Changes in Endogenous Auxin Concentration in Cultivars of Tomato Seedlings under Artificial Light

Eva María Almansa and Antonio Espín

Civil Engineering Department of Superior Technical School, University of Granada, Fuente Nueva S/N, CP18071 Granada, Spain

Rosa María Chica

Rural Engineering Department of Superior Engineering School, University of Almería, La Cañada de San Urbano CP 04120, Almería, Spain

María Teresa Lao¹

Crop Production Department of Superior Engineering School, University of Almería, La Cañada de San Urbano CP 04120, Almería, Spain

Additional index words. B-LEDs, fluorescent lamps, PAR:NIR, B:R, B:FR and R:FR ratios

Abstract. In this work, we present the study of the behavior of 15 tomato cultivars under different grow lights to evaluate the quality of seedlings in the production system. The lamps used are: compact fluorescent, high-efficiency fluorescent, fluorescent, and pure blue light-emitting diodes (B-LEDs). The trial was carried out in a culture chamber with the temperature and relative humidity continuously controlled. Spectral radiation was measured at the canopy level. The following were quantified: fresh, dry biomass partitioning organs (leaves, stems, and roots), the total dry weight/total fresh weight relationship, shoot/root ratio, and indole acetic acid. We found high-efficiency fluorescent light treatment has a very interesting spectral quality for all cultivar applications as a result of it having the lowest photosynthetically active radiation (PAR):near infrared (NIR), blue:red (B:R), blue:far red (B:FR), and red:far red (R:FR) ratios; ‘Conquista’, ‘Velasco’, and ‘Lynna’ are cultivars that show sensitivity to special wavebands (ultraviolet, B, R, and FR). ‘Ikram’, ‘Saladar’, and ‘Delizia’ tolerate the lack of minimum energy and spectral quality.

There are a large number of cultivars of tomato used in commercial production under greenhouse conditions. Their growth is influenced by environmental conditions, cultural techniques, and market requirements (Moreno, 1993, 2002). Moreover, the physiological responses of different cultivars are not similar (Gojkovic and Saavedra, 2007) and, therefore, it is necessary to make a detailed study of each variety separately.

The most studied environmental factors used to differentiate among cultivars are: light and temperature (Allen and Rudich, 1978; Bartsur et al., 1985; Dinar and Rudich, 1985; el Ahmadi and Allen, 1979), salinity resistance to pests and diseases (Hanafi and Schnitzler, 2004), and nutritional factors.

Indole-3-acetic acid (IAA) is the most studied auxin and, moreover, it has the highest natural occurrence in plants. Different types of auxin are found in plants as free acids or conjugated forms such as ester and amide derivatives (Normanly et al., 2004).

It is believed that the most important sites of IAA synthesis are generally in young tissues (buds and young leaves, young fruits, and immature seeds) because the endogenous levels

in these tissues are higher than in other tissues. There seem to be two sites of biosynthesis inside the cells, as tryptophan, considered as a precursor of IAA, which is synthesized in plastids, but it has also been found at the cytoplasm (Srivastava, 2002). It can be synthesized in leaves and travels down by polar transport promoting plant growth (Hartmann and Kester, 1983); synthesis and polar transport-promoting growth was observed only with light grown seedling (Boerjan et al., 1995; Jensen et al., 1998; Romano et al., 1995). On the other hand, it has also been observed that one of the two major peaks of auxin production is in the cell division phase (Mapelli et al., 1978).

Bohner and Bangerth (1988) observed in experiments with isogenic lines of tomato that the decrease in the rate of cell divisions is associated with rapid reductions in the levels of IAA. Although not finding a correlation between the concentration of IAA and cell expansion, positive correlations were found between the level of auxin and cell expansion in various tissues of other species (Cleland, 2004). Auxin, in very small quantities, stimulates root growth and in larger amounts inhibits it, favoring the development of lateral roots (Campbell and Reece, 2007).

Auxin controls other organic processes: initiation of radicle and adventitious roots (Hartmann et al., 2002; Weaver, 1998), flowers and fruit retention (Erner, 1989), transition from flower to fruit (Raghavan, 2003), young

foliage (complex interaction) (Zeiger and Taiz, 2007), and tropisms (Campbell et al., 2001; Evert and Eichhorn, 1992; Starr-Taggart et al., 2004; Zeiger and Taiz, 2007). At low concentrations, auxins stimulate metabolism and development; however, high concentrations of auxin inhibit metabolism and development (Campbell et al., 2001).

Auxin synthesis was modified by intensity and quality spectrum light (Kurepin et al., 2007a, 2008; Pacheco, 2001; Tofiño et al., 2007). Concerning the activity of auxin, the light produces a transfer of electrons to the molecule of auxin that blocks its synthesis on the side that receives the light. This causes a higher gradient of concentration on the side without any light (Thornton and Thimann, 1967). The longitudinal and lateral transport of auxin results in its asymmetric distribution and this causes differential growth in plants (Horwitz, 1994; Yi and Guilfoyle, 1991). Irradiation at 730 nm (FR) promotes auxin synthesis in leaves, and irradiation at 660 nm (R) promotes synthesis of the inhibitor (Muir and Zhu, 2006). Blue light (B) produces a higher quantity of auxin in leaves; this production can be put down to cell differentiation (Horwitz, 1994) and growth of secondary roots (Günes, 2000) to ensure the survival of young plants (Geßner et al., 1999).

Transplant seedling production has increased in recent years as a result of the huge advantages of this production system compared with bare-root seedling production. The successful production of seedlings for transplantation requires the control of several factors, one of which is light (Ohya et al., 2003). In the cultivation of tomato seedlings, incident radiation on the canopy affects photosynthesis (Papadopoulos and Ormrod, 1990).

There are parameters to define quality tomato seedlings: total fresh weight (aerial part and roots), total dry weight (aerial part and roots), dry weight/fresh weight partition, total height, number of leaves, foliar surface, stem diameter, root length, etc. (Carbonell, 1995). Hoyos (1990) states that the total dry weight is the best parameter to define quality tomato seedling. The effect of IAA on the length and fresh and dry weight of the stem segment is to increase them all (Saniewski et al., 2005). In wheat cultivars, auxin increased hypocotyl length, seedling fresh, and dry weight and hypocotyl dry weight but did not influence the seed germination percentage and radicle length (Akbari et al., 2007).

The aim of our study is to compare the effect of light sources: compact fluorescent lighting (low consumer), high-efficiency fluorescent, fluorescent tubular light donsbulbs (TLD), and light-emitting diode (LED) used in seedlings production on endogenous auxin concentrations in leaves of different cultivars of tomatoes.

Materials and Methods

The test began on 16 July 2009 with the planting of 15 cultivars of tomatoes (Table 1) in four expanded polyethylene trays. On each tray, 10 seeds of each variety were distributed.

Received for publication 23 Feb. 2011. Accepted for publication 28 Mar. 2011.

¹To whom reprint requests should be addressed; e-mail mtlao@ual.es.

Table 1. Commercial and industrial characteristics of different cultivars of tomato used in the assay.

Cultivars	Plant	Fruit	Caliber	High resistance (HR)
Ikram (I)	Vigor, semiopen, good setting even at low temperatures	In bouquets, very uniform, firm, good flavor and color	M-MM	ToMV 0-2; Fol 1-2, V
Saladar (S)	Suitable for salt water, long life, very productive during all the cycle of cultivation	In bouquets, firm, ideal for export	M-MM	M, TSWV, TYLC
Atlético (A)	Hybrid, long conservation, small leaves of average half-knots, great fecundation	In bouquets, smooth, red very attractive	G-GG	ToMV, Fol 0-1, Va, Vd.
Delizia (D) and Conquista (C _{ON})	Good production, short cultivation, cycle hybrid	Black neck, sweet taste	M-G	Fusarium
Cornabel (C)	Average yield, bears the heat	Good shape fruit pear, red color	G	Va, Vd, Fol 0-1
Rambo (R)	Vigorous plant, of scant distance between posies, cultivation in greenhouse	Slightly marked shoulders, good flavor and color	G-GG	ToMV 0-2; V; Fol 1-2; For; intermediate resistance (IR): M
Anemon (A _N)		Towering quality excellent color		TYLCV, M, For
Velasco (V)	Type beef, extraordinary vigor, excellent curdled with low temperatures	Consistent, uniform, white neck	G-GG	ToMV; Ff: 1-5; Va; Vd; Fol: 0, 1; For
Bigran (B)	Vigorous	Bouquet	M	TYLCV
Myriade (M _V)	Vigorous, very precocious	Lengthened good conservation postharvest	G-GG	TMV, M, V, For, Fol2, Ff5
Montenegro RZ (M _O)	Homogeneous cultivation	Large, green collar, great flavor, excellent preservation postharvest	G-GG	M, TYLC
Prodigy RZ (P)	Very balanced regarding internode length and vegetation	Green collar, good: uniformity, turning to red in the maturation, firmness, conservation	G-GG	ToMV, Va., Fol 0-1, For, My, TSWV, TYLCV
Zayno RZ (Z)	Internode compact plant environment	Dark markedly neck, Bouquet, Excellent taste, firmness and conservation	GG	ToMV, Va, Fol 0-1, For, M, IR: TYLCV
Lynna RZ (L)	Vigorous, uniform fields	Red, collection in cluster or individually, great firmness, commercial long life	M-MM	ToMV, Goes, Fol 0-1, My, TSWV, TYLCV

ToMV 0-2 = *Tomato mosaic virus*; Fol 1, 2 = *Fusarium oxysporum* f. sp. *lycopersici*; V = *Verticillium*; M = nematodes; TSWV and TYLC = *suntan tomato spotted wilt virus*; and *spoon*; Va = *viral amplicon*; Vd = *Verticillium dahliae*; For = *Fusarium oxysporum* f. sp. *radicis lycopersici*; Ff5 = *Cladosporium* 5.

Peat moss covered with vermiculite substrate was used. The density was 421 plants/m². In the pre-experiment period, for 2 d, the trays were kept in a germination chamber at 27 °C with 90% relative humidity (RH) without illumination. The sprouts were moved to the greenhouse at 34 to 35 °C and 53% to 55% RH. After 8 d, the seedlings had a vigorous appearance and they were scheduled for follow-up in a chamber where they were then randomly assigned to each light treatment. The chamber was kept at a constant temperature and humidity (34 °C and 55% RH, respectively). The chamber was equipped with four light sources as described in Table 2. All plants were grown under a 24-h photoperiod, and a complete nutrient solution was used to avoid any water or nutrient limitation. The trial ended on 24 Aug. 2009 when it came to sampling. Experimental design consisted of four lighting treatments (Fig. 1) with 10 replications for each variety and treatment.

Although T₄ shows less energy than the other treatments, it allows us to study the morphogenetic reaction of the crop generated by *PAR* and B which, according to Dougher and Bugbee (2001), allows the effect of B on the photoequilibrium level of phytochrome and *PAR* radiation to be separated.

Spectral radiation was measured in each shelf using a LI-COR 1800 (LI-COR Inc., Lincoln, NE) at the canopy level.

At the end of the trial, plants were evaluated. Fresh and dry weight partitioning among assimilation (leaves), conductive (stems and petioles), and absorption (roots) organs were

Table 2. Characteristics of light treatments.

Treatments	Lamps and lighting	Power (W·m ⁻²)
T1	Compact fluorescent (8 lamps 23 W)	184
T2	Fluorescent TL5 (2 lighting × 2 lamps 35 W)	140
T3	TLD fluorescent (3 lighting × 2 lamps 18 W)	108
T4	Pure blue light-emitting diodes (B-LEDs) RGB (four lines ALUM 40*25 LED SMD RGB × 9 W with console DN-RGB fiber light)	36

Fig. 1. Spectral quality of different treatments measured at canopy level.

Fig. 2. (A–B) The relationship between TDW:TFW and TDW. TDW = total dry weight; TFW = total fresh weight.

measured by a precision balance (Mettler Toledo classic PB303-S, Greifensee, Switzerland).

Extraction was made by grinding fresh leaves with 95% + 70% (1:1 v/v) ethanol. After filtering and centrifuging the samples at 5500 rpm for 10 min, IAA was quantified in supernatant fractions by colorimetry with a Spectrophotometer (Shimadzu ultraviolet-1201; Shimadzu, Kyoto, Japan) (Tien et al., 1979).

Analysis of data was made using the software packages Excel 7.0 and Statgraphics (Stat-Point, Herndon, VA) plus 4.0. Analysis of variance and the Tukey test for $P < 0.05$ were used to assess the significance of parameters fresh weight (FW) and dry weight (DW) for all parts of the plants; least significant difference (LSD) test for $P < 0.05$ was used to assess the significance of the relationship between aerial and root parts [Leaves+Stem Dry Weight:Root Dry Weight (LSDW:RDW)] in the treatments studied.

Results and Discussion

Spectral quality lights. Figure 1 shows spectral quality of different treatments measured at the canopy level. Common peak occurred at 436, 544, and 612 nm for T₁, T₂, and T₃, respectively but only T₄ presents a wide peak at 470 nm. The lowest total radiation is presented by T₄.

Interesting values associated with radiation from the agricultural point of view to characterize the quality of light (Baile et al., 2003) and the relationship between different spectral radiation ranges are presented in Table 3.

T₁ and T₂ show similar ultraviolet radiation (UV), higher than T₃, whereas T₄ does not show ultraviolet radiation. UVA and UVB can produce changes in the reduction of the stem length as a result of degrading IAA (Mark and Tevini, 1996).

Table 3. Agronomic characterization of quality light ($W \cdot m^{-2}$).

Treatments	T1	T2	T3	T4
Ultraviolet (300–400 nm)	0.31	0.32	0.11	0.01
B (400–500 nm)	3.90	3.42	4.24	2.55
R (600–700 nm)	4.50	6.62	4.73	0.00
FR (700–800 nm)	0.42	0.63	0.40	0.00
PAR (400–700 nm)	14.40	16.57	15.39	2.71
NIR (700–1100 nm)	0.66	0.95	0.58	0.00
Total (300–1000 nm)	15.18	17.70	15.94	2.72
PAR:total	0.95	0.94	0.97	1.00
PAR:NIR	21.73	17.50	26.48	—
B:R	0.87	0.52	0.90	—
B:FR	9.36	5.47	10.66	—
R:FR	10.81	10.59	11.90	—

B = blue; R = red; FR = far red; PAR = photosynthetically active radiation; NIR = near infrared.

The gradient of B radiation is $T_3 > T_1 > T_2 > T_4$. B light affects photomorphogenic aspects of plant growth and their development (Sundström, 2000). Carotene, xanthophylls (orange and yellow), and anthocyanins (red pigments) absorb mainly in the B region of the spectrum. Chlorophyll also absorbs in the B (Buiten and Clevers, 1993). Likewise, B light stimulates synthesis of auxin through the activity of the auxin:IAA protein family, which is related to endogenous levels of IAA (Folta et al., 2003). Also, Zeng et al. (2009) found in Arabidopsis that the cryptochrome photoreceptors regulate root growth by changing auxin transport.

T₂ shows the highest values of R and FR parameters, whereas T₁ and T₃ are similar. Briggs (1963) documented R light suppresses auxin production in corn coleoptiles. Phytochromes (Hall and Rao, 1999) are responsible for plant response at R and FR ranks.

T₂ shows the best value of PAR; T₂, T₃, and T₁ have higher values than those mentioned in the literature for all lighting systems (Gaudreau et al., 1994; Poudel et al., 2007; Tennessen

et al., 1994). PAR is the portion of the spectrum that participates in photosynthesis; PAR and temperature are critical parameters related to tomato plant performance in the greenhouse (Jones, 2008).

T₂ has a higher NIR value, although T₁ has greater power (Table 2); also, T₁ did not have a light system.

NIR is mainly determined by the absence of absorption by pigments; this means that the energy passes through the leaf (the leaf is transparent) or that it is reflected, producing more transition of air to cell walls (Buiten and Clevers, 1993). NIR is a useful part of the radiation for photosynthesis mainly related to heat and the greenhouse energetic balance (Castilla, 2005). Nevertheless, in a culture chamber with light at every level of the crop, NIR only results in plant overheating and the possibility of damaging tissues.

Total radiation received by the canopy plant in T₁ and T₃ is similar; T₂ has the highest value of all treatments. Total radiation measurement at T₄ is very low compared with other treatments.

High photosynthetic efficiency radiation can be connected with partition *PAR*:total whose value must be equal or closer to 1. In all treatments, this condition is known.

T₃ has the best relationship between both spectral regions. The *PAR*:NIR relationship must be high in artificial lighting systems because it can mean that there is no damage by heating.

T₃ has a B:R value equal to 0.90 and T₂ has the value furthest from 1 for this param-

eter with regard to all of the treatments. When there is an excess of B with very little R, growth will be shortened, and the cuticle will be dark-colored and hard; if there is an excess of R over B, the growth will become soft with long internodes, resulting in lanky plants (Jones, 2008). A value closer to 1 indicates balance in the B and R wavebands.

T₂ has the lowest values of these parameters. B:FR and R:FR may be critical parameters in the cultures. Blue light will result in

a thicker cuticle if it is reflective. These wavelength bands alter the proportions of esters and leaf wax alcohols in the leaves of pepper (Kasperbauer and Wilkinson, 1995).

Biomass evaluation. Table 4 shows morphological parameters of studied cultivars under light treatments. The cultivars A, R, M_O, P, Z, and L show a light compensation point higher than that offered by T₄, because they died in the course of the trial. The compensation point for light intensity varies according to

Table 4. Fresh and dry weight (g) for all parts of the plant and different partitions.

		LFW*	SFW	RFW	TFW	LDW	SDW	RDW	TDW	TDW:TFW	LSDW:RDW
I	T ₁	0.39 b	0.30bc	0.09 b	0.78 b	0.03 a	0.03 b	0.01 b	0.06 bc	0.07 b	5.62 a
	T ₂	0.76 a	0.92 a	0.23 a	1.91 a	0.04 a	0.11 a	0.02 a	0.17 a	0.09 a	6.50 a
	T ₃	0.46 ab	0.36 b	0.10 b	0.93 b	0.03 a	0.03 b	0.01 b	0.07 b	0.08 b	6.67 a
	T ₄	0.18 b	0.12 c	0.03 b	0.33 b	0.01 b	0.01 b	0.002 b	0.01 c	0.04 c	8.44 b
S	T ₁	0.34 b	0.22 b	0.05 b	0.60 b	0.02 a	0.02 b	0.003 c	0.04 b	0.06 b	6.97 a
	T ₂	0.53 a	0.51 a	0.11 a	1.16 a	0.03 a	0.05 a	0.02 a	0.10 a	0.09 a	5.4 b
	T ₃	0.41 ab	0.26 b	0.10 a	0.76 a	0.02 a	0.02 b	0.01 b	0.05 b	0.07 ab	4.84 b
	T ₄	0.15 c	0.09 c	0.02 b	0.26 c	—	0.003 c	0.001 c	0.01 c	0.02 c	2.75 c
A	T ₁	0.34 b	0.23 b	0.03 b	0.60 b	0.02 b	0.02 b	0.005 b	0.04 b	0.06 b	6.35 a
	T ₂	0.64 a	0.58 a	0.20 a	1.41 a	0.03 a	0.06 a	0.02 a	0.12 a	0.08 a	3.96 b
	T ₃	0.28 b	0.13 b	0.05 b	0.46 b	0.02 b	0.01 b	0.005 b	0.03 b	0.06 b	5.67 b
	T ₄	—	—	—	—	—	—	—	—	—	—
D	T ₁	0.31 b	0.20 b	0.05 b	0.55 b	0.01 b	0.01 b	0.003 b	0.03 b	0.05 b	6.41 a
	T ₂	0.51 a	0.55 a	0.16 a	1.22 a	0.03 a	0.05 a	0.02 a	0.10 a	0.08 a	5.55 ab
	T ₃	0.23 b	0.18 b	0.05 b	0.46 b	0.01 b	0.01 b	0.004 b	0.03 b	0.06 b	3.99 b
	T ₄	0.01 c	0.006 c	—	0.02 c	—	—	—	—	0.01 c	—
C	T ₁	0.41 b	0.33 b	0.09 bc	0.84 b	0.02 b	0.03 b	0.01 b	0.05 b	0.05 b	8.02 a
	T ₂	0.69 a	0.79 a	0.31 a	1.79 a	0.04 a	0.11 a	0.03 a	0.18 a	0.08 a	5.57 b
	T ₃	0.40 b	0.30 b	0.12 b	0.82 b	0.02 b	0.02 b	0.01 b	0.05 b	0.06 b	5.96 b
	T ₄	0.16 c	0.13 c	0.02 c	0.31 c	—	—	—	—	0.04 c	—
R	T ₁	0.33 b	0.24 b	0.06 b	0.64 b	0.015 b	0.02 b	0.01 b	0.04 b	0.06 b	5.44 a
	T ₂	0.52 a	0.60 a	0.22 a	1.34 a	0.03 a	0.06 a	0.02 a	0.11 a	0.08 a	4.33 a
	T ₃	0.37 b	0.25 b	0.09 b	0.70 b	0.02 a	0.02 b	0.01 b	0.05 b	0.07 a	5.57 a
	T ₄	—	—	—	—	—	—	—	—	—	—
A _N	T ₁	0.35 b	0.25 b	0.05 bc	0.65 b	0.02 b	0.02 bc	0.01 b	0.05 bc	0.07 b	7.29 a
	T ₂	0.64 a	0.80 a	0.21 a	1.65 a	0.03 a	0.09 a	0.02 a	0.14 a	0.08 a	5.30 b
	T ₃	0.44 b	0.31 b	0.09 b	0.84 b	0.02 b	0.03 b	0.01 b	0.06 b	0.07 ab	5.13 b
	T ₄	0.16 c	0.09 c	0.02 c	0.28 c	—	0.01 c	—	0.01 c	0.02 c	—
C _{ON}	T ₁	0.29 b	0.20 b	0.06 bc	0.55 bc	0.01 b	0.02 b	0.01 b	0.03 bc	0.06 ab	5.90 a
	T ₂	0.71 a	0.87 a	0.27 a	1.58 a	0.04 a	0.09 a	0.02 a	0.15 a	0.10 a	5.37 a
	T ₃	0.37 b	0.22 b	0.12 b	0.71 b	0.02 b	0.02 b	0.01 b	0.04 b	0.06 ab	4.43 a
	T ₄	0.11 c	0.05 c	0.01 c	0.17 c	0.002 c	0.002 b	—	0.004 c	0.02 b	—
V	T ₁	0.35 b	0.22 bc	0.07 b	0.65 b	0.017 b	0.02 b	0.004 b	0.04 bc	0.06 b	7.93 a
	T ₂	0.56 a	0.61 a	0.19 a	1.36 a	0.03 a	0.07 a	0.02 a	0.12 a	0.09 a	7.04 a
	T ₃	0.44 ab	0.27 b	0.09 b	0.79 b	0.02 ab	0.02 b	0.007 b	0.05 b	0.06 b	6.08 a
	T ₄	0.12 c	0.07 c	0.01 b	0.20 c	0.002 c	—	0.001 b	0.003 c	0.02 c	2.00 b
B	T ₁	0.32 b	0.22 b	0.06 bc	0.60 b	0.01 b	0.02 b	0.01 b	0.03 c	0.06 c	5.46 a
	T ₂	0.53 a	0.54 a	0.18 a	1.25 a	0.03 a	0.06 a	0.02 a	0.11 a	0.09 a	4.01 a
	T ₃	0.37 b	0.22 b	0.08 b	0.67 b	0.02 a	0.02 b	0.01 b	0.05 b	0.08 b	5.03 a
	T ₄	0.12 c	0.08 c	0.02 c	0.22 c	—	0.004 c	—	0.004 c	0.02 d	—
M _Y	T ₁	0.41 a	0.29 b	0.09 bc	0.79 b	0.02 b	0.02 b	0.01 b	0.05 bc	0.06 b	5.15 a
	T ₂	0.58 a	0.71 a	0.25 a	1.54 a	0.04 a	0.09 a	0.02 a	0.15 a	0.10 a	5.52 a
	T ₃	0.50 a	0.31 b	0.14 b	0.94 b	0.03 ab	0.03 b	0.01 b	0.07 b	0.07 b	4.12 a
	T ₄	0.13 b	0.10 b	0.01 c	0.23 c	—	0.01 b	—	0.005 c	0.02 c	—
M _O	T ₁	0.32 b	0.20 b	0.07 b	0.59 b	0.01 b	0.02 b	0.01 b	0.03 b	0.058 b	4.97 a
	T ₂	0.61 a	0.55 a	0.19 a	1.34 a	0.03 a	0.05 a	0.02 a	0.10 a	0.073 a	4.52 a
	T ₃	0.43 ab	0.24 b	0.12 b	0.79 b	0.03 a	0.02 b	0.01 b	0.05 b	0.069 ab	5.38 a
	T ₄	—	—	—	—	—	—	—	—	—	—
P	T ₁	0.38 b	0.23 c	0.08 a	0.68 b	0.016 b	0.02 c	0.007 b	0.04 b	0.058 b	4.20 a
	T ₂	0.56 a	0.45 a	0.11 a	1.12 a	0.034 a	0.04 a	0.014 a	0.09 a	0.08 a	5.71 a
	T ₃	0.41 b	0.32 b	0.12 a	0.86 b	0.02 ab	0.03 b	0.01 ab	0.06 b	0.066 ab	4.26 a
	T ₄	—	—	—	—	—	—	—	—	—	—
Z	T ₁	0.39 b	0.25 b	0.08 a	0.72 b	0.02 b	0.02 b	0.007 b	0.04 b	0.056 b	5.06 a
	T ₂	0.68 a	0.54 a	0.14 a	1.36 a	0.04 a	0.05 a	0.014 a	0.11 a	0.08 a	6.60 a
	T ₃	0.39 b	0.33 b	0.09 a	0.82 b	0.02 b	0.03 b	0.01 ab	0.06 b	0.07 a	4.90 a
	T ₄	—	—	—	—	—	—	—	—	—	—
L	T ₁	0.23 a	0.11 b	0.02 a	0.36 b	0.01 a	0.01 a	0.001 b	0.02 b	0.05 a	6.00 a
	T ₂	0.30a	0.19 a	0.04 a	0.53 a	0.02 a	0.02a	0.005a	0.04 a	0.08 a	7.13 a
	T ₃	0.24a	0.12 b	0.02a	0.38ab	0.01 a	0.01a	0.001b	0.03 ab	0.07 a	7.00 a
	T ₄	—	—	—	—	—	—	—	—	—	—

*Significant difference at $P < 0.05$ by the Tukey's multiple range test with different letter(s) within column by variety.

FW = fresh weight; L = leaf; S = stem; R = roots; T = total; DW = dry weight; DWLS = dry weight leaf + dry weight stem.

the type of plant, but it is typically 40 to 60 W·m⁻² for sunlight. The compensation point for light, in the tomato plant, can be reduced (somewhat) by increasing the amount of carbon dioxide available to the plant, allowing the plant to grow under conditions of lower illumination.

Total dry weight (TDW) is higher in T₂ > T₃ > T₁ > T₄. Lighting systems produced different effects on TDW; a linear relationship between cumulative intercepted PAR and tomato dry mass production has been reported (Heuvelink and Dorais, 2005; Riga et al., 2008).

S and V seem to have an acceptable behavior to T₄, although they are not the highest quality plants; they are cultivars that can survive poorly under this quality light. This behavior was mentioned by Geßner et al. (1999) and they explained that the B light supplied by the LED appears to increase the survival of young seedlings such as these ones.

Figures 2 (a) and (b) present the relationship between TDW/TFW and TDW. It can be observed that TDW:total fresh weight (TFW) is related to TDW but not to cultivars and treatments. The plant increases its hardness in relation to the dry material that accumulates. These results agree with those of Miller and Timmer (1997) who found an increase of shoot (99% to 142%) and root (five- to 10-fold) biomass in *Picea mariana* during hardening.

TDW:TFW ratios close to 0.10 may indicate that the seedling is a better quality one than others that show lower values. Likewise, plants with TDW:TFW close to 0.10 show greater hardening and more successful transplant (Wainwright and Marsh, 1986).

For the LSDW:RDW ratio, no direct effect of light treatment was found among treatments T₁, T₂, and T₃ except in cultivars S, A, D, C, and A_N. These cultivars show the highest values in T₁; this can be related to the low level of R, the R:FR ratio, and ultraviolet and PAR radiation (Table 3). Inada (1984) classified growth responses to light qualities into two groups: 1) species in which R inhibits cell elongation more effectively than B; and 2) species in which the response was reversed. Tomato could be considered in the first group. These results agreed with Kurepin et al. (2010) who found wild-type tomato seedlings responded to a low R:FR ratio with increased stem elongation. UVA and UVB can produce changes in reduction of stem length (Mark and Tevini, 1996).

Looking at Table 4 for cultivar I, it is noteworthy that T₄ shows the highest value of LSDW:RDW, as does the TDW, and if we consider the parameter LSDW:RDW, it is curious how this variety is capable of developing its aerial parts very quickly but has slow root development; the plants are not good quality but are survivors. On the other hand, the LSDW:RDW ratio clarifies the status of the seedling. If the values of this parameter are very high, we can deduce that the roots are not developed, so the plant is not getting its water and nutritional needs and because of this, the aerial part will not develop much more (Partida et al., 2007).

Table 5 shows the relationship between aerial and root parts (LSDW:RDW) for all

cultivars for all treatments. In general, the treatments did not affect these parameters, but the intrinsic morphological characteristics of each variety can affect it. 'I', 'C', 'A_N', 'V', 'Z', and 'L' are the group with higher values, presenting significantly lower values for other cultivars. A lower value of this parameter involves obtaining a plant with a well-developed root and some tightening; it is important to transplant outdoors (Liptay et al., 1998; Nicola, 1998). Seedlings with a relatively large root system generally suffer less transplant stress and, thus, further growth is anticipated for them than for those with smaller roots (Weston and Zandstra, 1986).

Plant development and indole-3-acetic acid. Endogenous auxin concentration in leaves (Fig. 3) shows significant differences in each variety by treatment (LSD test $P < 0.05$). All cultivars under T₂ conditions show the highest auxin concentration and, under T₄, they always show a lower concentration. Most of the cultivars have similar concentrations of auxin in T₁ and T₃. Even in 'D' and 'V', no significant differences in the concentration of auxin among T₁, T₂, and T₃ have been found. Moreover, the concentration of auxin in 'C_{ON}' is similar in T₁ and T₂ but T₃ shows a lower concentration. However, 'S' and 'B' have a higher concentration in T₃ than in T₁. These results may be the result of the different sensitivity of different cultivars for different regions of the spectrum (UV, B, R, and FR) to act together. The most important sensi-

tivity is that related to R:FR with a maximum value in T₂ (Table 3), except in the performance of the cultivars D and V. These results are consistent with Kurepin et al. (2007a). They found low R:FR ratios associated with an increase in endogenous IAA levels.

No differences between the concentrations of auxin in T₁ and T₃ were found. We might consider that differences in UV and B applied in both treatments did not modify the synthesis of auxin in most of the cultivars studied. However, the highest concentration of auxin in the S and B cultivars in T₃ compared with T₁ may involve a high sensitivity to the B and UV region in these cultivars.

In lighting conditions produced by T₄, only nine cultivars survived ('I', 'S', 'D', 'C', 'A_N', 'C_{ON}', 'V', 'B', and 'M_Y'). Under T₄, variety 'I' has the highest value of auxin, but all parameters (Table 4) indicate that seedlings in this treatment are not good quality ones as a result of the low PAR radiation received.

Figure 4 shows the correlations between auxin concentration and TDW, in which all cultivars show a high correlation with both parameters. Correlation is shown by a linear equation and coefficient $R^2 = 0.63$. This coefficient of determination could be considered good because differential behavior of cultivars is also an important influence. These results agreed with Kurepin et al. (2007b), who found that TDW seedling is associated with endogenous levels of hormones such as auxins, cytokinins, and abscisic acid (Kurepin et al.,

Table 5. LSDW:RDW relationship among cultivars.

Variety/ (LSDW:RDW)	I	S	A	D	C	R	A _N	C _{ON}	V	B	M _Y	M _O	P	Z	L
I/6.77															
S/5.07	*														
A/5.19	*														
D/4.85	*														
C/6.52		*		*											
R/5.12	*				*										
A _N /5.91															
C _{ON} /5.23	*														
V/6.63		*	*	*		*		*							
B/4.83	*				*				*						
M _Y /4.93	*				*				*						
M _O /4.95	*				*				*						
P/4.72	*				*				*						
Z/5.52															
L/6.92	*			*		*				*		*	*		

*Significant differences among varieties according to the statistical analysis (least significant difference test $P < 0.05$) for (LSDW:RDW) parameter.

Fig. 3. Auxins concentration in leaves.

Fig. 4. Relationship between total dry weight and auxin concentration.

2007c). Also, Mapelli et al. (1978) considered that high amounts of auxin may be related to plant development in the phase of cell divisions and that auxin synthesized by the leaves has gone to the roots allowing rapid development and thus ensuring the survival of the seedling (Geßner et al., 1999; Günes, 2000). Veglio (2010) presents a model based on the consideration that plant growth is controlled by the auxin biosynthesis pathway, which is regulated by two signals: an internal one related to the hormone ethylene and an environmental one.

No correlation was found between TDW:TFW or LSDW:RDW parameters and the concentration of auxin.

Conclusion

Light treatments applied generate significant differences in the FW and DW of organs and plant as well as the concentration of auxin in leaves.

T₄ applied radiation is under compensation point and it is insufficient for the survival of cultivars Atletico, Rambo, Montenegro, Prodigy, Zayno, and Lynna.

The TDW:TFW ratio may be related to TDW presenting the same trend regardless of the treatments received and the cultivars concerned.

The LSDW:RDW ratio has neither significant correlation with treatments nor with the endogenous concentration of auxin in leaves.

The concentration of auxins differs significantly in terms of lighting treatments applied, being highest in T₂ for all cultivars; this could be related with a low R:FR ratio. Different responses in auxin concentration in T₃ and T₁ are presented for cultivars and could be related to the different sensitivity of cultivars to UV and B fraction of light received. A significant correlation between auxin concentration and TDW produced has been found.

T₂ characterized for the lowest PAR:NIR, B:R, B:FR, and R:FR provides adequate light quantity and quality for all cultivars within the parameters RDW, TDW, TDW:TFW, and LSDW:RDW.

Literature Cited

Akbari, G., S.A.M.M. Sanavy, and S. Yousefzadeh. 2007. Effect of auxin and salt stress (NaCl) on seed germination of wheat cultivars (*Triticum aestivum* L.). Pak. J. Biol. Sci. 10:2557–2561.

Allen, M.S. and D. Rudich. 1978. Genetic potential for overcoming physiological limitations on adaptability, yield, and quality in the tomato. Hort. Sci. 13:673–678.

Baille, A., M.M. González-Real, J.C. López, J. Cabrera, and J. Pérez-Parra. 2003. Characterization of the solar diffuse component under 'Parral' plastic greenhouses. Proc. 6th IS on Protected Cult. Acta Hort. 614, ISHS. p. 341–346.

Bartsur, A., J. Rudich, and B. Bravdo. 1985. High temperature effects on CO₂ exchange in heat tolerant and sensitive tomatoes. J. Amer. Hort. Sci. 110:582–586.

Boerjan, W., M.-T. Cervera, M. Delarue, T. Beekman, W. Dewitte, C. Bellini, M. Caboche, H. Van Onckelen, M. Van Montagu, and D. Inze. 1995. Superroot, a recessive mutation in arabidopsis, confers auxin overproduction. Plant Cell 7:1405–1419.

Boher, J. and F. Bangerth. 1988. Cell number, cell size and hormone levels in semi-isogenic mutants of *Lycopersicon pimpinellifolium* differing in fruit size. Plant Physiol. 72:316–320.

Briggs, W.R. 1963. Red light, auxin relationships and the phototropic response of corn and oat coleoptiles. Amer. J. Bot. 50:196–207.

Buiten, H.J. and J.G.P.W. Clevers. 1993. Land observation by remote sensing: Theory and applications. Gordon and Breach Science Publishers, The Netherlands.

Campbell, N.A., L.G. Mitchell, and J.B. Reece. 2001. Biology: Concepts & connections. 3rd Ed. Pearson Education, Mexico.

Campbell, N.A. and J.B. Reece. 2007. Biology. 7th Ed. Editorial. Médica Panamericana, Madrid, Spain.

Carbonell X. 1995. Seed, seedling and pattern. Horticulture 106.

Castilla, N. 2005. Invernaderos de plástico, tecnología y manejo. Mundi-Prensa, Madrid, Spain.

Cleland, R. 2004. Auxin and cell elongation, p. 204–220. In: Davies, J. (ed.). Plant hormones: Biosynthesis, signal transduction, action. Kluwer Acad. Pub., Dordrecht, The Netherlands.

Dinar, M. and J. Rudich. 1985. Effect of heat stress on assimilate partitioning in tomato. Ann. Bot. (Lond.) 56:239–248.

Dougher, T.A.O. and B. Bugbee. 2001. Differences in the response of wheat, soybean and lettuce to reduced blue light radiation. Photochem. Photobiol. 73:199–207.

el Ahmadi, B. and M.S. Allen. 1979. Reproductive responses of heat tolerant tomatoes to high temperatures. J. Amer. Hort. Sci. 104:686–691.

Emer, Y. 1989. Citrus fruit set: Carbohydrate, hormone, and leaf mineral relationship, p. 233–242. In: Wright, C.J. (ed.). Manipulation of fruiting. Butterworths, London, UK.

Evert, R.F. and S.E. Eichhorn. 1992. Biol. Plant 2. 4th Ed. Reverté, Barcelona, Spain.

Folta, K.M., M.A. Pontin, G. Karlin-Neumann, R. Bottini, and E.P. Spalding. 2003. Genomic and physiological studies of early cryptochrome 1 action demonstrate roles for auxin and gibberellin in the control of hypocotyl growth by blue light. Plant J. 36:203–214.

Gaudreau, L., J. Charbonneau, L. Vezina, and A. Gosselin. 1994. Photoperiod and PPF influence growth and quality of greenhouse-grown lettuce. HortScience 29:1285–1289.

Geßner, M., H.J. Köhler, and N. Christoph. 1999. El 'envejecimiento atípico' en el vino VIII. La Viña y el Vino 8:264–267.

Goykovic, V. and G. Saavedra. 2007. Algunos efectos de la salinidad en el cultivo del tomate y prácticas agronómicas de su manejo. Idesia 25:47–58.

Günes, T. 2000. Peroxidase and IAA oxidase activities during rooting in cuttings of three poplar species. Turk. J. Bot. 24:97–101.

Hall, D. and K. Rao. 1999. Photosynthesis: Studies in biology. Cambridge Univ. Press, Cambridge, UK.

Hanafi, A. and W.H. Schnitzler. 2004. Integrated production and protection in greenhouse tomato in Morocco. Acta-Horticulturae 659:295–300.

Hartmann, H.T. and D.E. Kester. 1983. Plant propagation: Principles and practices. 4th Ed. Prentice-Hall, Englewood Cliffs, NJ.

Hartmann, H.T., D.E. Kester, F.T. Davies, and R.L. Geneve. 2002. Plant propagation: Principles and practices. 7th Ed. Prentice Hall, Englewood Cliffs, NJ.

Heuvelink, E. and M. Dorais. 2005. Tomatoes: Crop growth and yield. CABI Publishing, Wallingford, UK.

Horwitz, B.A. 1994. Properties and transducers chainsof the UV and the blue light photoreceptors, p. 327–350. In: Kendrick, R.E. and G.H.M. Kronenberg (eds.). Photomorphogenesis in plants. 2nd Ed. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hoyos, P. 1990. The last in horticulture seedlings (II). Horticulture 54.

Inada, K. 1984. Photomorphogenesis: Light and plant growth. Yokendo, Tokyo, Japan.

Jensen, P.J., R.P. Hangarter, and M. Estelle. 1998. Auxin transport is required for hypocotyl elongation in light-grown but not dark-grown arabidopsis. Plant Physiol. 116:455–462.

Jones, J.B. 2008. Tomato plant culture: in the field, greenhouse, and home garden. 2nd ed. CRC Press. Taylor & Francis Group. p. 19–21; 56–60; 341.

Kasperbauer, M.J. and R.E. Wilkinson. 1995. Mulch surface color affects accumulation of epicuticular wax on developing leaves. Photochem. Photobiol. 62:940–944.

Kurepin, L.V., R.J.N. Emery, C.C. Chinnappa, and D.M. Reid. 2008. Light irradiance differentially regulates endogenous levels of cytokinins and auxin in alpine and prairie genotypes of *Stellaria longipes*. Physiol. Plant. 134:624–635.

Kurepin, L.V., R.J.N. Emery, R.P. Pharis, and D.M. Reid. 2007a. Uncoupling light quality from light irradiance effects in *Helianthus annuus* shoots: Putative roles for plant hormones in leaf and internode growth. J. Expt. Bot. 58:2145–2157.

Kurepin, L.V., R.J.N. Emery, R.P. Pharis, and D.M. Reid. 2007b. The interaction of light quality and irradiance with gibberellins, cytokinins and auxin in regulating growth of *Helianthus annuus* hypocotyls. Plant Cell Environ. 30:147–155.

Kurepin, L.V., R.J.N. Emery, R.P. Pharis, and D.M. Reid. 2007c. Uncoupling light quality from light irradiance effects in *Helianthus*

- annuus shoots: Putative roles for gibberellins, auxin, cytokinins, abscisic acid and ethylene in leaf and internode growth. *J. Expt. Bot.* 58:2145–2157.
- Kurepin, L.V., W.-K. Yip, R. Fan, E.C. Yeung, and D.M. Reid. 2010. The roles and interactions of ethylene with gibberellins in the far-red enriched light-mediated growth of *Solanum lycopersicum* seedlings. *Plant Growth Regulat.* 61:215–222.
- Liptay, A., P. Sikkema, and W. Fonteno. 1998. Transplant growth control through water deficit stress: A review. *HortTechnology* 8:540–543.
- Mapelli, S.C., C. Frova, G. Torti, and G. Soressi. 1978. Relationship between set, development and activities of growth regulators in tomato fruits. *Plant Cell Physiol.* 19:1281–1288.
- Mark, U. and M. Tevini. 1996. Combination effects of UV-B radiation and temperature on sunflower (*Helianthus annuus* L., cv Polstar) and maize (*Zea mays* L., cv Zenit 2000) seedlings. *J. Plant Physiol.* 148:49–56.
- Miller, B.D. and V.R. Timmer. 1997. Nutrient dynamics and carbon partitioning in nutrient loaded *Picea mariana* [Mill.] B.S.P. seedling during hardening. *Scand. J. For. Res.* 12:122–129.
- Moreno, R. 1993. Programa de tratamientos integrados en Hortalizas. *J. Hort.* 85:65–67.
- Moreno, R. 2002. Producción Integrada: Un reto científico. *J. Hortint. Extra* 1:145–153.
- Muir, R.M. and L.-J. Zhu. 2006. Effect of light in the control of growth by auxin and its inhibitor(s) in the sunflower. *Physiol. Plant.* 57:407–410.
- Nicola, S. 1998. Understanding root systems to improve seedling quality. *HortTechnology* 8: 544–549.
- Normanly, J., J.P. Slovin, and J.D. Cohen. 2004. Auxin biosynthesis and metabolism, p. 36–62. In: Davies, J. (ed.). *Plant hormones: Biosynthesis, signal transduction, action*. Kluwer Acad. Pub., Dordrecht, The Netherlands.
- Ohyama, K., K. Manabe, Y. Omura, C. Kubota, and T. Kozai. 2003. A comparison between closed-type and open-type transplant production systems with respect to quality of tomato plug transplants and resource consumption during summer. *Env. Control in Biology.* 41:57–61.
- Pacheco, R. 2001. Evaluación del efecto de la luz sobre la propagación masiva de *Sinningia speciosa* via organogénesis. Escuela de Biología. Costa Rica Inst. Technol., Cartago, Costa Rica.
- Papadopoulos, A.P. and D.P. Ormrod. 1990. Plant spacing effects on yield of the greenhouse tomato. *Can. J. Plant Sci.* 50:563–573.
- Partida, L., T.J. Velázquez, B. Acosta, F. Ayala, T. Díaz, J.F. Inzuza, and J.E. Cruz. 2007. Paclobutrazol y crecimiento de raíz y parte aérea de plántulas de pimiento morrón y berenjena. *Rev. Fitotec. Mex.* 30:145–149.
- Poudel, P.R., I. Kataoka, and R. Mochioka. 2007. Effect of red- and blue-light-emitting diodes on growth and morphogenesis of grapes. *Plant Cell Tissue Organ Cult.* 92:147–153.
- Raghavan, V. 2003. Some reflections on double fertilization from its discovery to the present. *New Phytol.* 159:565–583.
- Riga, P., M. Anza, and C. Garbisu. 2008. Tomato quality is more dependent on temperature than on photosynthetically active radiation. *J. Sci. Food Agr.* 88:158–166.
- Romano, C.P., P.R.H. Robson, H. Smith, M. Estelle, and H. Klee. 1995. Transgenemediated auxin overproduction in *Arabidopsis* hypocotyl elongation phenotype and interactions with the *hy6-1* hypocotyl elongation and *axr1* auxin-resistant mutants. *Plant Mol. Biol.* 27:1071–1083.
- Saniewski, M., H. Okubo, K. Miyamoto, and J. Ueda. 2005. Auxin induces growth of stem excised from growing shoot of cooled tulip bulbs. *J. Fac. Agr.* 50:481–488.
- Srivastava, L.M. 2002. Auxins, p. 155–169. In: *Plant Growth and Development: hormones and environment*. Academic Press, New York.
- Starr, C., R. Taggart, C.A. Evers, and L. Starr. 2004. *Biología: La unidad y diversidad de la vida*. 12th Ed. Cengage Learning, Mexico.
- Sundström, V. 2000. Light in elementary biological reactions. *Prog. Quantum Electron.* 24:187–238.
- Tennessen, D.J., R.J. Bula, and T.D. Sharkey. 1994. Efficiency of photosynthesis in continuous and pulsed light emitting diode irradiation. *Photosynth. Res.* 44:261–269.
- Thornton, R.M. and K.V. Thimann. 1967. Transient effects of light on auxin transport in the *Avena* coleoptile. *Plant Physiol.* 42:247–257.
- Tien, T.M., M.H. Gaskin, and D.H. Hubbell. 1979. Plant growth substance produced by *Azospirillum brasilense* and their effect on the growth of pearl millet (*Pennisetum americanum* L.). *Appl. Environ. Microbiol.* 37:219–226.
- Tofiño, A., H.M. Romero, and H. Ceballos. 2007. Effect of abiotic stress on starch, synthesis and degradation. A review. *Agronomía Colombiana* 25:246–254.
- Veglio, A. 2010. The shade avoidance syndrome: A non-Markovian stochastic growth model. *J. Theor. Biol.* 264:722–728.
- Wainwright, H. and J. Marsh. 1986. The micropropagation of watercress (*Rorippa nasturtium-aquaticum* L.). *J. Hort. Sci.* 61:251–256.
- Weaver, R. 1998. Reguladores de crecimiento de las plantas en la Agricultura. California Univ. Press, Davis ed. Trillas, Chapingo, Mexico.
- Weston, L. and B. Zandstra. 1986. Effect of roots container size and location of production on growth and yield of tomato transplants. *J. Amer. Soc. Hort. Sci.* 111:498–501.
- Yi, H.G. and T.J. Guilfoyle. 1991. An auxin responsive promoter is differentially induced by auxin gradients during tropisms. *Plant Cell* 3:1167–1175.
- Zeiger, E. and L. Taiz. 2007. *Plant physiology*. 3rd Ed. Universitat Jaume I, Castelló.
- Zeng, J., Q. Wang, J. Lin, K. Deng, D. Tang, X. Zhao, and X. Liu. 2009. The effects of cryptochrome photoreceptors on root growth in *Arabidopsis*. *Afr. J. Biotechnol.* 8:3179–3183.