# Growth of Tomato Plants and Fruit Production in High Humidity and at High Temperature[1]

W. J. Lipton[2]
*Environmental Research Laboratory*
*University of Arizona, Tucson*



*Abstract.* Tomatoes grown in Tucson, Ariz., in a closed, humid greenhouse, compared with those grown in a normal, vented one, lacked vigor in spring, were prone to high-temperature injury in summer, and had poor fruit-set in both seasons. Elongation of plants in the humid house during early growth exceeded that in the normal house only when RH was near 100%. Occurrence of microbial diseases of leaves or fruits was insignificant.

High humidity reduced fruit quality in summer but not in spring. High humidity induced uneven coloration, cracking, and surface dullness. These defects reduced yields of marketable fruit an estimated 56%. 'Large Red Cherry' and 'Floradel' grew reasonably well in a high-humidity, high-temperature environment but 9 other cultivars did not.

The results of these experiments are relevant to crop production in environments found in closed greenhouses designed for coastal desert areas and in open fields in the tropics.

The basic objective of proposals to establish power, water, and food-producing complexes in coastal desert areas is maximum use of all resources, particularly of fresh water (12). Loss of water from transpiration can be reduced if plants are grown in closed, plastic-covered greenhouses where the humidity is maintained close to saturation. In such closed houses the air is cooled and humidified by continuously circulating the air through a spray of sea water (12). However, many crops are not well adapted to an environment where relative humidity (29) and temperature are unusually high. Tomatoes were grown in spite of their sensitivity to high temperature (3) and susceptibility to leaf diseases at high relative humidity because of their relatively high value. The economic feasibility of establishing a power, water, food complex would be substantially increased if crops such as tomatoes could be grown successfully. Since the climate in such a greenhouse simulates, at least partly, that of the tropics, greenhouse studies also may be relevant to problems in the tropics, which some writers consider as focal points of the world food crisis (24).

## Facilities and Methods

*Greenhouses and environment.* Two greenhouses, located in Tucson, Ariz. (32° 15′ N), were used in 2 tests conducted from January to June and from June to November, 1968, respectively. In the conventional house relative humidity (RH) was normal (N) (Fig. 1A and 2A) while it was high (H) in the second house. In this house temperature of the air ($t_a$) depended on the temperature of the water ($t_w$) that flowed (150 l min$^{-1}$) through a dispersing tower. A fan forced air, at about 40 m$^3$ min$^{-1}$, through a spray of water in the tower and then through the greenhouse. The water temperature was regulated by means of an external cooling tower or by a heater. Generally, $t_w$ was about 20° ± 2° at the inlet side. Evaporation from the spray of water maintained RH near 100%, except during the warmest part of the day, when it dropped to near 70% (Fig. 1B and 2B). The house was vented by a small fan to prevent harmful accumulation of ethylene. Carbon dioxide, metered from a cylinder, was maintained at about 300 ppm.

Thermocouples for dry and wet bulb temperatures were located in a shelter that was continuously aspirated by a fan.

$T_a$ differed little between the 2 houses. During spring the average difference was 1.6° for the daily maxima and 1.0° for the minima. During summer, the average differences were less than 0.5° for the maxima and minima.

*Cultivars and cultural practices.* In spring the following cultivars were grown: 'Cherry', red, large (CL); 'Chico Grande' (CG); 'Floradel' (F); 'Homestead' (HS); 'Manapal' (M); 'Ohio WR-25' (O); 'Pink Deal' (PD); 'Supermarket' (SM); and 'Wolverine 119' (W). In summer, CL, F, O, and W were retained, and 'Red Cherry' (CR) (very small fruits), and 'White Beauty' (WH) (yellow fruits) were added.

The plants were grown in a 1:1 (v/v) mixture of sand and peat moss, and in roofing paper cylinders that were painted white, and were trained to a single stem. Plants were supplied daily with a complete nutrient solution (13), a maximum of 2.0 liters each day in house N and 1.4 liters in house H. The plants were also supplied with tap water as needed. During pollen shedding the inflorescences were vibrated to aid in pollination.

*Records related to growth.* Plant vigor, mottling and curling of leaves, incidence of adventitious shoots (28), and the occurrence of leaflet necrosis were periodically judged. Measurements were made on elongation of the plants during the month following thinning, distances between the points of attachment of the lowest 4 inflorescences to the stem, and time from seeding to the first open flower in the second inflorescence.

*Records related to fruiting.* Fruits were evaluated for defects in coloration, physical appearance, and overall quality. Ratings for quality ranged from 9 (no defects) to 1 (fruit inedible or unacceptable because of appearance alone).

Yield of fruit was evaluated on the basis of 1) percent fruit-set, 2) number of fruits per plant, 3) weight per fruit, 4) maximum diameter of fruit, 5) total yield, 6) yield of marketable fruit (ratings 4 to 9) and, finally, 7) yield of high quality fruit (ratings 7 to 9).

[1]Received for publication December 22, 1969.
[2]Permanent address: U. S. Dept. of Agric., ARS, Market Quality Res. Div., Fresno, Ca. 93727. I wish to thank C. N. Hodges, Supervisor of the ERL, and his staff, especially J. J. Riley, for their unstinting cooperation while I was Visiting Plant Physiologist at the ERL, and A. L. Ryall (ret.) and J. M. Harvey, U. S. Dept. of Agriculture, for their administrative cooperation. I also appreciate the advice of R. O. Kuehl, University of Arizona, for help with the statistical analysis of the data.


J. Amer. Soc. Hort. Sci. 95(6): 674–680. 1970.

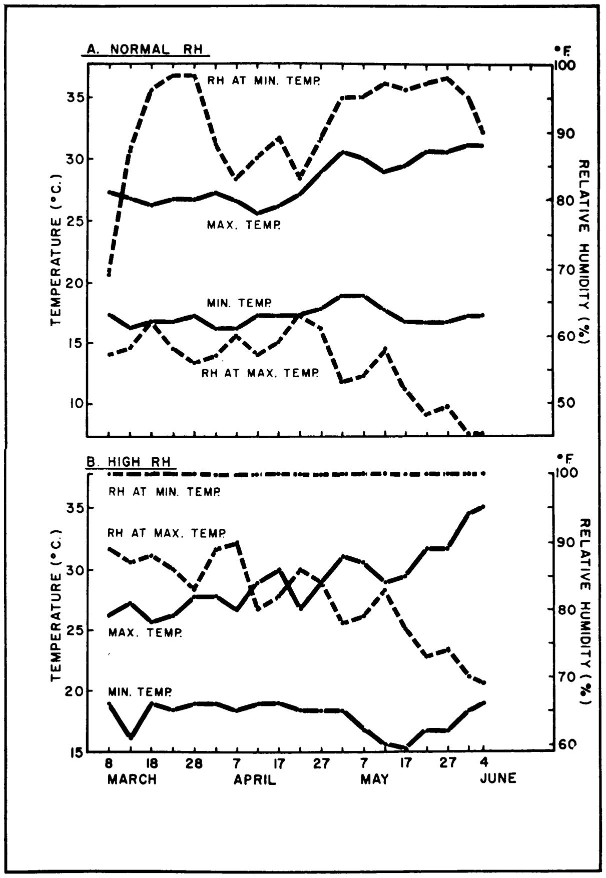


*Fig. 1.* Average maximum and minimum temperatures for 5-day periods and relative humidity for the corresponding temperatures and periods. Spring. (A. Normal RH; B. High RH.)

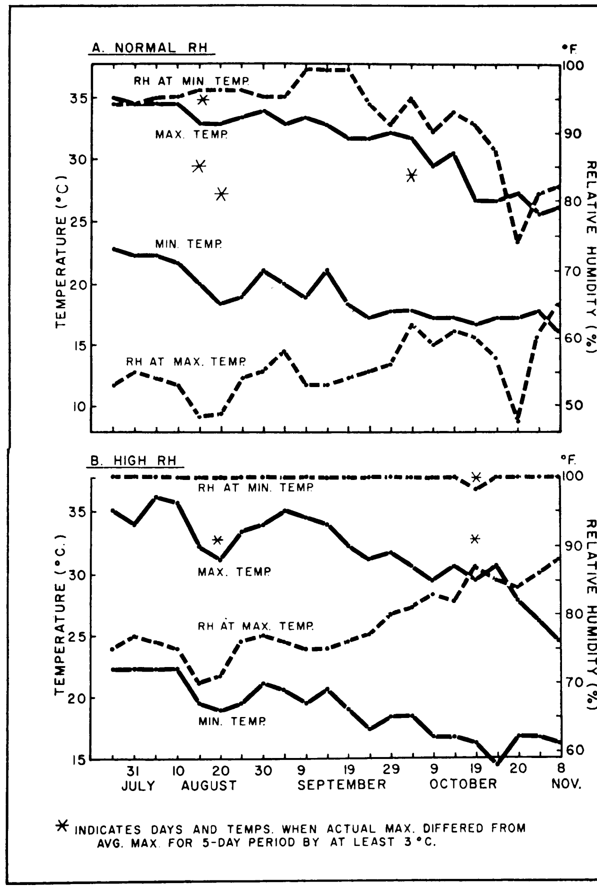


*Fig. 2.* Average maximum and minimum temperatures for 5-day periods and relative humidity for the corresponding temperatures and periods. Summer. (A. Normal RH; B. High RH.)

*Experimental design and analysis.* In each house plants were divided between 2 benches (about 4 m by 1 m) running north and south. Each bench held 18 plants which were subdivided into 2 (Test 1) or 3 (Test 2) groups (replications) with 1 plant of each cultivar per replication. Each house held 36 plants, 4 each of 9 cultivars in spring and 6 each of 6 cultivars in summer. Within replications the plants were randomly distributed in 2 rows; the same pattern was used in each house.

Data were tested by analysis of variance and Duncan's multiple range test. Percentage data were transformed before analysis to either the logarithmic or arcsin $\sqrt{\text{percentages}}$ form according to criteria given by Snedecor (22).

## Results and Discussion

### Growth Characteristics

*Qualitative responses.* Environmental conditions strongly influenced the appearance of the various cultivars in spring (Table 1A) and in summer (Table 1B). Vigor of the plants was generally lower in H than in N, although CL grew vigorously in either RH. Leaf diseases did not interfere with the growing of tomato plants in high RH even though the conditions for their spread were presumably ideal (8, 21).

A yellowish mottling of the leaves of all cultivars but CL occurred only in H in spring. Absence of mottling of any cultivar in summer, when RH was lower than in spring, suggests that continuously high RH caused the mottling, most likely via a substantial reduction in transpiration and a consequent nutrient imbalance (9).

Incidence of adventitious shoots (28) that developed on rachises of leaves was influenced by RH and by cultivar, in spring (Table 1A), but in summer their incidence depended only on cultivar. These results suggest that occurrence of adventitious shoots depends more on cultivar and environment than on vigor or pruning, as suggested by Went (28).

Rolling of leaflets occurred in both environments in both seasons. In spring, when temperatures were moderate, the incidence was low and not influenced by RH, but in summer rolling was common and more severe in H than in N (Table 1B). This pattern of incidence suggests that rolling of leaflets is primarily influenced by $t_a$ but is aggravated by high RH, and that it may be related to a temperature gradient across the leaflets (7).

Necrosis of partially expanded leaflets occurred only in high RH during summer (Table 1B). Since the necrosis first appeared following daytime maxima that averaged above 35°C (Fig. 2B), high $t_a$, combined with high RH, probably were responsible. The same conditions seemed responsible for the necrosis of the growing point of some plants in house H.

Epinasty of the leaves was much more pronounced in summer than in spring and it occurred about equally in H and N. This pattern of occurrence indicates that it was a response to $t_a$ rather than to RH or to ethylene in the air.

*Quantitative responses.* Growth rates of young plants in the 2 environments were compared by using the ratio of the daily rate of growth in high RH to the rate in normal RH during the same period (cm day$^{-1}$ in high

*Table 1.* Condition of tomato plants grown during 2 seasons in greenhouses with normal or high relative humidity.

| Season, characteristic[uv] and relative humidity | Condition of indicated cultivar[w] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CL | CG | CR | F | HS | M | O | PD | SM | W | WH |
| *A. SPRING:* | | | | | | | | | | | |
| *Plant vigor* | | | | | | | | | | | |
| Normal RH.......... | exl | mod | | mod | poor | good | good | mod | poor | good | |
| High RH............ | exl | x | | fair | poor | fair | mod | fair | poor | mod | |
| *Mottling of leaves*[y] (Severity) | | | | | | | | | | | |
| High RH............ | none | sl | | mod | mod | mod | sl | mod | sev | sl | |
| *Adventitious shoots* (Incidence) | | | | | | | | | | | |
| Normal RH.......... | high | low | | rare | low | none | none | none | none | low | |
| High RH............ | high | ext | | low | mod | low | low | low | mod | low | |
| *B. SUMMER:* | | | | | | | | | | | |
| *Plant vigor* | | | | | | | | | | | |
| Normal RH.......... | exl | | exl | good | | | good | | | good | exl |
| High RH............ | good | | good | mod | | | good | | | good | good |
| *Leaf rolling* (Severity) | | | | | | | | | | | |
| Normal RH.......... | sl | | tr | sl | | | sl | | | tr | mod |
| High RH............ | sl | | sl | sl | | | sl | | | sl | sev |
| *Leaflet necrosis*[z] | | | | | | | | | | | |
| High RH............ | low | | rare | low | | | mod | | | low | mod |

[u]During spring, plant condition was recorded on March 27, and during summer on August 20.
[v]Abbreviations: exl—excellent; ext—extreme; mod—moderate; sev—severe; sl—slight; tr—trace.
[w]CL, Large Red Cherry; CG, Chico Grande; CR, Red Cherry; F, Floradel; HS, Homestead; M, Manapal; O, Ohio; PD, Pink Deal; SM, Supermarket; W, Wolverine; WH, White Beauty.
[x]Not determined; plants extremely misshapen.
[y]Mottling did not occur in house with normal humidity.
[z]Leaflet necrosis did not occur in the house with normal humidity.

RH/cm day$^{-1}$ in normal RH). This ratio is termed "relative rate of elongation" (RRE). RRE ranged from 1.5 to 2.5 when RH was near saturation much of the time, as in spring (Fig. 3A), but was near unity when RH was below saturation, as in summer (Fig. 3B), when the conditions and results paralleled those of Went (28).

RH had little influence on the distances between the lowest 4 successive inflorescences, the means for high and normal RH differing by only 2 cm.

Anthesis in the second cluster occurred 39 days after transplanting in high RH, but after 42 days in normal RH during spring and after 30 and 32 days, respectively, in summer. (Means differ at $P$ 99% in both seasons). This acceleration is attributed to the cumulative effect of the slightly higher $t_a$ in H than in N.

## Fruiting Characteristics

*Qualitative responses.* High humidity decreased the

*Table 2.* Percentage of fruits of good color from several cultivars of tomatoes grown in greenhouses with normal or high relative humidity—summer.[x]

| Relative humidity | Cultivar | | | | | Mean |
|---|---|---|---|---|---|---|
| | CL | CR | F | O | W | |
| | *Fruits with good color*[y] | | | | | |
| | % | % | % | % | % | % |
| Normal RH....... | 91 abc | 93 ab | 80 bcd | 96 a | 44 e | 84 A |
| High RH......... | 73 cd | 57 de | 46 e | 12 f | 6 f | 36 B |

[x]The F values for the interaction Humidity × Cultivar and for the main effect Humidity were not significant in the test conducted in spring. The means for normal and high humidity were 50% and 45%, respectively.
[y]Means in a box without a common letter differ at $P$ 99% (capitals) or $P$ 95% (lower case). The standard errors are: Humidity, 0.1%; H × C, 0.7%. The data were analyzed as arcsin $\sqrt{\text{percentage}}$ values, and the means given were arrived at by retransformation to percentages.

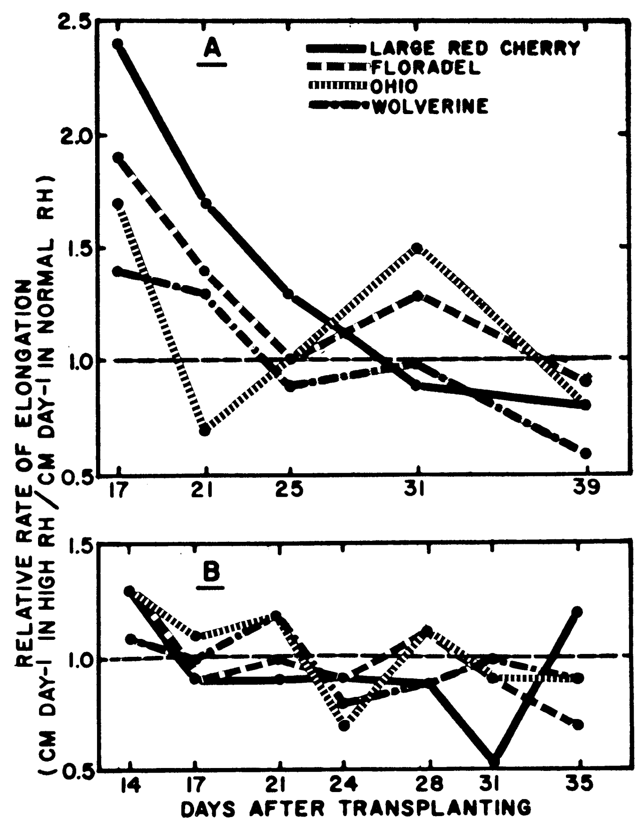


*Fig. 3.* Relative rate of elongation (RRE) of 4 cultivars of tomato plants during spring (A) and summer (B). RRE: (elongation in cm day$^{-1}$ in high RH)/(elongation in cm day$^{-1}$ in normal RH).

proportion of fruit with good color (fruits uniformly red or defects negligible) although the effect was greater during hot (25, 27) than during moderate temperatures (Table 2), a result that extends earlier work on the effect of RH at moderate temperatures (6, 19).

The poor coloration of fruit in high RH and during high $t_a$ indicates that $t_a$ at night was not low enough to negate the adverse effect of the high $t_a$ during day time, as might have been expected (11).

Among specific defects, a yellow mottling of the surface generally was more common in high than in normal RH and was aggravated by the high $t_a$ of summer (Fig. 4). Unilateral ripening (17, 20) (Fig. 4B) occurred similarly but affected fewer cultivars. The incidence of improperly colored shoulders (5) principally depended on cultivar, with no consistent influence of RH or $t_a$ being evident (Fig. 4).

The incidence of physical defects was lower in high than in normal RH during moderate $t_a$, while the reverse was true during the high $t_a$ of summer (Table 3). However, occurrence of specific disorders, was strongly dependent on cultivar (Fig. 5), which suggests that generalizations about environmental effects must be based on diverse cultivars.

High RH, combined with high $t_a$, induced protuberances resembling enlarged lenticels in potatoes, although tomato fruits lack lenticles (18). These objectionable blemishes were scattered over the surface and aligned radially, rather than concentrically like the "cuticle cracks" described by Young (30).

The skin of cultivars CL, F, O, and W was dull and slightly wrinkled in high RH during summer (Fig. 5B). This dullness (Fig. 6), which apparently has not previous-

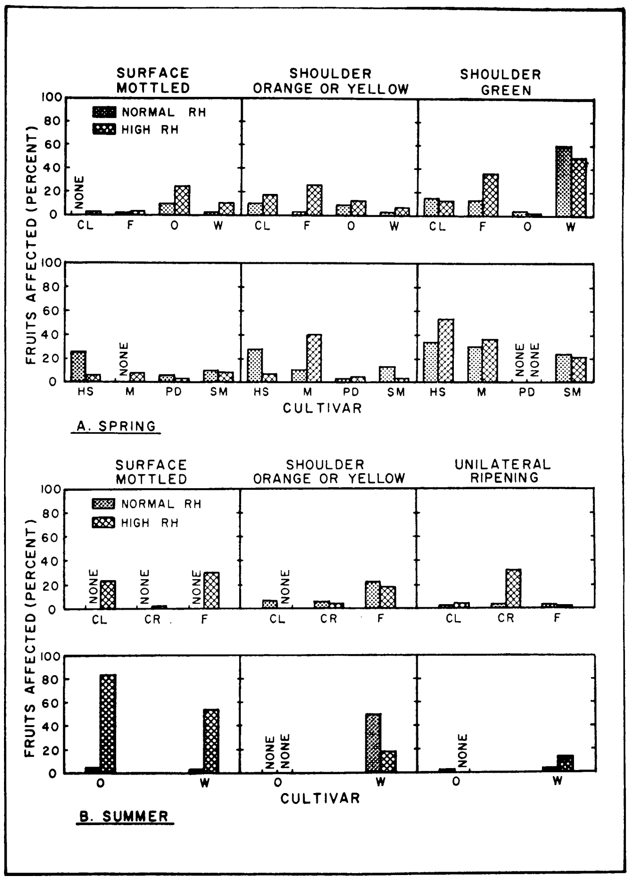


*Fig. 4.* Incidence of certain color defects on tomato fruits of several cultivars grown in greenhouses with normal or high relative humidity. A. Spring; B. Summer. (The total for a given cultivar may exceed 100% because some fruits had more than 1 defect).

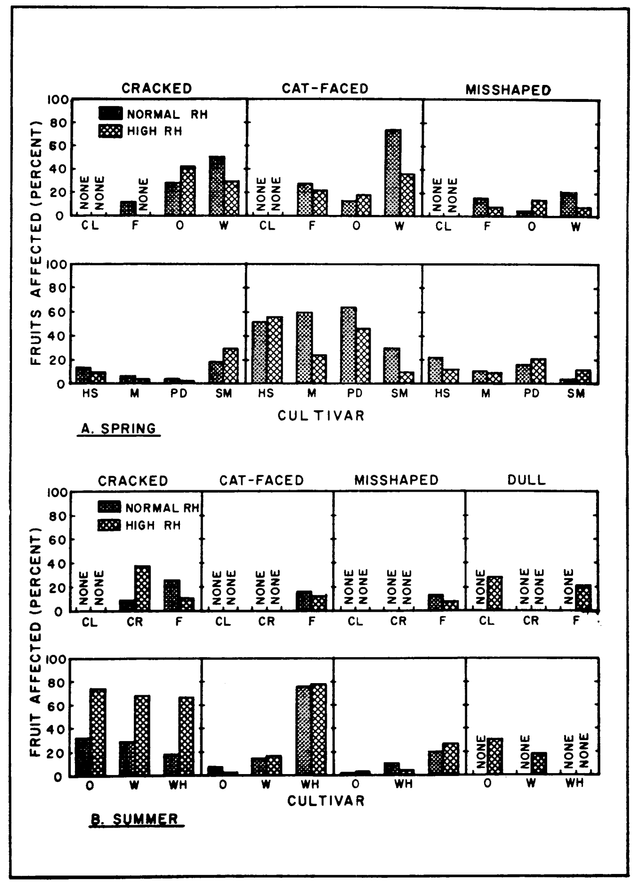


*Fig. 5.* Incidence of certain physical defects and of dullness of tomato fruits of several cultivars grown in greenhouses with normal or high humidity. A. Spring, B. Summer. (The total for a given cultivar may exceed 100% because some fruits had more than 1 defect).

*Table 3.* Percentage of normally shaped fruits from several cultivars of tomatoes grown in greenhouses with normal or high relative humidity—spring.[x]

| | Marketable fruit produced by indicated cultivar[y] | | | | | | | | Mean |
|---|---|---|---|---|---|---|---|---|---|
| | CL | F | HS | M | O | PD | SM | W | |
| | % | % | % | % | % | % | % | % | % |
| Normal RH | 100 a | 63 bcde | 17 f | 47 e | 75 bc | 3 g | 49 de | 9 f | 46 A |
| High RH | 100 a | 73 bcd | 49 de | 79 b | 54 cde | 46 e | 68 bcde | 54 cde | 68 B |

[x]The interaction Humidity × Cultivar was not significant in the test conducted in summer, however, the difference between humidities was significant at *P* 99%: Normal—57%, high—32%; standard error 0.1%.

[y]Means in a box without a common letter differ at *P* 99% (capitals) or *P* 95% (lower case). The standard errors are: Humidity 0.1%, H × C, 0.6%. The data were analyzed as arcsin $\sqrt{\text{percentage}}$ values, and the means given were arrived at by retransformation to percentages.

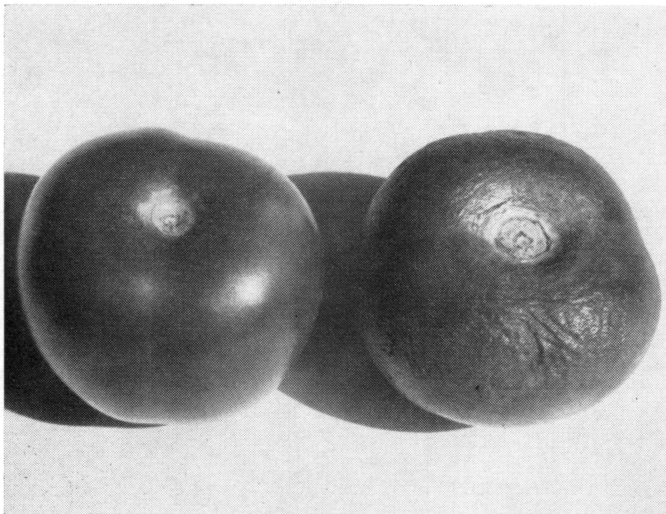

*Fig. 6.* Normal (L) and dull, shrivelled (R) tomato fruits (cultivar CL) grown in high RH and high $t_a$.

ly been described, may be the result of inadequate epidermal wax. Lack of wax also is suggested by the rapid shrivelling of such fruit after harvest.

Ratings for external quality that summarized all aspects of appearance indicated that in spring the high incidence of color defects in high RH was balanced by a low incidence of physical defects, while the opposite occurred in normal RH. Fruits grown in high RH in summer were definitely inferior in total appearance to those grown in normal RH, although cultivars differed substantially (Table 4). CL was superior in both environments.

*Quantitative responses.* Fruit set was significantly lower in high than in normal RH in spring and summer, but not on all 3 (1st, 2nd and 5th) test inflorescences (Table 5). In spring, poor set resulted from abortion of the flowers, whereas in summer, poor set probably resulted from improper fertilization during a period of high $t_a$ (means near 35°C) early in September. Although maxima consistently above 30° are inimical to fruit setting (3), in our tests, high RH must have been the deciding factor, otherwise fruit set should have been equally reduced in normal RH. High RH also depressed the total number of fruits harvested per plant and their mean weight (Table 6).

All the foregoing results are reflected in the total, marketable, and high-quality yields of fruit. Total yield encompassed all fruits harvested, marketable yield those that were rated 4 or better on the quality scale, and high-quality fruits those rated 7 or higher. Yields were consistently lower in high than in normal RH regardless of category or season, although only the results for summer are presented (Table 7), because of losses due to blossom-end rot in normal RH in spring. The total, marketable, and high-quality yields in high RH were 73%, 44%, and 24% of those in normal RH, respectively. The large reduction from total to marketable yields was primarily caused by the high proportion of defective fruits produced by certain cultivars. For CL and F, the cultivars that fared best in high RH, marketable yields were 61% and 84%, respectively, of those in normal RH.

*Table 5.* Percentage of fruits set on tomato plants grown during 2 seasons in greenhouses with normal or high relative humidity.

| Season and relative humidity | Fruit set on indicated inflorescence[x,y] | | | Mean |
|---|---|---|---|---|
| | First | Second | Fifth | |
| | % | % | % | % |
| Spring[z] | | | | |
| Normal RH | 97 a | 94 a | 74 ab | 85 A |
| High RH | 47 c | 78 ab | 57 bc | 62 B |
| Summer | | | | |
| Normal RH | 92 a | 87 a | 71 a | 83 a |
| High RH | 91 a | 59 a | 23 b | 50 b |
| Mean | 91 a | 72 ab | 41 b | |

[x]Inflorescence 1 was nearest the soil surface.
[y]Means in a box without a letter in common differ at $P$ 99% (capitals) or $P$ 95% (lower case). The standard errors are: Spring: Humidity, 1.0%; Humidity × Inflorescence, 1.1%; Summer: Humidity, 1.1%, Inflorescence, 1.1%, H × I, 1.2%. The data were analyzed as logarithms, the means are their antilogarithms.
[z]The F value for the main-effect Inflorescence was not significant.

*Table 6.* Mean numbers of fruits per plant and mean weights of tomato fruits grown during 2 seasons in normal or high relative humidity.

| Season[x] and relative humidity | Mean number of fruits per plant[y] | Mean weight of individual fruits[y] |
|---|---|---|
| | *No.* | *g* |
| Spring | | |
| Normal RH | 26 a | 215 A |
| High RH | 22 b | 158 B |
| SE[z] | 3 | 6 |
| Summer | | |
| Normal RH | 59 A | 111 A |
| High RH | 47 B | 104 B |
| SE[z] | 3 | 2 |

[x]The cultivars CL, F, HS, M, O, PD, SM and W were tested in spring, and CL, CR, F, O, W and WH in summer.
[y]Any two means for a given season without a common letter differ at $P$ 99% (capitals) or $P$ 95% (lower case).
[z]SE signifies standard error.

*Table 4.* Mean quality ratings of tomato fruits of several cultivars grown in greenhouses with normal or high relative humidity—summer.[x]

| Relative humidity | Cultivar | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | CL | CR | F | O | W | WH | |
| | Ratings[y,z] | | | | | | Rating |
| Normal RH | 8.6 a | 8.2 a | 6.0 bc | 7.5 ab | 6.5 bcde | 5.8 cde | 7.3 A |
| High RH | 6.6 bcd | 5.5 de | 5.4 e | 3.3 f | 3.3 f | 3.4 f | 4.6 B |

[x]There was no significant difference due to humidity in the test conducted in spring; the mean ratings for the fruits from normal and high humidities were 6.3 and 6.0, respectively.
[y]Means in a box without a common letter differ at $P$ 99% (capitals) or $P$ 95% (lower case). The standard errors are: Humidity, 0.2; Humidity × Cultivars, 0.4.
[z]Ratings: 9—excellent; 7—good; 5—fair; 3—poor; 1—unacceptable as food; for further description, see section on Facilities and Methods.

*Table 7.* Total, marketable, and high quality yield of tomato fruits of several cultivars grown in greenhouses with normal or high relative humidity—summer.

| Relative humidity | Yields per plant produced by indicated cultivar[z] | | | | | | Mean |
|---|---|---|---|---|---|---|---|
| | CL | CR | F | O | W | WH | |
| | | | *Total Yield* | | | | |
| | *kg* | *kg* | *kg* | *kg* | *kg* | *kg* | *kg* |
| Normal RH | 3.3 bc | 1.2 a | 4.6 e | 6.0 fg | 4.8 e | 6.3 g | 4.4 A |
| High RH | 2.4 b | 1.0 a | 5.0 ef | 4.5 de | 2.8 bc | 3.5 cd | 3.2 B |
| | | | *Marketable Yield* | | | | |
| Normal RH | 3.3 d | 1.0 ab | 4.4 ef | 5.2 f | 4.4 ef | 4.9 f | 3.9 A |
| High RH | 2.0 c | 0.6 a | 3.7 de | 1.8 bc | 1.0 ab | 1.2 abc | 1.7 B |
| | | | *High Quality Yield* | | | | |
| Normal RH | 3.2 c | 0.9 ab | 2.8 c | 4.8 d | 2.6 c | 2.9 c | 2.9 A |
| High RH | 1.6 b | 0.5 a | 1.6 b | 0.3 a | 0.2 a | 0.2 a | 0.7 B |

[z]Means for a given yield category without a letter in common differ at *P* 99% (capitals) or *P* 95% (lower case). The standard errors were numerically identical for the 3 yield categories: Humidity, 0.1 kg; Humidity × Cultivar, 0.3 kg.

Yield of these 2 cultivars was not only depressed less, proportionately, by high RH, but their actual yields in high RH were also the highest.

## General Discussion

The responses of horticulturally important species grown to maturity at high $t_a$ heretofore have received almost no attention. Consequently, we lack ready explanations for the variations in performance among cultivars of tomatoes under the stress imposed by high $t_a$ and high RH. Such knowledge would be useful for production of greenhouse crops in coastal deserts or for many crops in the tropics (4).

The pattern of occurrence of immature necrotic leaves and of fruit defects indicates that high RH aggravates the deleterious effects of high $t_a$. These results and similar ones on oats (16), raise the question: Is high RH, itself, deleterious at a given $t_a$, or does high RH lead to high and injurious temperatures in tissues at a given $t_a$? Leaf temperatures were not measured, but inhibition of transpiration by high RH increases the temperatures of leaves (7, 10, 16); for a field crop (23) the increase was 1° for a 10% reduction in transpiration. This effect likely would be greater in a greenhouse, and would be added to the heating of leaves in normal RH (10). Consequently, leaflets that were directly exposed to the sun in high RH may have exceeded $t_a$ by 5° to 10° during part of each sunny day, values that are consistent with those found for tomato leaflets treated to suppress transpiration (7). With $t_a$ between 30° and 35° the leaflets may have reached 35° to 45°, temperatures that approach those lethal to young cells of higher plants (2, 16). Thus much of the deleterious effect of high RH seems to be related to its retardation of transpiration and the consequent elevation of the temperature of the tissue. High RH as a cause of overheating of tissue is also suggested by the successful culture of tomatoes in the Central Valley of California where outdoor maxima frequently exceed those in these tests, but where low RH permits adequate transpirational cooling.

Poor fruit-set when RH and $t_a$ were high may be explained by abnormally high flower temperatures and consequently poor flower development or fertilization (1). The superior fruit-set on CL grown in high RH during moderate and high $t_a$ suggests that the flowers of CL are highly resistant to the combined effects of high RH and high $t_a$, as well as to low $t_a$ (14).

Dullness of tomato fruits, attributed to lack of wax on the surface, occurred as frequently on susceptible fruits shaded by leaves as on exposed ones, which eliminates direct radiation as a cause. Consequently, high RH, and possibly free moisture, appear to be chiefly responsible for the development of this defect in high $t_a$, a finding analogous to that for russeting of apples (26).

## Conclusions

Evidence presented above suggests the following conclusions: 1. Tomatoes of acceptable quality can be grown in an environment where RH and $t_a$ are substantially above levels considered satisfactory for this crop if adaptable cultivars are chosen. 2. Death of immature tissue and low yields will hinder successful production of tomatoes in the high RH and $t_a$ of closed greenhouses unless one or more of the following precautions are taken: avoid production during the hottest months, increase efficiency of cooling system, white-wash the greenhouse or the plants, or use chemical correctives (15). 3. Fungal or bacterial diseases are not necessarily a hazard in the growing of tomatoes in high humidity. 4. Further investigations of responses of tomatoes and of other crops to high RH and high $t_a$ could yield information on plant metabolism under stress that would be applicable not only to closed greenhouses but also to food production in the tropics.

## Literature Cited


1. Abdalla, A. A., and K. Verkerk. 1968. Growth, flowering and fruit-set of the tomato at high temperature. *Neth. J. Agr. Sci.* 16:71–76.
2. Alexandrov, V. Y. 1964. Cytophysiological and cytoecological investigations of heat resistance of plant cells toward the action of high and low temperatures. *Quart. Rev. Biol.* 39:35–77.
3. Anonymous. 1963. Growing tomatoes in greenhouses. *Wash. Agr. Exp. Sta. Circ. 276.* 12 p.
4. ————. 1969. Physiological limitations on crop production under temperature and moisture stress. Report of a Research Planning Conference. San Jose, Costa Rica, 1967. *U.S. Nat. Comm. Intern. Biol. Program Nat. Acad. Sciences (U.S.A.).* 23 p.
5. Bewley, W. F., and H. L. White. 1926. Some nutrient disorders of the tomato. *Ann. Appl. Biol.* 13:324–338.
6. Collin, G. H., and R. A. Cline. 1966. The interaction effect of potassium and environment on tomato ripening disorders. *Can. J. Plant Sci.* 46:379–387.
7. Cook, G. D., J. R. Dixon, and A. C. Leopold. 1964. Transpiration: Its effects on plant leaf temperature. *Science* 144: 546–547.
8. Cooper, A. J., D. Cooke, R. Gardner, and P. G. Allen. 1964. The effects of light intensity, day temperature and water supply on the fruit-ripening disorders and yield of two varieties of tomato. *J. Hort. Sci.* 39:42–53.
9. Cotter, D. J. and J. N. Walker. 1967. Occurrence and biological effects of humidity in greenhouses. *Proc. 17th Intern. Hort. Congress.* 1966. 3:353–368.

10. Gates, D. M. 1963. Leaf temperature and energy exchange. *Arch. Meteorol. Geophys. Bioklimatol. Ser. B. Allg. Biol. Klimatol.* 12:321–336.
11. Hall, C. B. 1964. The ripening response of detached tomato fruits to daily exposures to high temperatures. *Proc. Fla. State Hort. Soc.* 77:252–256.
12. Hodges, C. N., J. E. Groh, and A. W. Johnson. 1968. Controlled-environment agriculture for coastal desert areas. *Proc. 8th Nat. Agr. Plastics Conf., San Diego:* 20–22.
13. Hollis, H. F. 1964. Profitable growing without soil. English Univ. Press., London. 197 p.
14. Johnson, H., Jr. and R. A. Brendler. 1968. Cherry tomatoes. *Univ. Calif. Agr. Ext. Serv. AXT-266.* 3 p.
15. Ketellapper, H. J. 1963. Temperature-induced chemical defects in higher plants. *Plant Physiol.* 38:175–179.
16. Kinbacher, E. J. 1962. Effect of relative humidity on the high-temperature resistance of winter oats. *Crop Science.* 2:437–440.
17. Lorenz, O. A. and J. E. Knott. 1942. Studies of gray-wall of tomatoes. *Proc. Amer. Soc. Hort. Sci.* 40:445–454.
18. McCollum, J. P. 1946. Effect of sunlight exposure on the quality constituents of tomato fruits. *Proc. Amer. Soc. Hort. Sci.* 48:413–416.
19. Proctor, C. M. 1958. High humidity major factor in blotchy ripening in glasshouse tomatoes. *New Zeal. Comm. Grower.* 13(9):3.
20. Retig, Nira and N. Kedar. 1967. The effect of stage of maturity on heat absorption and suncald of detached tomato fruits. *Israel J. Agr. Res.* 17:77–83.
21. Small, T. 1930. The relation of atmospheric temperature and humidity to tomato leaf mold *(Cladosporium fulvum). Ann. Appl. Biol.* 17:71–80.
22. Snedecor, G. W. 1956. Statistical methods. 5th ed. Iowa State Univ. Press. Ames. 534 p.
23. Tanner, C. B. 1963. Plant temperatures. *Agron. J.* 55:210–211.
24. Thurston, H. D. 1969. Tropical agriculture. A key to the world food crisis. *BioScience* 19:29–34.
25. Tomes, M. I. 1963. Temperature inhibition of carotene synthesis in tomato. *Bot. Gaz.* 124:180–185.
26. Tukey, L. D. 1959. Observations on the russeting of apples growing in plastic bags. *Proc. Amer. Soc. Hort. Sci.* 74:30–39.
27. Vogele, A. C. 1937. Effect of environmental factors upon the color of the tomato and the watermelon. *Plant Physiol.* 12: 929–955.
28. Went, F. W. 1957. Environmental control of plant growth. Chronica Botanica, Waltham. 343 p. (p. 104).
29. Winneberger, J. H. 1958. Transpiration as a requirement for growth of land plants. *Physiol. Plant.* 11:56–61.
30. Young, P. A. 1947. Cuticle cracks in tomato fruits. *Phytopathology* 37:143–145.

# Effects of High Humidity and Solar Radiation on Temperature and Color of Tomato Fruits[1]

Werner J. Lipton[2,3]
*University of Arizona, Tucson*

*Abstract.* Tomatoes were grown at Tucson in plastic covered greenhouses with normal or high relative humidity (RH). The fruits were exposed to the sun (Ex) or shaded by foliage (Sh), and some exposed fruits were painted either black (B) or white (W).

Temperatures of the surface ($T_s$), wall ($T_w$) and center ($T_c$) of the fruit were 2 to 3° C lower in high than in normal RH, even though the maximum air temperature ($T_{a\ max}$) in high RH exceeded that in normal RH by 1.5°. When $T_s$ and air temperature ($T_a$) were measured simultaneously, $T_s$ of Ex and B fruits was always higher than $T_a$, that of Sh fruits lower, and that of W fruits about the same as $T_a$. The exact gradient depended on RH and $T_a$.

$T_w$ of Ex fruits almost invariably exceeded $T_s$ or $T_c$, and thus the wall was a heat sink. Further, $T_{c\ max}$ exceeded $T_{a\ max}$ in small (diam 35 to 40 mm) or large (diam 60 mm) fruits.

The gradient $T_c$–$T_a$ for large Ex fruits grown in normal RH ranged from −5° to 15° C during the day, while that for fruits grown in high RH ranged from 0° to 12°. The respective daily ranges for the gradient $T_w$–$T_a$ were −5° to 20° and 0° to 13°. For small fruits all gradients were similar and ranged from 3° to 13°.

The incidence of defective coloration of the shoulders or sides of fruits was highest in Ex and seemed to be influenced by infrared and short-wave radiation. The possibility of protecting tomatoes from excess radiation is discussed.

The influence of fruit temperature on ripening of tomatoes has been previously investigated in respect to preharvest (9, 10, 12, 14), or postharvest temperatures (8, 15), or both (16). However, one report dealt only with air temperature, another included that of fruits, but air temperatures were measured distant from the fruits, and none reported on surface temperatures, or on the relation between fruit temperature and ambient relative humidity. Further, effects of size of fruit or of infrared and shorter wave length solar radiation on fruit temperature or color were not critically distinguished. Improved understanding of response of tomato fruits to high humidity and to solar radiation may suggest ways to reduce defective ripening and attendant economic losses.

[1]Received for publication February 11, 1970.

[2]Environmental Research Laboratory. Permanent address: U. S. Department of Agriculture, Agricultural Research Service, Market Quality Research Division, 2021 S. Peach, Fresno, Cal.

[3]I am indebted to the following for their generous cooperation while I was Visiting Plant Physiologist at the ERL: C. N. Hodges, Supervisor; J. J. Riley, P. Kinyicky, Miss Y. Don and D. B. Thorud.

## Methods and Records

*General.* Cultural procedures, cultivars, and the environments in which tomatoes were grown have been described previously (11). In summary: normal relative humidity (RH) ranged from 50% to 90% and high RH from 70% to 100%, depending upon season and time of day. A spring (January to June) and a summer (July to November) crop were grown. Data in this report refer to the summer crop unless otherwise noted.

*Treatment of fruits.* Fruits with initial diameters of 15 to 30 mm, occasionally larger, were exposed to the sun either during part or all of each day, or they were shaded by leaves the entire day.


J. Amer. Soc. Hort. Sci. 95(6): 680–684. 1970.