.6
53.	Pusa Rohini	13.4	10.6	12.0	4.2	3.9	4.1	40.0	71.3	55.7	4.3	4.3	4.3	40.3	37.0	38.7	105.2	109.6	107.4
54.	Pusa ruby	7.3	5.0	6.2	3.8	2.8	3.3	69.7	80.7	75.2	4.5	4.0	4.3	43.1	37.5	40.3	66.3	66.0	66.1
55.	S Anmol	10.0	14.0	12.0	3.6	4.1	3.8	62.3	65.0	63.7	4.5	4.9	4.7	53.9	43.0	48.4	97.3	94.6	95.9
56.	S kanchan	16.3	12.7	14.5	4.3	3.2	3.7	51.0	55.7	53.3	5.3	4.6	5.0	46.1	52.3	49.2	105.6	98.5	102.0
57.	Satabdi	13.7	11.0	12.4	3.8	4.5	4.2	78.7	61.0	69.8	4.4	4.6	4.5	44.2	39.3	41.8	78.9	98.5	88.7
58.	Swarna Lalima	9.3	10.7	10.0	4.0	2.6	3.3	78.0	66.0	72.0	6.0	5.9	6.0	48.9	53.6	51.2	105.9	100.2	103.1
59.	Swarna suvarna	10.0	9.7	9.8	3.4	3.8	3.6	60.3	58.7	59.5	4.2	3.9	4.1	43.9	41.6	42.8	95.1	100.0	97.6
60.	Swarna Vijay	13.33	9.33	11.33	2.8	4.6	3.7	69.67	57.33	63.50	4.30	3.95	4.12	51.49	36.56	44.03	86.77	86.80	86.78
Mean		12.78	12.56	12.67	3.75	0.09	31.35	66.04	59.90	62.97	4.57	4.48	4.53	45.76	43.69	44.72	95.88	93.41	94.65
SE(m)		0.26	0.24	0.18	4.07	0.10	33.91	1.04	1.02	0.74	0.07	0.07	0.05	0.45	0.52	0.35	1.13	1.20	0.83
CV		27.24	25.17	26.22	3.91	0.07	32.99	21.16	22.79	22.44	19.91	19.80	19.85	13.33	15.87	14.76	15.86	17.28	16.60
LSD		5.00	4.48	3.38	4.21	2.32	1.87	17.23	18.73	14.15	1.20	1.27	0.88	5.19	9.46	5.95	21.73	23.85	15.44

Figure.2 PCA Biplot Showing Relationships Among Tomato Genotypes and Fusarium Wilt-Related Traits



Overall, the study confirms the existence of substantial genetic variability in tomato genotypes for resistance to Fusarium wilt as well as associated growth, biochemical, and yield traits. The identification of genotypes such as D1, Arka Rakshak, and Arka Alok with desirable combinations of tolerance, vigor, and fruit quality suggests their potential utility in resistance breeding. These findings reinforce the importance of integrating morphological and biochemical defense traits for developing wilt-tolerant cultivars.

Correlation coefficient among Traits

Correlation analysis among the studied traits revealed weak to moderate associations, suggesting that these characteristics contribute independently to genotype performance under Fusarium wilt pressure (Figure.1). The number of leaves per plant (NLPP) was positively but weakly correlated with phenolic content (r = 0.11) and fresh weight of fruit per plant (FWPF; r = 0.10), indicating that vegetative vigor may offer some contribution to biochemical defense and yield, though not strongly. Similarly, the number of branches per plant (NBPP) exhibited negligible correlations with all traits, suggesting that branching ability alone may not be a strong predictor of yield under disease stress.

Disease severity (DS) showed negative associations with total soluble solids (TSS; r = -0.15), phenolic content (r = -0.15), and FWPF (r = -0.14), implying that higher wilt incidence reduces both fruit quality and yield.

These findings align with earlier reports where increased pathogen pressure resulted in decreased physiological efficiency and fruit accumulation (McGovern, 2015). Interestingly, TSS was positively correlated with phenolic content (r = 0.27), indicating that genotypes with higher sugar content also tended to accumulate more phenolic compounds, which may enhance both nutritional quality and defense capacity (Mandal *et al.,* 2010).

The relationship between yield and biochemical traits suggests that disease tolerance mechanisms could help maintain fruit quality without major trade-offs. Although correlations were relatively weak, the observed trends are in agreement with previous studies, which showed that resistant tomato genotypes often sustain higher phenolic accumulation and yield compared to susceptible ones under Fusarium wilt pressure (Singh *et al.,* 2017; Hibar *et al.,* 2007).

This highlights the potential of incorporating biochemical markers such as phenolic content into breeding programs alongside morphological traits.

Principal component Analysis

The principal component analysis (PCA) biplot provided insights into the relationships among traits and the distribution of tomato genotypes under Fusarium wilt pressure (Figure.2). The first two principal components (Dim1 and Dim2) accounted for 34.5% and 20.2% of the total variation, respectively, explaining more than half of the observed variability. Traits such as number of leaves per plant (NLPP), number of branches per plant (NBPP), fresh weight of fruit per plant (FWPF), total soluble solids (TSS), and phenolic content were positively associated with Dim1, whereas disease severity (DS) showed a strong negative loading, indicating its contrasting contribution to genotype performance. The projection of traits indicated that NLPP, FWPF, phenolic content, and TSS clustered together in the same quadrant, suggesting a positive association among vegetative vigor, biochemical defense, and yield potential. Conversely, DS was oriented in the opposite direction, reinforcing its antagonistic relationship with these traits. This pattern confirms earlier findings that higher vegetative growth and phenolic accumulation contribute to reduced wilt incidence and improved yield stability (Mandal *et al.,* 2010; Singh *et al.,* 2017).

Genotypic distribution revealed considerable diversity, with certain entries such as genotypes 28, 37, and 56 aligning closely with NLPP, FWPF, and phenolic content, suggesting their potential as tolerant and high-yielding lines. In contrast, genotypes positioned closer to the DS vector, such as 6, 9, and 31, may be more susceptible. The separation of genotypes across quadrants demonstrates the utility of PCA in differentiating tolerant and susceptible groups, consistent with reports that multivariate approaches are effective in identifying resistance donors and quality trait combinations in tomato (Kumar *et al.,* 2020; McGovern, 2015).

Overall, the PCA biplot emphasized the negative association of disease severity with yield and quality-related traits, while highlighting the role of vegetative vigor and biochemical accumulation in mitigating Fusarium wilt effects.

These results suggest that genotypes clustering with favorable traits could serve as promising candidates for breeding programs aimed at developing wilt-tolerant and high-quality tomato cultivars.

In conclusion, significant variability was observed among tomato genotypes for growth, yield, biochemical traits, and resistance to Fusarium wilt. Disease severity was negatively associated with fruit quality and yield, while genotypes with higher vegetative vigor and phenolic content performed better under stress. Multivariate analysis further distinguished tolerant lines from susceptible ones, with D1, Arka Rakshak, and Arka Alok identified as promising candidates for resistance breeding.

These findings provide a useful basis for developing tomato cultivars combining wilt tolerance, stable yield, and good fruit quality.

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Authors' Contributions

KS conceptualized the study, conducted the pot experiments, collected data, performed analysis, and drafted the manuscript. SC supervised the research, guided the experimental design and data analysis, and revised the manuscript. SKY provided the genetic materials, offered guidance on Fusarium wilt screening, and critically reviewed the manuscript. SK assisted with data analysis, interpretation of results, and manuscript editing. KSg supported statistical analysis, interpreted PCA results, and contributed to critical revision of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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