Fruit Set, Pollen Fertility, and Combining Ability of Selected Tomato Genotypes under High-temperature Field Conditions

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Abstract. Selected tomato (Lycopersicon esculentum Mill) genotypes were evaluated for their fruit-setting ability under high-temperature field conditions. A temperature-controlled greenhouse study was conducted to determine the percent fruit set from the total number of flowers and fruit produced per plant. Ratings for set obtained under high-temperature field conditions were significantly (P = 0.001) correlated with percent fruit set determined under similar greenhouse conditions. Most of the Asian Vegetable Research and Development Center (AVRDC) selections, Beaverlodge lines, ‘Nagcarlan’, and ‘Red Cherry’ could be considered heat-tolerant. Small-fruited, abundantly flowering genotypes were less affected by heat stress than larger-fruited cultivars. Prolonged periods of high temperature caused drastic reductions in pollen fertility in most genotypes, except ‘Red Cherry’ and L. esculentum var. cerasiforme (PI 190256). Stigma browning and stigma exsertion commonly occurred on all lines, except AVRDC CL-5915-553 and PI 190256. Diallel analyses indicated that pollen fertility and fruit set under high field temperatures were primarily under additive gene control.

Materials and Methods

Screening for heat tolerance. Tomato breeding lines from the AVRDC, Taiwan; Canada (Beaverlodge); and Auburn Univ. (AU); plant introductions (PI) from the North Central Plant Introduction Station, Ames, Iowa; and cultivars from commercial companies were evaluated in 1985 and 1986 for their ability to set under high field temperatures at the Wiregrass Substation of the Alabama Agricultural Experiment Station, Headland. A randomized complete-block design with one (observational trial, 1985), two (1985), or three (1986) replications and 10 plants per replication or plot was used. Six-week-old plants were transplanted...
Table 1. Average %FS in the greenhouse, HS, %PF, stigma browning (SB), and stigma excretion (SE) of tomato genotypes under high temperatures in the field, 1985 and 1986.

| Entry            | %FS<sub>85</sub> | HS<sub>85</sub> | HS<sub>86</sub> | %PF<sub>85</sub> | SB | SE |
|------------------|------------------|----------------|---------------|-----------------|----|----|
| AVRDC-PT-3027    | 42.7 a           | 4.3 a-c        | 4.1 ab        | 7.7 b-d         | +  | +  |
| AVRDC CL-5915-153| 35.0 ab          | 4.3 a          | 4.5 ab        | 19.3 b-d        | +  | +  |
| AVRDC CLN05-392 | 28.8 bc          | 2.8 e-h        | 1.5 g-l       | 0.1 d           | -  | -  |
| AVRDC-PT-913     | 28.4 bc          | 4.5 ab         | 4.0 a-c       | 7.3 b-d         | +  | +  |
| Red Cherry       | 26.7 b-d         | (4.0)<sup>y</sup> | 4.2 a       | 80.6 a          | +  | -  |
| AVRDC CL-5915-553| 26.6 b-d         | 3.0 d-g        | 3.4 a-e       | 2.0 d           | -  | -  |
| AVRDC PT-4001    | 26.3 b-d         | 3.5 b-e        | 2.7 c-g       | 13.0 b-d        | +  | -  |
| AVRDC CL-5915-206| 25.5 b-f         | 2.9 d-h        | 2.7 b-g       | 30.6 b-d        | +  | +  |
| AVRDC CLN91-338  | 22.2 e-g         | 2.8 e-h        | 1.5 g-f       | 0.9 d           | +  | +  |
| Saladette        | 21.6 c-h         | 2.8 c-h        | 3.0 a-f       | 12.2 b-d        | -  | -  |
| AVRDC CLN95-280  | 20.5 c-i         | 3.3 c-f        | 3.1 a-e       | 2.0 d           | +  | +  |
| Nagcarlan        | 19.0 c-j         | 4.8 a          | 2.6 d-g       | 37.3 b          | +  | +  |
| AVRDC CLN65-349  | 18.3 d-k         | 3.3 c-f        | 4.1 ab        | 14.8 b-d        | +  | -  |
| AVRDC CL-5915-223| 16.5 e-l         | 4.3 a-c        | 3.2 a-e       | 6.2 cd          | +  | -  |
| PI 27275         | 15.7 f-l         | 3.2 c-f        | 2.6 d-g       | 34.5 bc         | +  | +  |
| AVRDC CL-5915-136| 15.4 g-l         | 4.0 a-d        | 2.8 b-g       | 24.6 b-d        | +  | +  |
| Beaverlodge 6808 | 14.8 g-l         | (4.0)          | 3.0 a-f       | 8.8 bc          | +  | +  |
| Karlick          | 14.3 g-m         | (4.0)          | 3.6 a-d       | 34.4 bc         | +  | -  |
| Hotset           | 13.7 g-m         | 2.3 f-i        | 2.1 c-e       | 2.9 d           | +  | -  |
| Beaverlodge 6806 | 12.9 g-m         | (4.0)          | 2.1 e-j       | 3.2 d           | +  | +  |
| PI 298633 Pioneer| 12.5 g-n         | (3.0)          | 3.4 a-e       | 9.5 b-d         | -  | +  |
| AVRDC CLN95-77   | 12.4 g-n         | 4.5 ab         | 4.1 ab        | 10.2 b-d        | +  | -  |
| Beaverlodge 6804 | 11.7 h-n         | (4.0)          | 4.0 a-c       | 26.2 b-d        | +  | +  |
| AVRDC TN-2       | 11.4 h-n         | 1.8 h          | 1.6 g-l       | 0.5 d           | -  | +  |
| Small Fry        | 11.0 i-n         | 3.3 c-f        | 2.2 e-j       | 9.5 b-d         | +  | +  |
| AVRDC CL-5915-93 | 10.3 i-o         | 4.5 ab         | 3.3 a-e       | 26.1 b-d        | +  | +  |
| Severianiin      | 10.3 i-o         | (3.0)          | 2.8 b-g       | 11.5 b-d        | -  | +  |
| Coldset          | 8.9 j-o          | (2.5)          |              |                |    |    |
| PI 204998        | 8.4 k-o          | 4.0 a-d        | 3.4 a-e       | 26.3 b-d        | +  | -  |
| Fresh Market 9   | 7.9 k-o          | 3.0 d-g        | 3.0 a-f       | 4.1 cd          | +  | -  |
| AVRDC PT-1707    | 7.8 l-o          | 2.8 e-h        | 2.6 d-g       | 25.4 b-d        | +  | +  |
| Tex Rock         | 7.5 l-o          | 2.8 e-h        | 1.8 f-k       | 11.1 b-d        | -  | +  |
| Maliutka         | 7.0 l-o          | 4.2 a-c        | 2.6 d-g       | 19.2 b-d        | +  | +  |
| Monte Carlo      | 6.8 l-o          | (2.0)          | 1.3 i-l       | 15.7 b-d        | -  | +  |
| Duke             | 6.6 l-o          | 1.8 h          |              |                |    |    |
| Beaverlodge 6810 | 6.5 l-o          | (4.0)          |              |                |    |    |
| Anahua           | 6.3 l-o          | (1.0)          | 1.0 i-l       | 2.0 d           | +  | -  |
| Flora-Dade       | 6.3 l-o          | 1.5 i          | 1.1 i-l       | 0.2 d           | +  | +  |
| Floradel         | 4.1 m-o          | 1.3 i          | 0.6 k-l       | 1.7 d           | +  | +  |
| Tropi-Gro        | 2.4 n-o          | (1.0)          |              |                |    |    |
| Summeraset       | 0.0 o            | (1.0)          |              |                |    |    |
| PI 190256        | 3.6 a-d          | 88.2 a         | -            | -               |    |    |
| PI 341155        | 2.5 d-h          | 1.7 d          | -            | +               |    |    |
| Chico III        | 2.4 d-i          | 7.2 b-d        | -            | +               |    |    |
| Floramerica      | 0.6 k-l          | 0.3 d          | -            | +               |    |    |
| AU-84-M-1        | 0.4 l            | 12.2 b-d       | +            | +               |    |    |
| AU-76            | 0.4 l            | 0.0 d          | +            | +               |    |    |

<sup>a</sup>Mean separation within columns by Duncan’s multiple range test (P = 0.05); +, observed; --, not observed.

<sup>y</sup>HS determined in observational trial.

Each year in mid-June. The daily maximum ranged from 29 to 36C and the daily minimum from 17 to 24C in July and Aug. 1985. Daily maxima and minima for 1986 are shown in Fig. 1. The total number of fruit produced per plant per entry was determined from three harvests during the first 2 weeks of Aug. 1985 and at biweekly intervals from three plants per plot in July and Aug. 1986. Mature flowers (six per plot) were tagged at biweekly intervals in 1986 to calculate the number of fruit set per tagged flower as percent fruit set (%FS); also, flowers were collected and fixed in a 3 ethanol : 1 45% acetic acid solution for pollen fertility determinations. Anthers from at least three flowers per entry were squashed in acetocarmine (Tsuchiya, 1971), and when possible, at least 100 pollen grains per flower were used to determine the percent fertile pollen (%PF). Pollen visibly filled with cytoplasm was considered fertile. The stigma position in relation to the antheridial cone and stigma coloration were recorded.

All lines were visually rated for their ability to set fruit, using a heat-set rating (HS) with 0 = no fruit to 5 = many fruits, similar to Villareal et al. (1978).
Table 3. Average HS and GCA of selected tomato genotypes in 10-parent nonreciprocal diallel in 1987.

| Entry                  | HS  | GCA  |
|------------------------|-----|------|
| Red Cherry             | 3.7 | 0.87*** |
| Beaverlodge 6804       | 3.3 | -0.69*** |
| AVRDC CLN-95-77        | 3.0 | 0.29  |
| Nagcarlan              | 2.5 | 0.66*** |
| PI 272735              | 2.1 | 0.27*  |
| AVRDC PT-913           | 1.9 | 0.09  |
| Hayslip                | 0.7 | -0.62*** |
| Floradel               | 0.3 | -0.71*** |
| Flora-Dade             | 0.0 | -1.01*** |

**Significant at P = 0.05 or 0.001, respectively.

A temperature-controlled greenhouse study was conducted in 1985 on single-plant plots to determine the %FS based on the total number of fruit and flowers produced per plant. A randomized complete-block design with four replications was used. The daily maxima ranged from 28 to 36°C and the minima from 22 to 28°C in July and August.

**Diallel analyses.** Nonreciprocal diallel hybrids between parents selected for their heat tolerance (PT-913, CLN95-77, Beaverlodge 6804, ‘Nagcarlan’, ‘Red Cherry’, and PI 272735) or heat sensitivity (‘Flora-Dade’, ‘Floradel’, ‘Suncoast’, and ‘Hayslip’) were rated for HS in the field in 1987. The design was a randomized complete block with four replications and three plants per plot. In a separate study, six parents and their F₁ diallel hybrids were more intensively studied. Percent FS on the first six flower clusters on one plant per plot and %PF on another plant per plot were determined. Flowers were collected at biweekly intervals in fixative, and where possible, 100 pollen from at least three flowers per entry per replication were analyzed as described.

Reciprocal diallel hybrids among heat-tolerant CL-5915-153, Beaverlodge 6804, ‘Nagcarlan’, ‘Red Cherry’, and heat-sensitive AU-76 and AU-84-M-1 were evaluated in 1988 for HS. Flowers collected during the heat-stress period were examined as described.

Parent and F₁ lines from the diallel studies and commercial cultivars were evaluated in 1989 for HS in a randomized complete-block design with four replications and 16 plants per plot for parent lines or cultivars and 36 plants per plot for F₁ lines. Daily maxima and minima for July and Aug. 1987 and 1988 are shown in Fig. 1. Temperatures observed in 1989 followed a similar pattern, with daily maxima ranging from 28 to 37°C and daily minima from 16 to 27°C.

Variables were subjected to regression analysis and to mean separation using Duncan’s new multiple range test. General (GCA) and specific (SCA) combining abilities were computed according to Model I, Method 2 in 1987 and Model I, Method 1 in 1988 (Griffing, 1956). The relative importance of GCA and SCA in determining progeny performance was assessed as $2 \times M_{SCA} : 2 \times M_{GCA} + M_{SCA}$ (Baker, 1978). Correlations between HS, %FS, mature fruit size, and %PF were determined.

**Results and Discussion**

**Screening for heat tolerance.** Most of the AVRDC entries and Beaverlodge lines, ‘Red Cherry’, and ‘Nagcarlan’ performed well under high temperature in the greenhouse and field (Table 1). The number of fruit produced per plant under high temperature in the greenhouse was highly correlated with the number of fruit produced under high temperature in the field ($r = 0.81***$). The HS ratings obtained in the field were found to be highly correlated with the average number of fruit produced per plant ($r = 0.87***$), confirming screening studies of Villereal et al. (1978). Small-fruited cultivars generally produced more fruit and showed a higher level of heat tolerance than large-fruited cultivars ($r = -0.42*$ between HS rating and fruit size; $r = -0.62***$ between %FS$_{GH}$ and fruit size). HS values obtained in 1985 were highly correlated with those obtained in 1987.

Table 4. Average HS, %PF, and estimated GCA of tomato genotypes in a six-parent nonreciprocal diallel in 1987 and six-parent reciprocal diallel in 1988.

| Entry                  | HS  | GCA  | %PF  | GCA  | %PF  | GCA  |
|------------------------|-----|------|------|------|------|------|
| CL-5915-153            | 3.7 | 0.47** | 45.6 | -3.69 | 3.4 | 0.38** |
| Red Cherry             | 3.7 | 0.36** | 76.0 | 5.25* | 2.0 | 0.21** |
| Beaverlodge 6804       | 3.3 | 0.17  | 85.3 | 6.91** | 2.9 | 0.22** |
| Nagcarlan              | 2.5 | 0.29* | 88.7 | 14.26** | 2.3 | 0.28** |
| CLN-65-349             | 1.3 | -0.36** | 32.3 | -9.87** | 1.1 | -12.85** |
| Flora-Dade             | 0.0 | -0.94** | 0.81 | 0.81 | 0.96 | 0.70 |

Ratio = $2 \times M_{GCA : SC}$, $2 \times M_{GCA : SC} + M_{SCA}$. **Significant at P = 0.05 or 0.01, respectively.
gene action. The correlation between HS rating and %FS on the first six flower clusters was highly significant ($r = 0.75^{***}$) in the 1987 six-parent diallel. The average %PF of the parents (72.9% on 27 July 1987, 54.8% on 10 Aug. 1987, 77.2% on 22 Aug. 1987, and 55.1% on 9 Aug. 1988), however, was higher than that of their F₁ hybrids (42.5%, 35.8%, 47.7%, and 38.4%, respectively). PF decreased during the prolonged period of heat stress and increased as temperatures decreased. Heat-tolerant entries generally maintained a higher level of pollen fertility ($r = 0.39^{**}$ between HS and %PF in 1987). A large portion of the combining ability variance for %PF was partitioned into the GCA component (Table 4), and nonsignificant maternal and reciprocal components were obtained in the reciprocal diallel.

From diallel analyses in 2 years, we conclude that heat tolerance is primarily under the control of additive genes, which is in agreement with results obtained by El Ahmadi and Stevens (1979b) and Hanna et al. (1982). Decreases in pollen fertility were a limiting factor during prolonged periods of heat stress. Pollen fertility under heat stress was also found to be governed by an additive gene system. Although several small-fruited genotypes maintained a high level of pollen fertility under heat stress, other genotypes, such as ‘Nagcarlan’ and Beaverlodge 6804, were better at transferring their degree of heat tolerance to their offspring. This transfer was especially apparent in the 1989 study evaluating F₂ populations for HS (Table 5). F₂ populations originating from hybrids between ‘Nagcarlan’, Beaverlodge 6804, or AVRDC CL-5915-153 significantly outperformed the parent lines in HS rating. Breeding progress for improved fruit set at high temperatures is feasible but, in combination with desirable fresh-market characteristics, has been difficult to achieve. More research clearly needs to be done to uncover the cause of the wide genotypic variation in heat tolerance and determine the relationship between fruit size and heat tolerance and the underlying physiological processes involved.

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| Table 5. Average HS of selected tomato genotypes and F₂ populations in 1989. |
| Entry | HS |
|-------|----|
| A VRDC CL-5915-153 | 3.0 a-e² |
| Nagcarlan | 3.0 b-e |
| Beaverlodge 6804 | 2.9 b-e |
| Red Cherry | 2.8 c-e |
| P1 190256 | 2.4 ef |
| Solar set | 1.9 f |
| Suncoast | 1.3 g |
| Flora-Dade | 0.9 h |
| F₂ populations (Table 5) | |
| CL-5915-153 x Beaverlodge | 3.8 a |
| Beaverlodge x Nagcarlan | 3.7 ab |
| CL-5915-153 x Nagcarlan | 3.5 a-c |
| Nagcarlan x Red Cherry | 3.2 a-d |
| Beaverlodge x Red Cherry | 3.1 a-c |
| CL-5915-153 x Flora-Dade | 2.8 c-e |
| CL-5915-153 x Red Cherry | 2.7 d-f |
| Red Cherry x Suncoast | 2.6 d-f |
| Nagcarlan x Flora-Dade | 2.4 ef |
| a-Mean separation within column by Duncan’s multiple range test ($P = 0.05$). |
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