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Dissecting thermotolerance traits of tomato (*Solanum lycopersicum* L.) genotypes for crop improvement

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Abstract
High temperature being a major abiotic stress affecting crop production, incorporating thermotolerance is a priority in crop improvement. Screening of 30 tomato genotypes for thermotolerance traits and yield was done under laboratory and field conditions in favourable and summer seasons. Thermotolerance traits namely, pollen and style characters and membrane stability, along with major yield characters were evaluated. Individual traits, combination of traits, and per cent change with season, were considered to identify superior genotypes. AVTO 0922, AVTO 1725, EC 523851, EC 528368, EC 620486, EC 620488, and Vellayani Vijay displayed superior membrane stability coupled with above average pollen viability and germination in laboratory screening. Per cent change in tolerance traits in summer compared to favourable season was lower in EC 528360, EC 528368, EC 523851, EC 636872, EC 620494, and EC 549819. Akshaya, Anagha, Arka Rakshak, AVTO 1707 and AVTO 1314 which had higher fruit set per cent, fruit yield per plant and average fruit weight can be utilised for yield improvement.

Keywords: Heat tolerant genotypes, High temperature screening, Morphological traits, Pollen thermotolerance, Thermotolerance, Tomato.

Introduction

Global temperature shows an increasing trend, particularly in low latitude tropical regions. High temperature is seen as a serious threat to agriculture in the current context of global warming, with significant effects on yield and quality. Tomato (*Solanum lycopersicum* L., 2n=24), the most widely grown and consumed vegetable in the world, can be used in both raw and processed form. Tomatoes are grown in both tropical and sub-tropical regions, but they require a dry, relatively cold climate to produce the best quality and yield. The crop needs a temperature between 18°C and 25°C to thrive (Hurd and Cooper, 1970). Tomatoes prefer a daily mean temperature of between 21°C and 24°C, depending on their stage of growth (Ayankojo and Morgan, 2020).

Heat stress alters plant morphology, physiology, biochemistry, and molecular pathways in crop species including tomato. Each degree rise in temperature above 25°C significantly impacts tomato yield. It has been reported that high temperatures can reduce tomato yield by 28 to 70 percent (Alsamir et al., 2019; Ro et al., 2021). Extreme heat has a significant impact on a number of floral characteristics, which in turn influences fruit set and yield. Parameters like membrane stability, photosynthetic activity, pollen viability, style exsertion and fruit set can be used to assess thermotolerance. Fruit set was found to be the best

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indicator of the ability of genotype to withstand high temperatures (Firon et al., 2006). Screening a wild species population of tomato for reproductive traits under heat stress conditions by Gonzalo et al. (2020) found that pollen viability and fruit set were not correlated. Tolerance of tomato genotypes to heat stress has been found to be reliably assessed by a number of parameters, including membrane thermo-stability, floral characteristics (such as stigma exsertion and antheridia cone splitting), flower number, and fruit yield per plant (Alsamir et al., 2021). Heat stress during anthesis stage leads to abnormal style elongation, and anther and pollen development,which in turn leads to a dramatic decrease in fruit set in tomato (Giorno et al., 2013). Identifying thermo-tolerant tomato genotypes is crucial for crop improvement programs in climate-resilient agriculture.

Materials and methods

The study was conducted at College of Agriculture, Vellanikkara, Thrissur, Kerala situated between 10°32’47" N and 76°16’43" E at an altitude of 97 m above MSL. Thirty tomato genotypes evaluated in this study included NBPGR accessions, hybrids from IIHR, Bengaluru, lines from the World Vegetable Centre, Taiwan, and varieties released from Kerala Agricultural University (Table 1). To assess their performance for yield traits and thermotolerance, field and laboratory screening were conducted in summer and favourable season respectively.Weather parameters at Vellanikkara during the study period is given in Table 2. Flowers utilised for laboratory screening experienced an average maximum and minimum temperature of 32/23°C. Temperature during flowering period in the field screening was 42.8/29.1°C (Max/Min temperature).

Table 1. Genotypes used for the study

No.	Genotypes	Source
1	Akshaya	KAU
2	Anagha	KAU
3	Arka Abhed	IIHR, Bengaluru
4	Arka Rakshak	IIHR, Bengaluru
5	Arka Samrat	IIHR, Bengaluru
6	Arka Vishesh	IIHR, Bengaluru
7	AVTO 0301	World Vegetable Centre, Taiwan
8	AVTO 0922	World Vegetable Centre, Taiwan
9	AVTO 1314	World Vegetable Centre, Taiwan
10	AVTO 1702	World Vegetable Centre, Taiwan
11	AVTO 1706	World Vegetable Centre, Taiwan
12	AVTO 1707	World Vegetable Centre, Taiwan
13	AVTO 1725	World Vegetable Centre, Taiwan
14	AVTO 1726	World Vegetable Centre, Taiwan
15	EC 315489	NBPGR
16	EC 523851	NBPGR
17	EC 528360	NBPGR
18	EC 528368	NBPGR
19	EC 538153	NBPGR
20	EC 549819	NBPGR
21	EC 567305	NBPGR
22	EC 620428	NBPGR
23	EC 620486	NBPGR
24	EC 620488	NBPGR
25	EC 620494	NBPGR
26	EC 631354	NBPGR
27	EC 636872	NBPGR
28	Manuprabha	KAU
29	Manulakshmi	KAU
30	Vellayani Vijay	KAU

Table 2. Weather parameters at Vellanikkara during the study period

Month	Temperature (°C)				Mean Relative humidity (%)
	Mean maximum	Highest maximum	Mean minimum	Lowest minimum	
August (2022)	29.9	32.6	23.6	22.2	84
September (2022)	31.1	33.3	23.7	22.9	81
October (2022)	32.0	33.8	23.6	21.6	77
November (2022)	32.4	34.1	23.0	21.0	73
December (2022)	32.2	34.4	22.6	18.6	66
January (2023)	33.3	35.0	22.6	18.9	56
February (2023)	34.8	36.2	23.3	19.5	84
March (2023)	37.0	38.0	36.1	24.2	57
April (2023)	36.8	40.0	25.5	23.6	67
May (2023)	34.7	36.2	25.7	23.5	74
June (2023)	31.8	35.1	24.4	22.8	83

Experiments were laid out in completely randomised design (CRD), with two and three replications for field and laboratory screening respectively. Physiological traits (electrolyte leakage), morphological traits (pollen viability, pollen germination, style length and style protrusion), phenological trait (days to 50 per cent flowering), yield characters (fruit set per cent, deformed fruits per cent, number of fruits per plant, average fruit weight and fruit yield per plant) and plant height were evaluated during the study.

Newly opened flowers were collected for pollen viability study and anthers were dissected. Dissected anthers were cut into pieces, kept in an Eppendorf tube and distilled water was added to make a suspension of pollen. Pollen viability was determined using one per cent acetocarmine stain (Singh, 2003), and count of viable and non-viable pollen was recorded.

$$\text{Pollen viability} = \frac{\text{No. of viable pollen}}{\text{Total no. of pollen}} \times 100$$

(Mosquera et al., 2021). Pollen suspension was spread on germination medium (Zhou et al., 2015) containing, sucrose (120 g/L), boric acid (120 mg/L), gibberellin (4 mg/L), thiamine (0.5 mg/L) and agar (1%). After incubating at room temperature (27-30 °C), 35 °C and 40 °C for eight hours, number of germinated pollen and total number of pollen per field was recorded under a microscope (40X).

$$\text{Pollen germination (\%)} = \frac{\text{No. of pollen germinated}}{\text{Total no. of pollen}} \times 100$$

When the stigma is elongated above the anther cone, the style is considered as protruded. Thus, number of flowers with protruded style and total number of flowers were recorded to find out style protrusion per cent.

$$\text{Style protrusion (\%)} = \frac{\text{No. of flowers with protruded style in a cluster}}{\text{Total no. of flowers in a cluster}} \times 100$$

Leaf tissue was used for determining electrical conductivity (EC) using the method suggested by Yeh and Lin (2003) and electrolyte leakage per cent was calculated.

$$\text{Electrolyte Leakage (\%)} = \frac{\text{Initial EC}}{\text{Final EC}} \times 100$$

On the day of flower opening, the length of the style was measured from the tip of the ovary to the tip of the stigma.

Number of flowers that have been transformed to fruits were accounted in fruit set per cent.

$$\text{Fruit set (\%)} = \frac{\text{No. of set flowers / cluster}}{\text{Total no. of flowers buds cluster}} \times 100$$

(Dahal et al., 2015)

Number of flowers that failed to attain the status of mature harvestable fruits were accounted in deformed fruits per cent.

$$\text{Deformed fruits (\%)} = \frac{\text{No. of flowerbuds - No. of fruits harvested}}{\text{No. of flowers buds}} \times 100$$

Total number, average weight, and total weight of the fruits produced by each plant was recorded. Plant height, from the ground level to the topmost leaf bud was also recorded as a growth parameter. Observations on morphological and physiological traits were statistically analysed using KAU GRAPES software (Gopinath et al., 2021).

Results and discussion

Electrolyte leakage, pollen viability, pollen germination and style protrusion were assessed under laboratory screening during the favourable season (October). Under field screening (summer season), morphological traits were assessed in addition to plant height and yield characteristics.

Laboratory screening (September – January)

The least electrolyte leakage was recorded by Arka Samrat (18.47%) (Table 3). Akshaya, Arka Rakshak, AVTO 0301, EC 523851, EC 528368, EC 549819, EC 636872, and Manulakshmi had significantly higher electrolyte leakage compared to Arka Samrat.

Table 3. Pollen germination (%) at different temperature conditions and electrolyte leakage (%) of genotype

Accessions	Room temperature	At 35°C	At 40°C	Electrolyte leakage (%)
Akshaya	16.35 (29.73[cdef])	9.28 (16.75[def])	8.81 (15.90[b])	58.08[bc]
Anagha	12.19 (21.99[cdef])	3.57 (6.42[f])	3.45 (6.22[bcdef])	26.10[ghi]
Arka Abhed	13.10 (23.66[cdef])	6.71 (12.29[ef])	2.01 (3.78[cdef])	25.67[ghi]
Arka Rakshak	13.21 (23.89[cdef])	9.00 (16.25[ef])	1.23 (2.39[def])	41.27[defg]
Arka Samrat	18.56(33.68[bcdef])	15.28(27.65[bcdef])	3.81 (6.86[bcdef])	18.47[i]
Arka Vishesh	14.37 (25.96[cdef])	4.34 (7.81[f])	2.22 (4.00[cdef])	21.42[i]
AVTO 0301	38.67 (72.69[a])	22.03(40.02[abcd])	3.89 (7.01[bcdef])	79.50[a]
AVTO 0922	26.44(48.24[abcd])	24.61 (44.78[ab])	2.53 (4.55[cdef])	30.57[fghi]
AVTO 1314	15.83 (28.73[cdef])	9.20 (16.59[def])	0.00 (0.50[f])	20.22[i]
AVTO 1702	23.78(43.31[bcde])	13.48(24.35[bcdef])	2.21 (3.98[cdef])	28.47[fghi]
AVTO 1706	39.56 (73.21[a])	32.48 (62.39[a])	8.95 (16.15[b])	22.78[hi]
AVTO 1707	14.17 (25.64[cdef])	4.65 (8.38[f])	2.01 (3.61[cdef])	27.68[fghi]
AVTO 1725	25.55(46.88[abcd])	22.71 (41.26[abc])	3.21 (5.78[bcdef])	22.78[hi]
AVTO 1726	32.72 (60.40[ab])	18.06(32.71[bcde])	3.12 (5.78[bcdef])	24.66[hi]
EC 315489	11.48 (20.73[def])	6.20 (11.35[ef])	2.56 (4.77[cdef])	30.33[fghi]
EC 523851	23.83 (43.50[bcd])	18.00(32.61[bcde])	3.31 (5.96[bcdef])	38.16[defgh]
EC 528360	27.04 (49.51[abc])	12.24(22.09[bcdef])	1.96 (3.86[cdef])	27.69[fghi]
EC 528368	11.49 (20.75[def])	9.92 (17.90[cdef])	7.20 (13.15[bc])	51.46[bcd]
EC 538153	14.33 (25.89[cdef])	3.09 (5.57[f])	0.64 (1.49[ef])	21.27[i]
EC 549819	16.04 (29.00[cdef])	2.81 (5.22[f])	0.76 (1.70[ef])	43.60[cdef]
EC 567305	15.38 (27.81[cdef])	8.25 (14.90[ef])	1.52 (3.06[cdef])	34.07[efghi]
EC 620428	8.11 (14.61[ef])	7.17 (12.93[ef])	6.48(11.88[bcde])	33.99[efghi]
EC 620486	23.49(42.82[bcde])	9.12 (16.47[def])	8.99 (16.22[b])	27.96[fghi]
EC 620488	22.45(40.83[bcde])	5.25 (9.46[ef])	1.60 (3.05[cdef])	28.42[fghi]
EC 620494	11.51 (20.85[cdef])	10.45(19.05[cdef])	6.85(12.53[bcd])	31.15[fghi]
EC 631354	17.80(32.41[bcdef])	6.58 (11.85[ef])	1.60 (3.05[cdef])	29.40[fghi]
EC 636872	3.69 (6.64[f])	2.60 (4.85[f])	2.41 (4.51[cdef])	62.12[b]
Manulakshmi	3.93 (7.08[f])	2.68 (4.83[f])	0.00 (0.50[f])	48.94[bcde]
Manuprabha	20.02(36.29[bcde])	11.08 (20.00[cdef])	0.23 (0.75[f])	19.59[i]
Vellayani Vijay	32.37 (60.50[ab])	24.52 (44.80[ab])	17.85(32.32[a])	29.57[fghi]
CD	15.28 (28.74)	12.29 (23.65)	5.94 (10.56)	16.4
SE(d)	7.64 (14.37)	6.14 (11.83)	2.97 (5.28)	8.2

Table 4. Performance of superior genotypes based on combination of traits in the favourable season

Genotypes	PV-PG (room temperature)	PV-PG at 35°C	PV-PG at 40°C	PV-SP
EC 523851	✓	✓		✓
EC 620486	✓		✓	✓
EC 620488	✓			✓
EC 528368			✓	✓
AVTO 0922	✓	✓		✓
AVTO 1725		✓		✓
Vellayani Vijay	✓	✓	✓	✓

✓ Indicates that the genotype performed well under the trait combination. PV-Pollen Viability, PG-Pollen Germination and SP-Style protrusion

Alsamir et al. (2017) found a mean electrolyte leakage of 27.5+0.79 μmhos/cm in tomato under control conditions. Ullah and Ayub (2021) reported a leakage of 57.77 per cent in tomato genotypes under field conditions. In this study, the mean leakage was 33.51 per cent, which was lower than the above reports. Srivastava et al. (2012) reported 18-52 per cent electrolyte leakage in tomato (38/22.2°C), while 18.47- 79.50 per cent was observed in the current study indicating higher variability among genotypes tested.

Pollen viability was highest in EC 523851 (81.64%) and lowest in EC 631354 (21.16%). In terms of pollen viability, EC 523851 (81.64%) outperformed Vellayani Vijay (59.47%), whereas, EC 549819, EC 620428, and EC 631354 were significantly below and all other genotypes were on par with Vellayani Vijay (Table 5). Laxman et al. (2018) reported 44.65 per cent average pollen viability in tomato at 30 +

Table 5. Performance of genotypes under both seasons for thermotolerant traits

Accessions	Pollen viability (%)		Style length (cm)		Style protrusion (%)	
	October	May	October	May	October	May
Akshaya	62.28(126.19^{abcde})	12.59 (22.72^{bcd})	0.61^{efghi}	0.64^{ab}	45.67(85.64^{cd})	78.32 (162.11^{a})
Anagha	59.83 (116.34^{bcde})	10.58 (19.08^{bcd})	0.63^{defgh}	0.53^{defg}	43.33(80.70^{de})	65.69 (129.56^{b})
Arka Abhed	47.33 (88.78^{cdefg})	7.87 (14.18^{bcd})	0.54^{hijkl}	0.44^{jklm}	15.33(27.71^{lm})	32.82 (60.22^{gh})
Arka Rakshak	47.67 (89.49^{cdefg})	4.30 (7.73^{cd})	0.65^{cdefg}	0.62^{abc}	23.67(43.01^{hijk})	73.13 (147.78^{a})
Arka Samrat	45.22 (84.47^{defg})	4.14 (7.46^{cd})	0.49^{jkl}	0.44^{jklm}	20.00 (36.25^{jkl})	47.13 (88.34^{e})
Arka Vishesh	41.66 (77.37^{efg})	3.68 (6.62^{cd})	0.59^{efghij}	0.62^{abc}	24.33(44.47^{ghijk})	29.70 (54.28^{ghi})
AVTO 0301	47.33 (88.78^{cdefg})	5.87 (10.57^{cd})	0.72^{abcd}	0.64^{ab}	20.67 (37.47^{jkl})	47.47 (89.05^{e})
AVTO 0922	66.22(130.34^{abcde})	6.27 (11.29^{cd})	0.48^{kl}	0.40^{lm}	7.67 (13.84^{no})	14.64 (26.44^{lm})
AVTO 1314	41.66 (77.37^{efg})	1.85 (3.33^{d})	0.74^{abc}	0.66^{a}	23.33 (42.40^{hijk})	51.46 (97.30^{de})
AVTO 1702	62.56 (121.67^{bcde})	7.33 (13.21^{bcd})	0.50^{jkl}	0.46^{ijkl}	11.67 (21.05^{mn})	44.06 (82.22^{ef})
AVTO 1706	47.67 (89.49^{cdefg})	6.61 (11.91^{cd})	0.77^{ab}	0.59^{bcd}	19.33 (35.03^{kl})	49.76 (93.80^{de})
AVTO 1707	45.22 (84.47^{defg})	6.74 (12.15^{cd})	0.82^{a}	0.62^{abc}	27.33 (49.84^{ghij})	60.74 (117.53^{bc})
AVTO 1725	63.67(124.28^{abcde})	5.07 (9.13^{cd})	0.50^{jkl}	0.47^{ghijk}	23.00 (41.78^{hijk})	33.06 (60.68^{gh})
AVTO 1726	52.67(99.91^{cdef})	7.41 (13.35^{bcd})	0.54^{hijkl}	0.49^{fghij}	19.67 (35.64^{kl})	48.87 (91.96^{de})
EC 315489	63.67(124.28^{abcde})	7.67 (13.81^{bcd})	0.67^{bcde}	0.45^{jklm}	30.00 (54.88^{gh})	27.73 (50.58^{ghij})
EC 523851	81.64(176.62^{a})	9.08 (16.36^{bcd})	0.55^{fghijk}	0.46^{hijkl}	0.00 (0.01^{p})	20.28 (36.76^{ijklm})
EC 528360	67.79(136.11^{abcd})	55.50 (108.23^{a})	0.65^{cdef}	0.65^{ab}	76.33 (156.50^{a})	55.80 (106.95^{cd})
EC 528368	59.42(120.11^{bcde})	10.06 (18.15^{bcd})	0.52^{ijkl}	0.42^{jklm}	31.00 (56.79^{fg})	19.86 (35.99^{jklm})
EC 538153	69.85(141.29^{abc})	7.11 (12.81^{bcd})	0.72^{abcd}	0.54^{def}	25.67(46.74^{ghijk})	13.15 (23.73^{m})
EC 549819	32.04(58.94^{fg})	17.89 (32.39^{b})	0.47^{kl}	0.45^{ijklm}	58.67 (112.89^{b})	16.95 (30.65^{klm})
EC 567305	71.82(154.37^{ab})	6.43 (11.58^{cd})	0.44^{lm}	0.39^{m}	2.34 (4.21^{op})	11.94 (21.55^{m})
EC 620428	30.94(57.05^{fg})	6.99 (12.59^{cd})	0.59^{efghij}	0.53^{defgh}	37.33 (68.91^{ef})	20.10 (36.43^{jklm})
EC 620486	66.22(130.34^{abcde})	4.87 (8.76^{cd})	0.65^{cdef}	0.56^{cde}	52.33 (99.17^{c})	24.54 (44.63^{hijk})
EC 620488	62.52(129.19^{abcde})	6.86 (12.35^{cd})	0.35^{m}	0.39^{m}	22.00 (39.93^{ijkl})	28.93 (52.84^{ghij})
EC 620494	44.06(84.89^{defg})	12.53 (22.61^{bcd})	0.55^{fghijk}	0.45^{jklm}	0.00 (0.01^{p})	20.39 (36.97^{ijklm})
EC 631354	21.16(38.38^{g})	1.87 (3.37^{d})	0.53^{hijkl}	0.43^{jklm}	29.00 (52.96^{ghi})	23.18 (42.10^{ijkl})
EC 636872	58.08(114.64^{bcde})	14.43 (26.06^{bc})	0.55^{ghijkl}	0.46^{hijkl}	8.00 (14.44^{mno})	19.71 (35.74^{jklm})
Manulakshmi	43.09 (80.32^{efg})	3.46 (6.22^{d})	0.53^{hijkl}	0.52^{efghi}	29.33 (53.62^{gh})	16.96 (30.68^{klm})
Manuprabha	59.67(116.53^{bcde})	4.41 (7.94^{cd})	0.74^{abc}	0.65^{ab}	21.33(38.72^{jkl})	36.61 (67.53^{fg})
Vellayani Vijay	59.47(117.95^{bcde})	8.25 (14.87^{bcd})	0.52^{ijkl}	0.41^{klm}	45.00 (84.11^{d})	27.16 (49.60^{hij})
CD	22.78 (53.75)	9.20 (19.67)	0.11	0.07	7.17 (13.68)	8.41 (17.65)
SE(d)	11.39 (26.87)	4.50 (9.63)	0.05	0.03	3.59 (6.84)	4.12 (8.64)

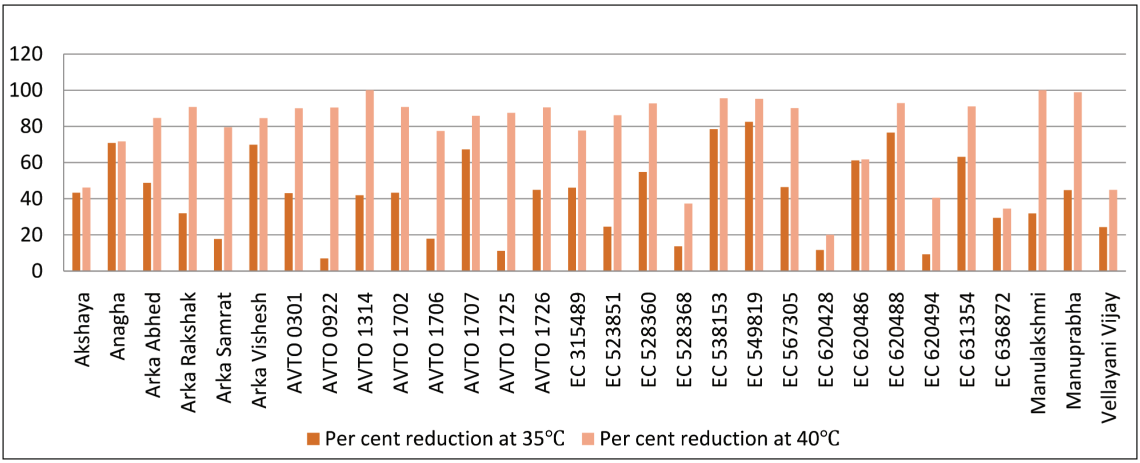

Figure 1. Per cent reduction in pollen germination at 35 °C and 40 °Ccompared to room temperature.

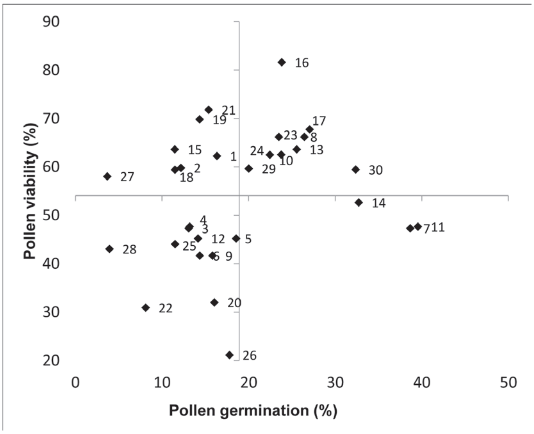

Figure 2. Pollen viability and pollen germination at room temperature of pollen collected from the genotypes in favourable season (October). Note: 1-30 order of genotypes as specified in Table 1

0.5°C, while Srivastava et al. (2012) reported average pollen viability between 66.36 to 95.48 per cent (27.12/15.15°C). These results were in agreement with our observations, which showed that at 32 °C, pollen viability varied from 21.16 to 81.64 per cent.

Pollen viability was higher than pollen germination for all the genotypes, indicating that all viable pollen grains need not germinate. Pollen germination at 35°C and 40°C were lower than that at room temperature, *i.e.*, there was an evident decrease in pollen germination as temperature increased. In comparison to room temperature, EC 528368, EC 620428, and EC 620494 recorded a smaller decrease in pollen germination at 35°C and 40°C. AVTO 0922 and EC 620428 recorded the lowest and highest reduction in pollen germination under 35°C and 40°C, respectively (Fig. 1). Despite having a high pollen viability, EC 636872 and Manuprabha exhibited lower germination percentage at all temperatures. Although, EC 523851, followed by EC 567305, EC 538153, EC 528360, EC 620486 and AVTO 0922 had the highest pollen viability, AVTO 0301 and AVTO 1706 had the highest pollen germination rate at room temperature. At 35°C, there was higher pollen germination (>20%) in AVTO 0922, AVTO 0301, AVTO 1706 and Vellayani Vijay compared to other genotypes. At 40°C, EC 620494, EC 620428, EC 620486, EC 528368, AVTO 1706, Akshaya, and Vellayani Vijay exhibited higher pollen germination compared to other genotypes, while AVTO 1314 and Manuprabha pollen did not germinate (Table 3). Zhou et al. (2015), Srivastava et al. (2012), Laxman et al. (2018), and Lee et al. (2022) reported similar reduction in pollen germination at high temperature (above 30°C) in tomato. Scatter plot comparing pollen viability and pollen germination at 35°C showed that, EC 523851, EC 528360, AVTO 0922, AVTO 1702, AVTO 1725, and Vellayani Vijay were superior for these traits (Fig. 3).

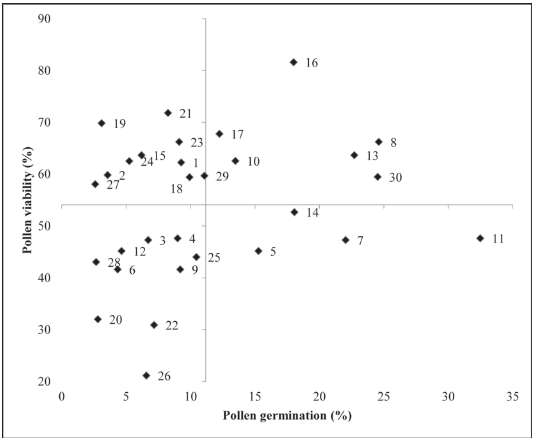

Figure 3. Pollen viability and pollen germination at 35°C of pollen collected from the genotypes in favourable season (October). Note: 1-30 order of genotypes as specified in Table 1

Style length was shorter than the overall mean (0.59 cm) and on par with Vellayani Vijay (0.52 cm) for EC 523851, EC 620494, EC 636872, Arka Abhed, AVTO 1726, Manulakshmi, EC 631354, EC 528368, AVTO 1702, AVTO 1725, Arka Samrat, AVTO 0922, EC 549819, EC 567305 and EC 620488 (Table 5). The current study observed a larger variation for the trait than observed by Pan et al. (2019) in tomato. Driedonks et al. (2018) reported higher style lengths for wild tomato genotypes which is considered beneficial for the reproductive success and adapting to the environment. The position of stigma relative to anthers can be influenced by high temperature conditions, leading to stigma exsertion and subsequently causing fruit set failure (Pan et al., 2019; Alsamir et al., 2021; Riccini et al., 2021).

Style protrusion of Akshaya and Anagha was comparable to that of Vellayani Vijay (45%). Compared to Vellayani Vijay, EC 549819 and EC 528360 had substantially greater style protrusion. All other genotypes were significantly superior with lower style protrusion than Vellayani Vijay. The highest style protrusion was recorded by EC 528360 (76.33%). EC 523851 and EC 620494 showed absence of style protrusion (Table 5). Our findings were in agreement with that of Pan et al. (2019) who reported 65.2 per cent average style protrusion under 33/28°C in tomato.

To identify the genotypes superior for combination of desirable traits, scatter plot combining male and female reproductive characters was used. EC 523851, EC 528360, EC 620486, EC 620488, AVTO 0922, AVTO 1702, Manuprabha and Vellayani Vijay were superior with respect to pollen viability and pollen germination at room temperature (Fig. 2). Considering pollen viability and pollen germination at 35°C, EC 523851, EC 528360, AVTO 0922, AVTO 1702, AVTO 1725 and Vellayani Vijay performed better (Fig. 3). EC 528368, EC 620486,

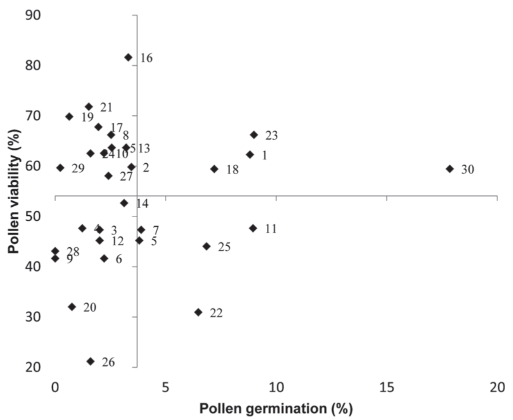

Figure 4. Pollen viability and pollen germination at 40°C of pollen collected from the genotypes in favourable season (October). Note: 1-30 order of genotypes as specified in Table 1

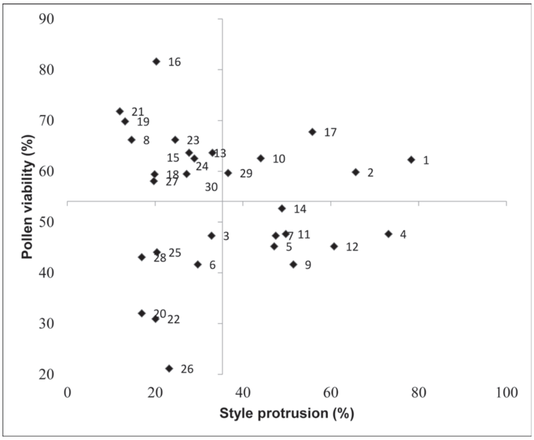

Figure 5. Performance of genotypes for combination of pollen viability and style protrusion. Note: 1-30 order of genotypes as specified in Table 1

Akshaya and Vellayani Vijay performed better for both pollen viability and pollen germination at 40°C (Fig. 4). EC 315489, EC 523851, EC 528368, EC 538153, EC 567305, EC 620486, EC 620488, EC 636872, AVTO 0922, AVTO 1725 and Vellayani Vijay were the genotypes having higher pollen viability coupled with low style protrusion (Fig. 5). Pollen germination and style protrusion are the main male and female reproductive traits that will influence yield of tomato under stress condition. Thus, EC 528351, EC 620486, EC 620488, EC 528368, AVTO 0922, AVTO 1725 and Vellayani Vijay can be considered as the superior genotypes for reproductive traits (Table 4).

Field screening (March - June)

Genotypes were evaluated in the summer season in open field, and morphological traits were assessed in addition to plant height and yield characteristics. For pollen viability, EC 528360 (55.5%) was significantly superior than all tested genotypes including Vellayani Vijay. AVTO 1314 recorded the lowest pollen viability. A reduction in pollen viability was observed in the summer season compared to that under favourable season. EC 528360 and EC 549819 showed less than 50 per cent reduction, while, AVTO 1314 recorded more than 90 per cent reduction in pollen viability. EC 636872, EC 523851, EC 528360, EC 528368,

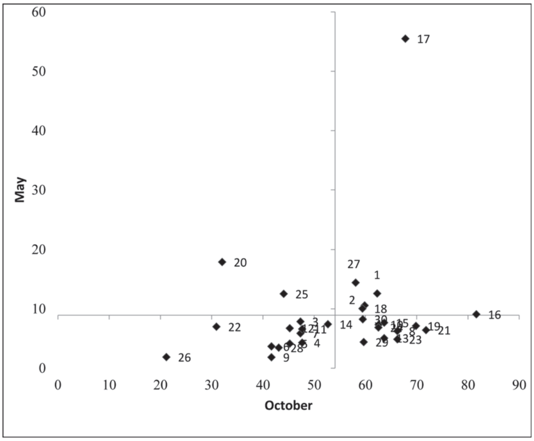

Figure 6. Scatter plot of pollen viability (%) in both favourable (October) and summer (May) seasons. Note: 1-30 order of genotypes as specified in Table 1.

Anagha and Akshaya performed well under both seasons (Fig. 6) and had lower reduction in pollen viability (Table 5).

Genotypes differed in their response to temperature with respect to style length. Increase in style length was shown by Arka Vishesh, Akshaya and EC 620488, while all other genotypes showed reductionin style length. Saeed et al. (2007) and Akhtar et al. (2012) reported an increase in style length in tomato due to rise in temperature. Style length is a genotype dependent trait, and Saeed et al. (2007) observed that style length increased by

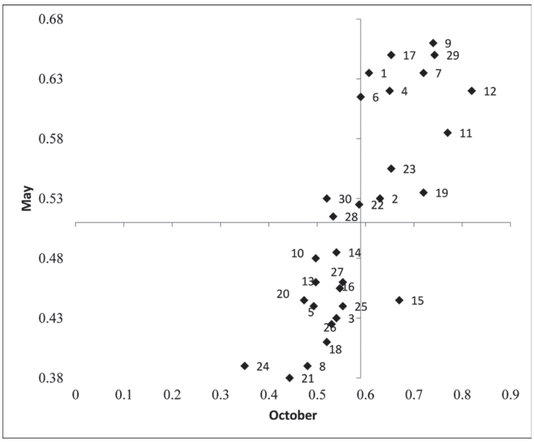

Figure 7: Scatter plot of style length (cm) in both favourable (October) and summer (May). Note: 1-30 order of genotypes as specified in Table 1.

25-55 per cent when exposed to high temperatures in different tomato genotypes. Current study also observed an increase in style length in some genotypes, while a reduction in style length was seen in some genotypes, and this reduction can be attributed to the smaller size of the flowers during high temperature.

Genotypes that performed superior than Vellayani Vijay in summer season with low style protrusion were AVTO 0922, EC 538153, EC 549819, EC 567305 and Manulakshmi. Genotypes other than EC accessions, Vellayani Vijay and Manulakshmi showed an increase in style protrusion in summer compared to favourable season (Table 5). According to Srivastava et al. (2012), at an average day/night temperature of 38°C/22.2°C, there was a significant increase in stigma exertion (7.82-50.35%). Arka Abhed, Arka Vishesh, AVTO 0922, AVTO 1725, EC 523851, EC 538153, EC 567305, EC 620488, EC 620494 and EC 636872 performed well (exhibited lower style protrusion) in both seasons (Fig. 8).

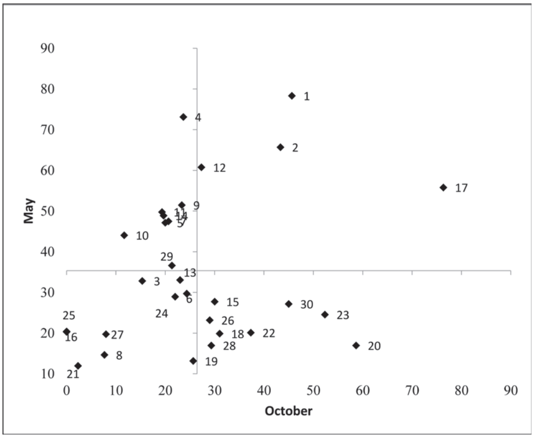

Figure 8: Scatter plot of style protrusion (%) in both favourable (October) and summer (May) seasons. Note: 1-30 order of genotypes as specified in Table 1

High pollen viability and low style protrusion are desirable thermotolerance traits. EC 528360 had high pollen viability, while AVTO 0922, EC 538153, EC 567305, EC 620428, EC 620486 and Manulakshmi showed low style protrusion. EC 523851, EC 528368, EC 549819, EC 620494, EC 636872 and Vellayani Vijay were superior when

Table 6. Yield traits of genotypes in the summer season

Accessions	Fruit set (%)	Plant height (cm)	Deformed fruits (%)	Days to 50% flowering	Number of fruits/plant	Fruit yield/ plant (g)	Average fruit weight (g)
Akshaya	68.24 (135.25^{b})	46.95^{efghi}	92.79 (214.04)	39.50^{jk}	1.75^{de}	27.00^{b}	21.43^{cd}
Anagha	35.01 (64.47^{fgh})	41.15^{hijk}	93.06 (215.61)	35.00^{kl}	1.88^{cd}	26.53^{bc}	16.38^{gh}
Arka Abhed	25.86 (47.09^{ijklm})	38.83^{ijk}	89.25 (199.43)	52.50^{abc}	1.14^{gh}	16.17^{efghijk}	20.17^{cde}
Arka Rakshak	57.30 (109.85^{c})	68.04^{a}	91.08 (206.29)	49.00^{bcdef}	1.44^{defgh}	37.11^{a}	34.42^{a}
Arka Samrat	28.02 (51.13^{hijk})	66.87^{ab}	89.73 (203.03)	42.50^{ghij}	1.29^{efgh}	22.57^{bcdef}	25.22^{b}
Arka Vishesh	47.53 (89.15^{d})	66.20^{ab}	84.74 (182.46)	45.50^{efgh}	1.42^{defgh}	21.64^{bcdefg}	18.61^{ef}
AVTO 0301	21.75(39.47^{klmnop})	50.20^{cdef}	93.63 (218.57)	55.00^{a}	1.42^{defgh}	25.74^{bc}	22.21^{c}
AVTO 0922	22.15 (40.21^{klmno})	49.15^{defgh}	89.24 (199.38)	51.50^{abcd}	1.13^{gh}	10.99^{jklmn}	18.23^{efg}
AVTO 1314	75.63 (154.40^{a})	53.70^{cde}	90.55 (203.85)	50.00^{bcde}	1.34^{efgh}	24.34^{bcde}	25.50^{b}
AVTO 1702	24.64 (44.82^{ijklmn})	44.30^{fghi}	94.07 (220.63)	42.00^{hij}	1.55^{defgh}	15.16^{fghijk}	17.59^{fg}
AVTO 1706	35.78 (65.87^{fg})	49.80^{defg}	94.06 (220.94)	55.00^{a}	1.39^{defgh}	20.33^{bcdefgh}	18.22^{efg}
AVTO 1707	47.84 (89.79^{d})	48.67^{defgh}	89.75 (200.56)	49.00^{bcdef}	2.26^{bc}	26.53^{bc}	13.57^{i}
AVTO 1725	38.70 (71.54^{ef})	54.54^{cde}	93.39 (217.08)	48.00^{cdef}	1.18^{fgh}	16.26^{defghijk}	18.88^{ef}
AVTO 1726	16.64 (30.09^{op})	49.67^{defg}	94.62 (223.81)	45.50^{efgh}	1.24^{fgh}	18.23^{cdefghijk}	21.07^{cd}
EC 315489	14.44 (26.09^{p})	33.22^{kl}	94.53 (222.96)	34.00^{l}	1.14^{gh}	9.80^{klmn}	12.83^{i}
EC 523851	29.83 (54.53^{ghij})	39.20^{ijk}	91.35 (208.49)	44.50^{fghi}	1.33^{efgh}	13.31^{ghijkl}	12.77^{i}
EC 528360	29.84 (54.61^{ghij})	43.12^{fghij}	91.72 (209.07)	40.50^{ij}	1.42^{defgh}	12.54^{hijklm}	10.63^{j}
EC 528368	27.40 (49.96^{ijkl})	54.60^{cde}	94.99 (227.04)	26.50^{m}	1.45^{defgh}	6.52^{lmn}	4.61^{k}
EC 538153	27.67 (50.47^{ijk})	41.45^{ghijk}	92.03 (211.45)	52.50^{abc}	1.09^{h}	11.93^{hijklmn}	14.53^{hi}
EC 549819	24.40 (44.39^{ijklmn})	54.74^{cde}	94.77 (224.44)	29.00^{m}	1.61^{deg}	3.56^{n}	2.91^{k}
EC 567305	22.56 (40.95^{jklmno})	29.47^{l}	94.61 (223.41)	47.00^{defg}	1.17^{fgh}	4.05^{mn}	4.17^{k}
EC 620428	49.41 (93.13^{d})	44.22^{fghi}	95.57 (229.18)	45.50^{efgh}	1.30^{efgh}	16.77^{defghijk}	21.92^{c}
EC 620486	20.10 (36.44^{lmnop})	34.07^{kl}	93.67 (218.43)	50.00^{bcde}	1.24^{fgh}	11.26^{ijklmn}	12.70^{ghi}
EC 620488	18.33 (33.19^{nop})	42.94^{fghij}	92.97 (216.30)	53.00^{ab}	1.11^{gh}	5.70^{lmn}	9.02^{j}
EC 620494	30.29 (55.42^{ghi})	47.29^{efghi}	92.67 (214.12)	50.00^{bcde}	1.30^{efgh}	14.01^{fghijkl}	14.15^{i}
EC 631354	24.10(43.82^{ijklmno})	58.50^{bc}	94.10 (220.58)	50.00^{bcde}	1.27^{efgh}	19.81^{bcdefghi}	21.03^{cd}
EC 636872	78.46 (162.47^{a})	43.02^{fghij}	88.43 (195.33)	35.00^{kl}	2.72^{ab}	9.91^{klmn}	3.72^{k}
Manulakshmi	19.33 (35.03^{mnop})	56.00^{cd}	93.71 (218.57)	48.50^{bcdef}	1.29^{efgh}	18.75^{bcdefghij}	17.54^{fg}
Manuprabha	35.93 (66.17^{efg})	47.70^{defgh}	87.09 (190.65)	51.00^{abcd}	1.66^{def}	24.82^{bcd}	19.71^{de}
Vellayani Vijay	42.88 (79.85^{de})	35.70^{jkl}	92.33 (211.88)	50.50^{abcd}	2.94^{a}	24.34^{bcde}	9.51^{j}
CD	7.05 (13.83)	8.5	NS	4.93	0.5	8.63	2.07
SE(d)	3.45 (6.77)	4.16	2.73 (12.21)	2.41	0.25	4.22	1.01

combination of both traits was considered. Hence, based on the field screening in summer season, EC 528360, EC 523851, EC 528368, EC 549819, EC 620494, EC 636872, EC 538153, EC 567305, EC 620428, EC 620486, AVTO 0922 Vellayani Vijay and Manulakshmi were identified for thermo tolerance traits.

For plant height, genotypes on par with Vellayani Vijay were, Anagha, Arka Abhed, EC 315489, EC 523851, EC 528360, EC 538153, EC 567305, EC 620486, EC 620488 and EC 636872. Plant height observed in the current study was in accordance with observations made by Solankey et al. (2017) and Chippy et al. (2021).

Reducing the time taken to reach 50 per cent flowering in tomatoes under high temperature condition plays a crucial role in plant adaptation. EC 315489, EC 528360, EC 528368, EC 523851, EC 549819, EC 620428, EC 636872, AVTO 1702, AVTO 1726, Arka Samrat, Arka Vishesh, Akshaya and Anagha recorded shorter days to 50 per cent flowering than Vellayani Vijay (50 DAT). EC 528368 showed earliest and AVTO 0301 recorded longset days to 50 per cent flowering (Table 6). The earlier flowering of tomato genotypes under high temperature was also reported by Solankey et al. (2017) and Chippy et al. (2021).

Akshaya, Arka Rakshak, AVTO 1314, and EC 636872 were superior to Vellayani Vijay for fruit set per cent. Highest and lowest fruit set per cent was recorded by EC 636872 and EC 315489 respectively and average fruit set recorded was 34.67 per cent. Due to ineffective physiological processes during the flowering and fruit development stages, fruit set is hindered at day/night temperatures above 32°C/21°C (Muthuvel et al., 2000). Vijayakumar and Beena (2020) and Srivastava et al. (2012) reported increased flower drop under prolonged heat stress.

Zhou et al. (2015), Srivastava et al. (2012) and Akhtar et al. (2012) also reported a reduction in fruit set per cent in tomato due to heat stress. There was no significant difference between the genotypes for deformed fruits percent (Table 6). All the genotypes recorded greater than 80 per cent deformed fruits per cent and average deformed fruits per cent recorded was 92.15 per cent.

Highest mean number of fruits per plant was recorded in Vellayani Vijay (2.94) and EC 636872 (2.72) while lowest was recorded in EC 538153 (1.09) (Table 6) in the summer season. Previous studies also reported a decrease in the number of fruits per plant in tomatoes when air temperature increased from 25°C to 29°C (Harel et al., 2014). Vellayani Vijay had low average fruit weight even though the number of fruits per plant was high. Except EC 528360, EC 620488, EC 528368, EC 549819, EC 567305 and EC 636872, all other genotypes were superior to Vellayani Vijay for average fruit weight. Solankey et al. (2017), and Rajametov et al. (2021) reported a reduction in average fruit weight in tomato under high temperature conditions.

Arka Rakshak had the highest fruit yield per plant as well as average fruit weight and was significantly superior than all the tested genotype (Table 6). Genotypes which were on par with Vellayani Vijay for fruit yield per plant were Arka Abhed, Arka Samrat, Arka Vishesh, AVTO 0301, AVTO 1314, AVTO 1706, AVTO 1707, AVTO 1725, AVTO 1726, EC 620428, EC 631354, Akshaya, Anagha, Manulakshmi and Manuprabha. According to Alsamir et al. (2017), high temperature stress caused an 88.8 per cent decrease in tomato fruit yield. Akhtar et al. (2012) and Vijayakumar et al. (2021) reported yield reduction ranging from 69 to 99 per cent in tomato under heat stress. Reduced assimilate allocation under high temperature stress compared to control temperature condition, according to Singh et al. (2005), resulted in lower yield. Yield-related traits are adversely affected by a decreased supply of photosynthates and a poor production of growth regulators in sink tissues, as noted by Islam (2011) and Hasanuzzaman et al. (2013).

In the present study, Arka Samrat, Arka Vishesh, EC 538153, AVTO 1314 and Manuprabha were identified for low electrolyte leakage; EC 636872, EC 523851, EC 528360, EC 528368, Anagha and Akshaya for superior pollen viability; and Arka Abhed, Arka Vishesh, AVTO 0922, AVTO 1725, EC 523851, EC 538153, EC 567305, EC 620488, EC 620494 and EC 636872 for low style protrusion. EC 523851, EC 528368, EC 549819, EC 620494, EC 636872 and Vellayani Vijay displayed high pollen viability along with low style protrusion in summer season. Akshaya, Anagha, Arka Abhed, Arka Samrat, Arka Vishesh, AVTO 0301, AVTO 1314, AVTO 1706, AVTO 1707, AVTO 1725, AVTO 1726, EC 620428, EC 631354, Manulakshmi and Manuprabha performed better for yield traits and had intermediate to poor performance for thermotolerance traits.

Conclusion

In the current scenario of changing climate, breeding for abiotic stress resistance is crucial. Tomato is a major vegetable crop cultivated in Kerala and is very much sensitive to fluctuating temperature. Evaluation of 30 tomato genotypes under favourable and summer season followed by yield assessment during summer revealed that EC 523851, EC

549819, EC 636872, EC 620494 and EC 528368 had thermotolerant traits, and were identified as tolerant genotypes. Akshaya, Anagha, Arka Samrat, Arka Vishesh, Arka Rakshak, AVTO 0301, AVTO 1314, AVTO 1707, EC 631354 and EC 620428 were the genotypes that performed better for yield traits.Among them Akshaya, Anagha, Arka Rakshak, AVTO 1707 and AVTO 1314 are the genotypes suggested for yield improvement as they possessed higher fruit set per cent, fruit yield per plant and average fruit weight. Thus, for incorporating thermotolerance and high yield in tomato, genotypes with high thermotolerance traits and high yield should be included in the breeding programme and evaluated for their co-existence.

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