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Bioassimilation behaviour of tomato seedling cultivars under different sources of artificial light

Eva María Almansa[1], Antonio Espín[2], Rosa María Chica[3] and María Teresa Lao[1*]

[1]Agronomy Department of Higher Engineering School, University of Almeria, Ctra. Sacramento s/n, La Cañada de San Urbano, 04120, Almería, Spain
[2]Higher Technical School of Civil Engineering,University of Granada, Campus Universitario de Fuentenueva, Edificio Politécnico C/ Severo Ochoa s/n, 18071, Granada, Spain
[3]Engineering Department of Higher Engineering School, University of Almería,Ctra. Sacramento s/n, La Cañada de San Urbano, 04120, Almería, Spain

***Corresponding author: mtlao@ual.es**

Abstract

The behaviour of fifteen tomato cultivars under different lights was carried out and quality of seedlings (biomass, plant structure, water status, carbohydrates starvation), was studied. The lamps used were compact fluorescent (184 $W \cdot m^{-2}$), high efficiency fluorescent (140 $W \cdot m^{-2}$) and tubular don's bulb fluorescent (108 $W \cdot m^{-2}$). The trial was carried out in a culture chamber with the temperature and relative humidity continuously controlled (34 °C and 55% RH, respectively) and continuous light for 30 days. Experimental design consisted of three lighting treatments with 10 replications for each variety and treatments. Spectral radiation of artificial lighting sources was measured at canopy level. Fractions mass (leaves, stems and roots) were weighed fresh and dry. The total fresh weight: total dry weight relationship, sugars and starch concentration were quantified. Cultivars did not show the same behaviour under light treatments. The maximum response in biomass production of cultivars is obtained under high efficiency fluorescent treatment (16.56 $W \cdot m^{-2}$ PAR). For all cultivars, the relationship between total fresh weight and total dry weight presented the lowest value under high efficiency fluorescent treatment (low ratio, grate hardening). Starch quantity was higher than sugars for all treatments. 'Ikram' cultivar has the greatest capacity to synthesize carbohydrates in all treatments. Plants, under lighting with high efficiency fluorescents, show the highest quality (leaf mass is lower; root partitioning is unaffected with greater hardening and the highest amounts of total carbohydrates synthesized).

Keywords: Biomass; B:FR; B:R; Fluorescent lamps; PAR:NIR; (R+B):FR; R:FR ratios.
Abbreviations: A_Atlético; A_N_Anemon; B_Bigran; B_Blue; C_Cornabel; C_{ON}_Conquista; D_Delizia; FR_Far Red; FW:DW_Fresh weight:Dry weight partition; G_Green; I_Ikram; L_Lynna RZ'; M_O_Montengro RZ; M_Y_Myriade; NIR_Near infrared radiation; P_Prodigy; PAR_Photosynthetically active radiation; R_Red; R_Rambo; S_Saladar; T_Treatment; TDW_Total Dry Weight; TFW_Total Fresh Weight; TL5_Tubular Lamp with the diameter of the bulb in eighths of an inch 5/8"; TLD_Tubular Lamp Don's bulb; UV_Ultraviolet; V_Velasco; Z_Zaino RZ.

Introduction

Under most conditions, greenhouse and field, the energy level impacting the plant canopy is one of the main factors that influences plant growth, and for horticultural crops it determines plant performance (Restrepo-Díaz et al., 2010). Light is the most important factor affecting productivity in greenhouse tomato (Papadopoulos and Pararajasingham, 1997). Parker (1994) described light requirements of tomato and others common crops. Tomato crops must be provided with high light conditions and warm temperatures (Leopod and Kriedman, 1975; Daie and Campbell, 1981); flowering is initiated by high temperatures, but is not affected by the length of the day (Kristoffersen, 1965); nevertheless, it is necessary to provide supplemental lighting indoors under winter greenhouse conditions in central and north Europe (McAvoy and Janes, 1988). On the whole, tomato leaves have low sugar content in cloudy weather; the stems become pale and thin and the fruit may fail to materialize. With bright and sunny weather sugar production in leaves is higher, the leaves are dark and thick, the stems are dark green and robust, the clusters have numerous fruit sets and the root system is very robust (Resh, 2001). Continuous light increases leaf starch and sugar content. High sugar concentrations, together with relatively high acidity are required for the best flavour in fruit (Yahia and Brecht, 2012). Leaf chloroses of tomato plants grown under continuous light can be explained by starch and sugar accumulation due to leaf limitations,rather than a sink limitation (Demers et al., 1998). Cultivars available today for use by commercial gardeners are specifically adapted to a particular set of growing conditions (temperature, field and greenhouse conditions), and fresh market versus processing tomato-type fruit. Fruit size, colour, texture and acidity can be selected by variety, whether adapted to field or greenhouse conditions, and for long or short-day suitability (Zahedi and Ansari, 2010). Genetic engineering techniques applied to tomato cultivation have been used to produce fruit with a long shelf life (Della Vecchia and Koch, 2000), resistance to bruising and high lycopene content. Greenhouse production is one more development in the trend towards better quality and more diversified tomato offerings: vine ripened, organically grown, TOV (tomato-on-the-vine), cherry and grape sizes, pear-shaped, and various colours; the trend increases value-added produce for consumer selection. The greenhouse tomato is better positioned to compete with field-grown tomatoes when quality and short supplies occur due to disease (Gualberto et al., 2002) and weather factors. In the development of seedlings, supplementary artificial lighting is economically practical (Resh, 2001). For tomato, supplemental lighting has been shown to have a beneficial effect on growth and yield according to the physiological stage of the plant and the natural light level (Yelle et al., 1987; Dorais et al., 1992). In a previous study, which surveyed horticultural seedling producers in the Mediterranean area, we found that tomato producers use breeding chambers with artificial light, in order to reduce the period of production and to get better quality plants. Fluorescent lamps (TL5-tubular lamp with the diameter of the bulb in eighths of an inch 5/8 and standard or TLD-tubular lamp don’s bulb) are usually used in breeding greenhouse, TLD being the most useful lamps (Almansa et al., 2007). Energetic efficiency values associated with strength were studied for different lamps available in the market, and compact fluorescent lamps proved to have the best qualities (Almansa et al., 2011). Yield and biomass have been correlated with plant water uptake in several crops (Reina-Sánchez et al., 2005) and several stress conditions including salinity (Shani and Dudley, 2001). On the whole, the parameters used to define quality tomato seedling are: Total Fresh Weight (TFW; aerial part, roots), Total Dry Weight (TDW; aerial part, roots), fresh weight:dry weight partition (FW:DW), total height, leaf number, foliar surface, stem diameter, root length, etc. (Carbonell, 1995). The wavelength response of plants is given by Coene, 1995. Dorais (2003) pointed out that the phytochrome system (Phys, 350-800 nm) regulates metabolic events that result in adaptive responses such as stem length, leaf shape and thickness, and carbon partitioning between plant organs. Cryptochrome (320-500 nm) and UVB (280-350 nm) receptors are two other kinds of photoreceptors involved in stomata opening, leaf colour and thickness, and stem elongation. The aim of our study is to compare the effect of light sources on the biomass and carbohydrates status of different cultivars of tomatoes. The sources were compact fluorescent lighting (low consumer), high-efficiency fluorescent and standard fluorescent, two of these are employed in seedling development.

Results and Discussion

Spectral quality of artificial lights and wavelength response of plants

The spectral quality of different treatments measured at canopy level is shown in Fig. 1. All sources of illumination present notable peaks in the same wavelengths. Interesting values associated with radiation from the wavelength response of plants to characterize the quality of light (Coene, 1995) and the relationship between different spectral radiations are presented in Table 1. T_1 and T_3 show similar amounts of energy in the 320-500 nm wavelength range. The phototropins absorb in the UVA and Blue regions. Phototropins are, like cryptochromes, flavoprotein photoreceptors. As their name suggests, phototropins are the main photoreceptors governing phototropic curvature and, in general, operate to control a range of processes that optimize the photosynthetic efficiency of plants and promote growth (Christie, 2007). In high light intensities, chloroplasts are arranged along the anticlinal wall of the cell to prevent photo-damage, whereas in low light intensities, chloroplasts are arranged on the upper periclinal wall in order to maximize light absorption. Phototropins also function to regulate leaf positioning and expansion, stomata opening, and the rapid, but transient growth inhibition of young seedlings upon their emergence from the soil (Devlin et al., 2007). T_2 shows the least amount of green band energy. Recent photochemical and photophysiological studies have been able to clearly indicate that green light does have a regulatory influence on various plant responses. For instance, cryptochrome activity is reversed by green light (Bouly et al., 2007). Cryptochromes regulate light-induced stomata opening. Green light promotes hypocotyl elongation in dark-grown *Arabidopsis* seedlings in a dose-dependent manner (Folta, 2004), that coincides with a down-regulation of plastid transcripts (Dhingra et al., 2006). In addition, supplementary green light irradiation has been reported to increase plant biomass (Sommer et al., 2001). T_2 shows the greatest amount of energy to phytochrome system, but T_3 has a greater R:FR relationship than T_1 or T_2. Partitioning biomass (root/aerial part), the length of the petioles and the plant morphology depend on the spectral balance R:FR, and on the relative content of blue light with regard to red light (Kasperbauer and Hunt, 1990; Benavides, 1998). The phytochromes are reversibly photochromic proteins encoded in plants. They exist as red and far-red absorbing forms, Pr and Pfr, with absorption of red light by Pr triggering a conversion to the Pfr form, and absorption of far-red light converting Pfr back to the Pr form (Rockwell et al., 2006). In addition to enabling the detection of light, the photoreversibility of phytochrome is the key to phytochrome's role in shade avoidance. Light reflected from a plant is depleted in red and blue wavelengths, but is rich in far-red light. As a consequence, the majority of the phytochrome pool is converted into the inactive Pr form. The loss of Pfr removes an inhibitor of elongation growth and triggers an avoidance shade effect (Devlin et al., 2007).

Ratios to evaluate shade avoidance effect and other radiation influences

To evaluate the possible shade avoidance effect generated by radiation on the canopy, we proposed the ratio (R+B):FR in accord with Rockwell et al.(2006). The degree of shading is related to the R:FR ratio (600 to 800 nm) and determines the position of the reversible Pr/Pfr equilibrium and the degree of elongation (Franklin and Whitelam, 2005). Photomorphogenesis in seedlings is largely controlled by red/far red absorbing phytochromes (phyA–E) and by blue/UV-A-absorbing cryptochromes (Quail, 2002). T_2 shows the highest value of PAR. PAR radiation, along with temperature, is critical parameters for tomato plant performance in greenhouses (Jones, 2008). Temperature has a stronger influence on tomato quality than PAR because growers can obtain tomatoes of similar quality under a wide PAR range (Riga et al., 2008). T_3 has the lowest value of NIR and the highest PAR:NIR ratio. NIR is related with low absorption of radiation, cell elongation stimulation and lowering-germination. NIR is a useful part of radiation mainly related to heat, and the greenhouse energy balance (Castilla, 2005), but in a culture chamber with controlled temperature, it only results in plant over-heating and possible tissue damage. T_2 has the highest value of FR radiation (700 – 800 nm). When FR radiation was applied to tomato plants it modified photosynthate partitioning and morphology, also longer internodes were found when compared to plants

Table 1. Agronomic characterization (Coene, 1995) and quality of artificial light measured by LI-COR 1800 in W·m^{-2}.

Wavelength Range (nm)	T1	T2	T3
315 to 400 (UV)	0.30	0.32	0.11
400 to 520 (B)	4.22	3.57	4.41
520 to 610 (G)	6.83	8.08	7.41
610 to 720 (R)	3.99	5.86	4.20
720 to 1000 (FR)	0.14	0.32	0.11
Over 1000	0.18	0.11	0.13
PAR (400-700)	14.40	16.56	15.39
NIR (700-1100)	0.66	0.95	0.58
TOTAL (300-1100)	15.36	17.81	16.07
350 to 800 (Phys)	15.06	17.47	15.87
PAR:TOTAL	0.94	0.93	0.96
PAR:NIR	21.73	17.48	26.48
B:R	0.87	0.52	0.90
B:FR	9.36	5.47	10.66
R:FR	10.81	10.57	11.90
(R+B):FR	20.17	16.03	22.56

B (blue); FR (far red); G (green); NIR (near infrared radiation); PAR (photosynthetically active radiation); R (red); T1 (compact fluorescent lamps); T2 (fluorescent lamps TL5); T3 (fluorescent lamps TLD); UV (ultraviolet); B (blue); G (Green); R (red); FR (Far Red); PAR (Photosynthetically Active Radiation); NIR (Near Infrared Radiation).

treated with R (Decoteau et al., 1988). R:FR ratio during the light period in controlled environments affects plant height and number of tillers in wheat (Kasperbauer and Karlen, 1986).

Biomass evaluation

The biomass production of leaves (LDW), stems (SDW), roots (RDW) as well as the total (TDW) for all treatments is shown in Fig. 2. The maximum response in biomass production is obtained in T_2, followed by T_3 and the minimum response is presented for T_1 for photosynthetic, conductive and absorption organs. These values could be related with PAR received. This behavior is similar for all cultivars except for 'Lynna' which does not respond to PAR differences. The interception by leaves of the incoming PAR is a major process of biomass production (Plénet et al., 2000). Plants with higher dry matter content are more resistant to transplanting, and adapt more easily (Cornillón, 1999). Fig. 3 shows the distribution of biomass (%) between organs. The Tukey Test for $P \leq 0.05$ was used to assess the significance of biomass (%) in the treatments studied. The mass of stem increases to T_2 in all cultivars except 'Z' and 'L' which do not show differences between treatments. Similar stem mass was found under T_1 and T_3 for 'I', 'S', 'D', 'R', 'A_N', 'V', 'M_Y', 'M_O' and 'P'; and higher in T_1 than T_3 in 'A', 'C', 'C_{ON}' and 'B'. These results could be related with the shade avoidance (Morelli and Ruberti, 2000) effect through (R+B):FR (Rockwell et al., 2006) and R:FR (Green-Tracewicz et al., 2011) ratios. T_2 has the lowest value of R:FR and produced more elongation in the stems, this is consistent with Ballaré et al. (1991). Nevertheless, Huimin et al. (2010) found that cotton plants under B:R=1 show greater fresh weight, dry weight and stem length than B:R=0.33; our results were the opposite of this. Leaf mass percentage obtained in T_2 is always significantly less than the other treatments, except for 'P', 'Z' and 'L'. T_1 and T_3 present similar percentages except for 'A' and 'M_O'. These results agree with those of Kasperbauer (1970) considering the higher shade avoidance effect in T_2 evaluated thought (B+R):FR ratio. Root biomass is inferior to leaf and stem biomass. These do not show significant differences between treatments for all cultivars. All cultivars do not show similar lighting morphological responses. In general, plants under T_2 show the highest quality because leaf mass is lower but root partitioning is unaffected.

Hardening and PAR, NIR influence

Dependence on water status with light treatments was evaluated using the ratio of total fresh weight divided by total dry weight (TFW:TDW). Values of TFW:TDW parameter are shown in Fig. 4. For all cultivars, T_2 presents the lowest value of TFW:TDW parameter. Hardening is evaluated by the TFW:TDW ratio (Wainwright and Marsh, 1986). T_2 has the highest NIR and PAR values but the PAR:NIR relationship is the lowest of all the treatments. NIR could increase the leaf temperature and transpiration, and therefore decrease the TFW:TDW ratio (Pieruschka et al., 2010). Although, there is a linear relationship between NIR absorption and leaf thickness (Dallon, 2005), PAR and spectral distribution determine the differences in plant biomass (Smith, 1982). These results indicate that T_2 provides the greatest hardening associated with low leaf mass, increasing the plant quality. Franco et al. (2006) concluded that hardening and acclimation processes (pre-conditioning), during the nursery period, are correlated with the ability to withstand the shock of transplantation and to increase survival and plant growth following transplantation. Also, Apherton and Rudich (1987) established that in tomato seedling at a lower leaf mass, lower transpiration, and greater tolerance to water stress are more effective in increasing seedling resistance to transplantation.

Total carbohydrates: reduction in sugars and starch

The valuation of total carbohydrates (TCHs) such as starch and soluble sugars (structural and metabolic) were measured in mg·organ^{-1}. Carbohydrate synthesis capacity between cultivars is shown in Fig. 5 where TDW (g) is represented on the right axis. Looking at the data obtained from the valuation of total carbohydrates (starch and soluble sugars) (TCHs measured in mg·organ^{-1}), both structural and metabolic, we can find different carbohydrate synthesis capacity between cultivars. There are some cultivars that present similar behavior and have been classified into interesting groups as shown in Fig. 5. When looking at the total carbohydrates, the classification is as follows:

a) TCHs are highest in T_2; T_1 and T_3 present similar values: 'I', 'S', 'M_Y', 'A', 'C', 'A_N', 'C_{ON}', 'V', 'P', 'Z' and 'L'.

b) TCHs are similar in $T_1$and $T_{2,}$ and both are higher than $T_{3:}$'D'.

c) TCHs are similar in T_3 and $T_{2,}$ and both are higher than T_1: 'R', 'M_O' and 'B'.

Carbohydrates are used in biomass production and power energy storage as starch. Also, sugars constituted the power energy implied directly in metabolism. Biomass production valuated as TDW is higher in T_2 for all cultivars, related with higher PAR, which agrees with Marcelis et al. (1998) and also, the quantity of starch is higher than sugars for all treatments. These results agree with Hocking and Steer (1994) who showed concentration of glucose (9.5 mg g^{-1} TFW) and starch (56.4 mg g^{-1} TFW) in tomato leaves after 49 days under constant light, intensity 750 µmol·s^{-1}·m^{-2} (PAR). There are two simultaneous light effects: 1) an increase in TCHs biosynthesis due to PAR in T_2 where the first group is included, this agrees with Bunce and Sicher (2003); 2) an increase in starch and decrease in sugars due to a high R:FR

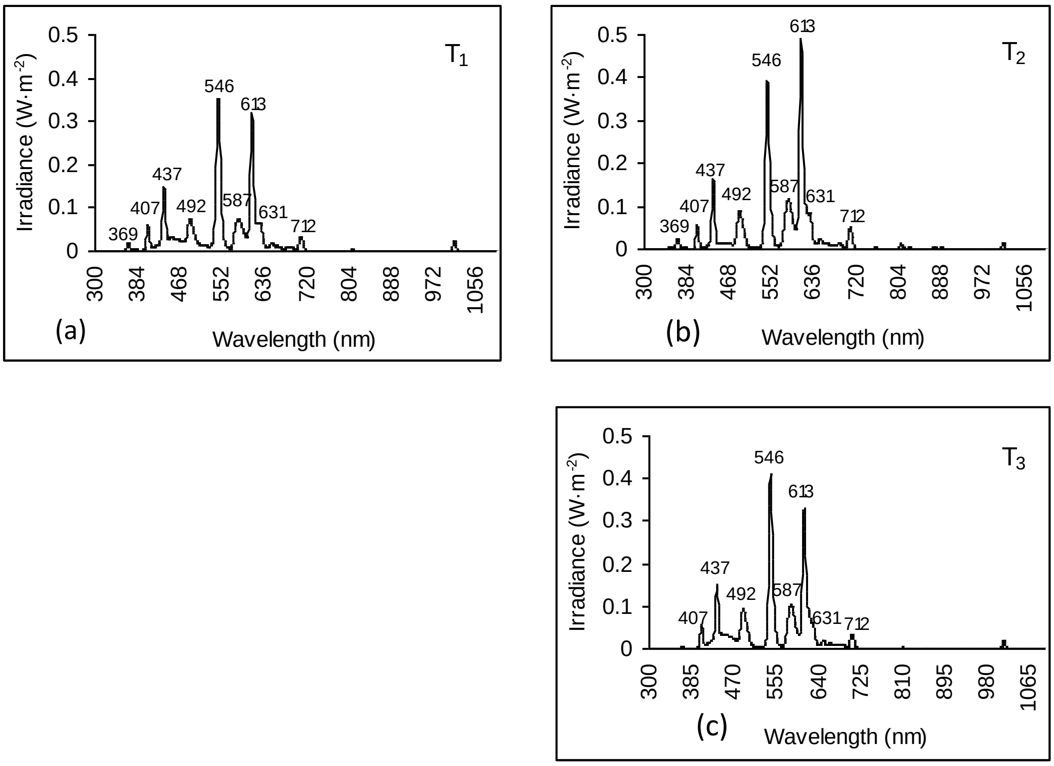

Fig 1. Spectral quality measured at canopy level. Spectral radiation was measured using a spectroradiometer LI-COR 1800 at canopy level and captured data plotted using Excel. Numbers on the peaks of the spectrum mean the maximum emission wavelength of the lamps: a) compact fluorescent lamp (T_1); b) high efficiency fluorescent lamp (T_2); c) TLD fluorescent lamp (T_3 or control).

ratio in T_3 where the third group is included, this agrees with the findings of Kasperbauer and Hamilton (1984).

Capacity to synthesize sugars, starch and TCHs

On the other hand, 'Ikram' has the greatest capacity to synthesize in all treatments. Other cultivars like 'S', 'M_Y', 'M_O', 'A', 'P' and 'Z' have a middle-range synthesis capacity; 'D', 'R', 'C', 'A_N', 'C_{ON}', 'V', 'B' and 'L' have a low one. 'C_{ON}' presented chlorosis in T_1 and T_3, 'V' and 'B' in all treatment. The different response of plants to continuous light may be due to different species having evolved different mechanisms to respond to the photoperiod (Jackson, 2009).Also, plant response to continuous light may vary depending on the stage of plant development. Demers and Gosselin (2002) stated, however, that long-term use of continuous light is detrimental to tomato. Nevertheless, early vegetative growth and fruit production can be improved by short-term use (5 to 7 weeks), tomato plants being sensitive to continuous light.

Materials and Methods

Plant materials

Fifteen cultivars of tomatoes were sown in expanded polyethylene trays. The cultivars chosen were: 'Ikram' ('I'), 'Saladar' ('S'), 'Atlético' ('A'), 'Delizia' ('D'), 'Cornabel' ('C'), 'Rambo' ('R'), 'Anemon' ('A_N'), 'Conquista' ('C_{ON}'), 'Velasco' ('V'), 'Bigran' ('B'), 'Myriade' ('M_Y'), 'Montengro RZ' ('M_O'), 'Prodigy' ('P'), 'Zaino RZ' ('Z') and 'Lynna RZ' ('L'). Specific characteristics and information about these cultivars was taken in Almansa et al. (2011). On each tray, 10 seeds of each variety were distributed. Peat moss covered with vermiculite substrate was used. The density was 421 plants·m^{-2}. For two days, the trays were kept in a germination chamber at 27ºC, 90% relativity humidity (RH) without illumination. The sprouts were moved to the greenhouse to 34-35 °C and 53-55% RH.

Light treatments

After eight days, the seedlings, with vigorous and homogeneous appearance of each cultivar, were scheduled for follow-up in chamber; the chamber kept at a constant temperature and humidity level (34°C and 55% RH, respectively), and continuous light for 30 days. The chamber was equipped with three light sources: T_1 (8 Compact Fluorescent Lamps 23 W, total power 184 W·m^{-2}), T_2 (2 Lighting x 2 Fluorescent Lamps TL5 35 W, total power 140 W·m^{-2}) and T_3 (3 Lighting X 2 Fluorescent Lamps TLD 18 W, total power 108 W·m^{-2}). Experimental design consisted of three lighting treatments with 10 replications for each variety and treatment. Spectral radiation was measured in each shelf using a LI-COR 1800 (LI-COR inc. P.O. Box 4425; Lincoln, Nebraska 68504 USA) at canopy level.

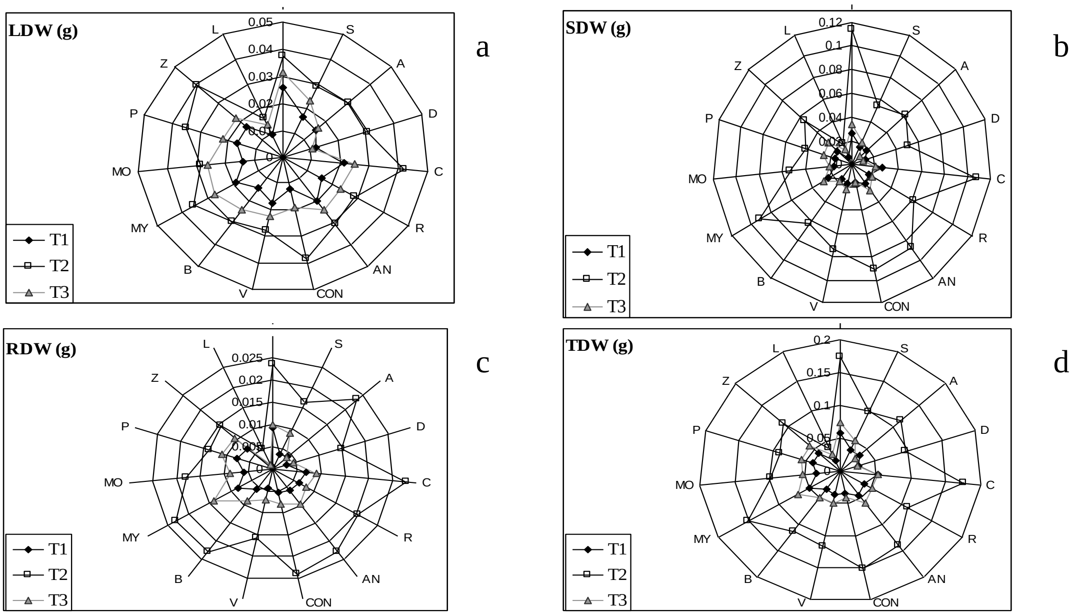

Fig 2. Dry weight of cultivars: a) Leaves (L); b) Stem (S); c) Roots (R) and d) Total. Dry weight partitioning was measured by precision balance. The measures were analyzed in program Excel and represented in radial graphic.

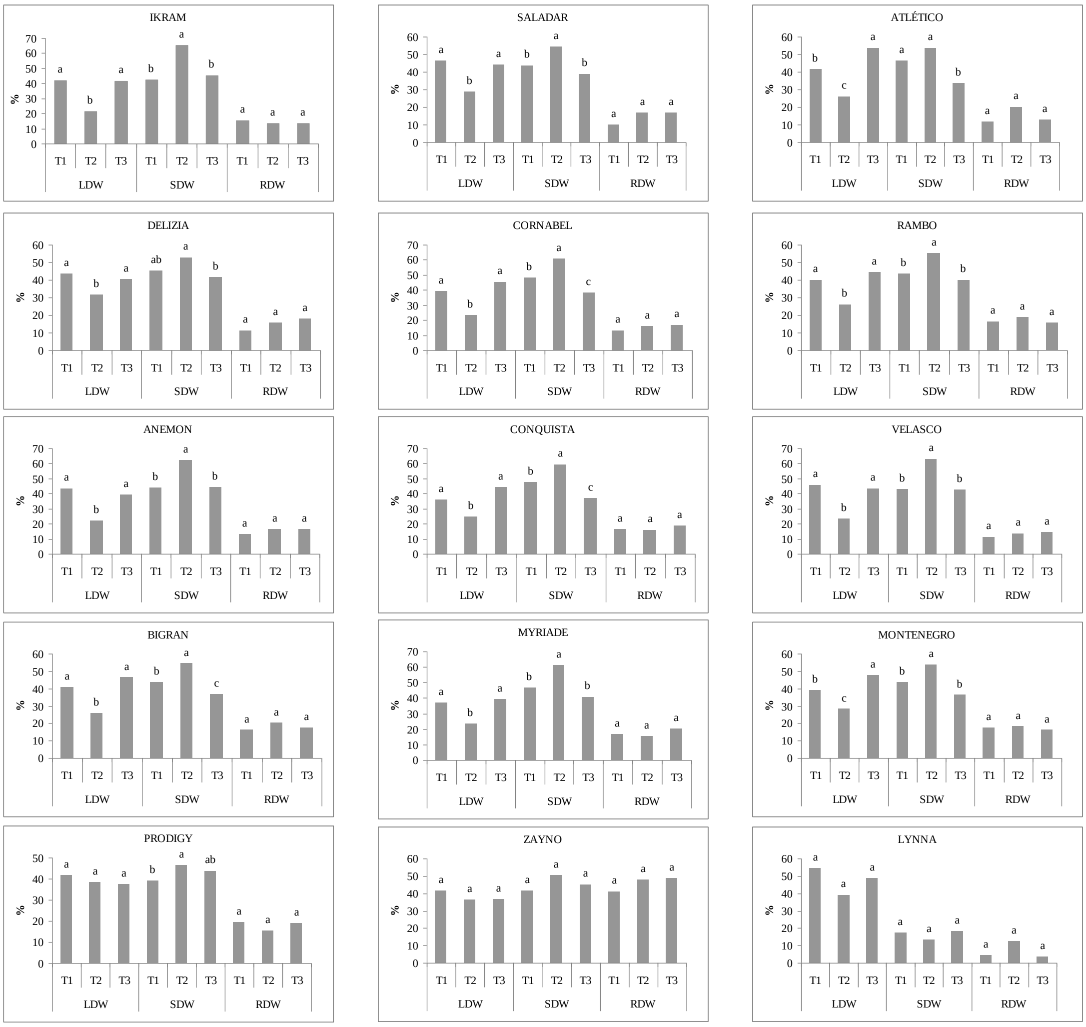

Fig 3. Distribution of biomass (%) between organs depending on the source of light received: leaves (LDW), stems (SDW) and Roots (RDW) depending on the source of light received.*Different letter (s) to significant differences among cultivars according to statistical analysis (Tukey's Test P ≤ 0.05) for biomass (%) parameter.

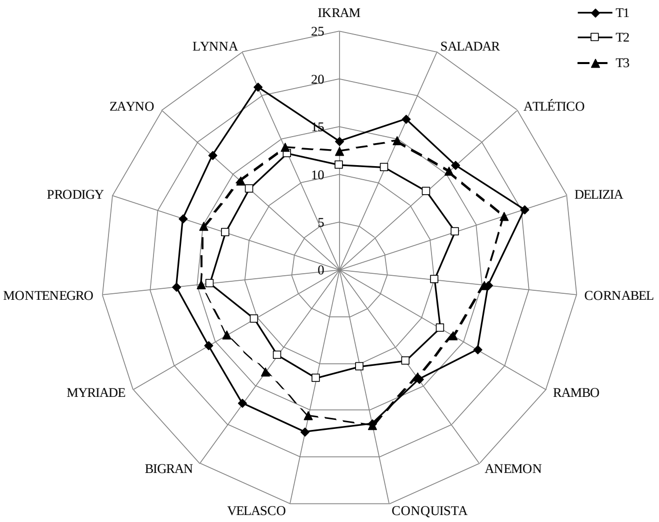

Fig 4. TFW:TDW parameter (water status) depending on light source. Excel was used to represent this parameter in radial graphic.

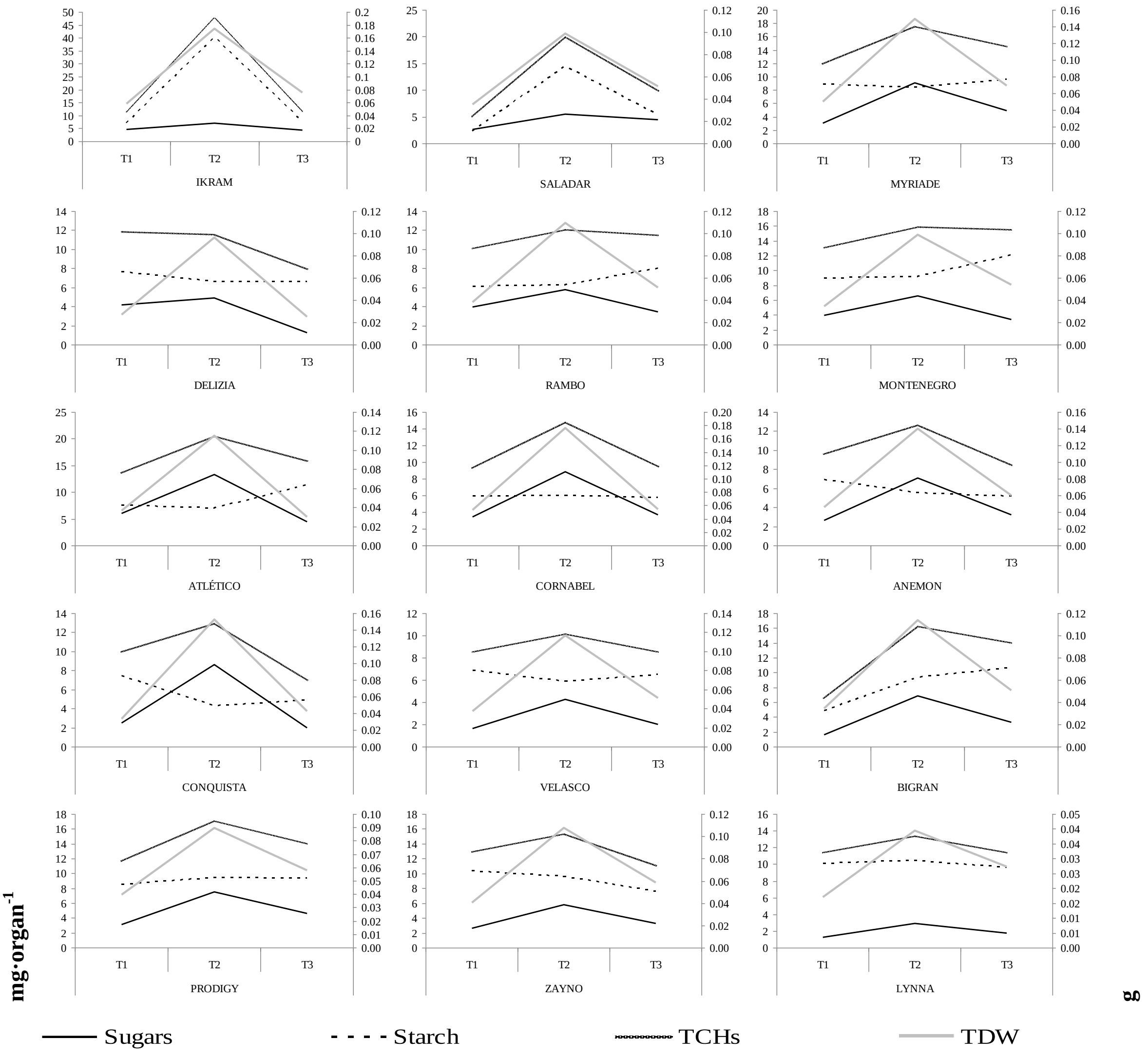

Fig 5. Synthesis Capacity in plant treatments: sugars, starch and TCHs measured in mg·organ^{-1} (left axe); Total Dry Weight in g (right axe). Sugars and starch were estimated by colorimetry with a spectrophotometer. Measurements were analyzed and represented in Excel.

Traits measured

At the end of the trial, the plants were evaluated. Fresh and dry weight partitioning among assimilation (leaves), conductive (stems and petioles) and absorption (roots) organs were measured using a precision balance (Mettler Toledo classic PB303-S; CH-8606 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 minutes, sugars (Irigoyen et al., 1992) were quantified in supernatant fractions by colorimetry with a Spectrophotometer (Shimadzu UV-1201, Shimadzu; Kyota, Japan) (Tien et al., 1979). The residue was dried for 48 hours at 40 ºC to determine the starch concentration, via incubation with α-glucoamilase, measuring the resulting sugars (Irigoyen et al., 1992).

Statistical analysis

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's Test for $P \leq 0.05$ were used to assess the significance of treatment means.

Conclusion

All cultivars do not show the same behavior under light treatments. In general, the maximum response in biomass production is obtained in T_2, followed by T_3 and the minimum response is presented for T_1 related with PAR received. Pattern biomass between organs is related with the shade avoidance effect through (R+B):FR and R:FR ratios. Partitioning root is inferior to leaf and stem, and does not show significant differences between treatments for all cultivars. For all cultivars, T_2 presents the lowest ratio TFW:TDW related with a greater hardening. The quantity of starch is higher than the quantity of sugars in all treatments. Total carbohydrate synthesis under treatments applied allow cultivars to be classified into three groups related to two simultaneous light effects: higher TCHs biosynthesis due to PAR in T_2 where the first group is included, and an increase in starch and a decrease in sugars due to a higher R:FR ratio in T_3, where the third group is included. In general, plants under T_2 display the highest quality because leaf mass is lower than in other treatments, but the root partitioning is unaffected and is not associated with the greatest degree of hardening or the highest TCH synthesis.

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