Basic growth analysis in strawberry plants (*Fragaria* sp.) exposed to different radiation environments

Análisis básico del crecimiento en plantas de fresa (*Fragaria* sp.) expuestas a diferentes ambientes de radiación

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ABSTRACT

The present study sought to understand how quantity and quality of light affect growth and development in strawberry plants. Plants were grown in a greenhouse in Tunja, Colombia, under different light quality regimes provided by polypropylene films (yellow, green, blue, transparent, red, and a control without plastic film cover). These colored filters also provided different shading levels to plants. The authors measured growth parameters and calculated various indices commonly used in basic plant growth analysis. Plastic light filters were placed 1 m above crop foliage and were kept in place from initial transplanting until final harvest. Net assimilation rate was reduced under colored filters, but not under the transparent film or the film-free control. Green cover induced an increase in leaf area ratio, root to shoot ratio, leaf weight ratio, and specific leaf area. Harvest index and absolute and relative growth rate were reduced in plants grown under green film. The growth response of strawberry plants was the consequence of the combined effect of light quantity and quality. Results also showed the striking influence of green light on strawberry growth.

Key words: shading, light spectrum, light quantity, photomorphogenesis, colored films.

RESUMEN

Este estudio se orientó a establecer cómo la cantidad y la calidad de la luz afectan el crecimiento y desarrollo de las plantas de fresa. Las plantas se desarrollaron en un invernadero en Tunja (Colombia), bajo diferentes calidades de luz (amarilla, verde, azul, transparente, roja y control sin cobertura de color), proporcionadas por películas de polipropileno. Los filtros coloreados aportaron también diferentes niveles de sombreado a las plantas. Se calcularon los índices comúnmente utilizados para el análisis básico del crecimiento en vegetales. Los filtros se ubicaron 1 m sobre el follaje del cultivo, desde el trasplante hasta la cosecha de las plantas. La tasa de asimilación neta se redujo con las coberturas de color con excepción de la cobertura transparente y el control. La cobertura verde indujo un incremento en la relación de área foliar, la relación raíz:vástago, la relación de peso foliar y en el área foliar específica; sin embargo, el índice de cosecha, las tasas absoluta y relativa de crecimiento se redujeron en plantas que crecieron bajo esta cobertura. La respuesta de las plantas de fresa en relación con las tasas de crecimiento fue la consecuencia del efecto conjunto de la cantidad y la calidad de la luz incidente. Los resultados mostraron un fuerte efecto de la luz verde sobre el crecimiento de plantas de fresa.

Palabras clave: sombra, espectro lumínico, cantidad de luz, fotomorfogénesis, coberturas de color.

Introduction

Growth analysis is a widely-used tool in research areas ranging from plant breeding to crop physiology to plant ecology (Poorter and Garnier, 1996). Growth analysis represents the first step in analysis of primary productivity, which makes it an important link between the measurement of crop yield and the understanding of physiological phenomena that determine yield. A major advantage of growth analysis lies in the ease of measuring the raw data on which it is based, such as dry plant weight, leaf area, and time (Santos-Castellanos *et al.*, 2010). Detailed plant growth analysis permits researchers to quantify aspects such as the duration of the plant life cycle, the definition of phenological and developmental stages, and the distribution of assimilates in different organs (Azofeifa and Moreira, 2004). Furthermore, growth analysis is essential to achieving a better understanding of the physiological processes that define plant production. In this respect it serves to define the best crop management alternatives in terms of fertilization, irrigation, phytosanitary practices, pruning, and planting arrangement and density, among other things (Lambers and Poorter, 1992).

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Solar radiation is the energy source used by plants in the process of photosynthesis, which is the means by which plant matter is produced. Part of this plant matter is the harvested crop (Hernández *et al*., 2001). Li *et al.* (2010) affirm that strawberry yield has a negative correlation with solar radiation, which suggests that high solar radiation and high temperature (associated with water loss) can induce a negative response in strawberry plants, with a consequent decrease in fruit formation. The optimization of plant use of resources such as fertilizer depends in large part on the quality of solar radiation received by plants, which exhibit higher or lower production as a function of this radiation. On the high plains of central Colombia, 6.3% of total production costs for small farmers producing strawberry on a 20-month cycle consist in fertilizers and soil conditioners, while in Antioquia these inputs represent 7.7% of total production costs (Agronet, 2009). If photosynthetic efficiency could be improved by changing the light wavelengths to which plants are exposed so as to promote fruit production, it would be possible to increase yield using the same level of inputs (Hernández *et al*., 2001; Patil *et al*., 2001; Casierra-Posada and Rojas, 2009).

Plant response to different colors of light has been documented by various authors (Casierra-Posada and Rojas, 2009). Inoue *et al.* (2008) and Hoang *et al.* (2008) reported changes in morphological and physiological behavior in *Arabidopsis* sp. plants under the influence of blue and red light. These plant responses are mediated by cryptochromes and phytochromes, and are related to the regulation of leaf position and other processes related to light capture. In this same line, farmers have used colored covers to increase yield and growth in different plant species. The use of red and blue polyshade mesh have an effect on growth and flowering on different cultivars of *Phalaenopsis* sp.; red mesh induced precocity in the majority of accessions evaluated, while plants growing under blue mesh developed higher leaf area (Leite *et al*., 2008).

In the spirit of offering farmers new cropping alternatives that increase total yield, the objective of the present study was to evaluate the effect of different colored coverings on basic growth parameters in greenhouse-grown strawberry plants.

Materials and methods

The experiment was carried out in Tunja, Colombia, under glass greenhouse conditions. Ten plants per treatment were subjected to solar radiation filtered through 15 µm-thick polypropylene films of different colors: red, yellow, blue, green, and transparent. Control plants grew in the greenhouse without any polypropylene covering. Photosynthetically active radiation (PAR) and light reduction (opacity) registered beneath the different covers are shown in Tab. 1. Average temperature inside the greenhouse was 15.8°C, with 72% relative humidity.

TABLE 1. Radiation and opacity measured under colored covers.

Cover color	Photosynthetically active radiation (μmol m^{-2} s^{-1})	Opacity (%)
Control	299.94	0
Transparent	210.46	29.83
Yellow	152.19	49.25
Blue	99.31	66.89
Red	86.95	71.01
Green	78.87	73.70

Planting material consisted of strawberry plantlets (*Fragaria* sp. var. Chandler) previously exposed to stratifying temperatures of 4±1°C during three weeks. After this period they were placed in glass jars containing a nutrient solution with the following composition in mg L^{-1}: nitric nitrogen 40.3; ammonium nitrogen 4.0; phosphorus 20.4; potassium 50.6; calcium 28.8; magnesium 11.4; sulfur 1.0; iron 1.12; manganese 0.112; copper 0.012; zinc 0.0264; boron 0.106; molybdenum 0.0012; cobalt 0.00036.

Frames were covered with polyethylene film of the different experimental colors and fitted over the glass jars on tables in the greenhouse, each frame covering 10 plants at a height of 1 m above the plants. The greenhouse was equipped with piping and hoses connected to an aeration system to oxygenate the plants growing in glass containers. At the beginning of the experiment dry weight was measured in 10 plantlets to give an initial value for the calculation of growth indices, according to the methodology reported by Hunt (1990).

Treatments were arranged in a completely randomized design with 10 replications. Results were subjected to analysis of variance (ANOVA) and treatments were compared using Tukey's range test with a significance level of 5%. Statistical analyses were performed with version 19.0.0 of the IBM®-SPSS statistics program (Statistical Product and Service Solutions, IBM Corporation, New York, NY).

Results and discussion

Net assimilation rate (NAR)

Significant differences were found ($P\leq 0.05$) in the values of NAR. Plants grown under blue, red, green, and yellow

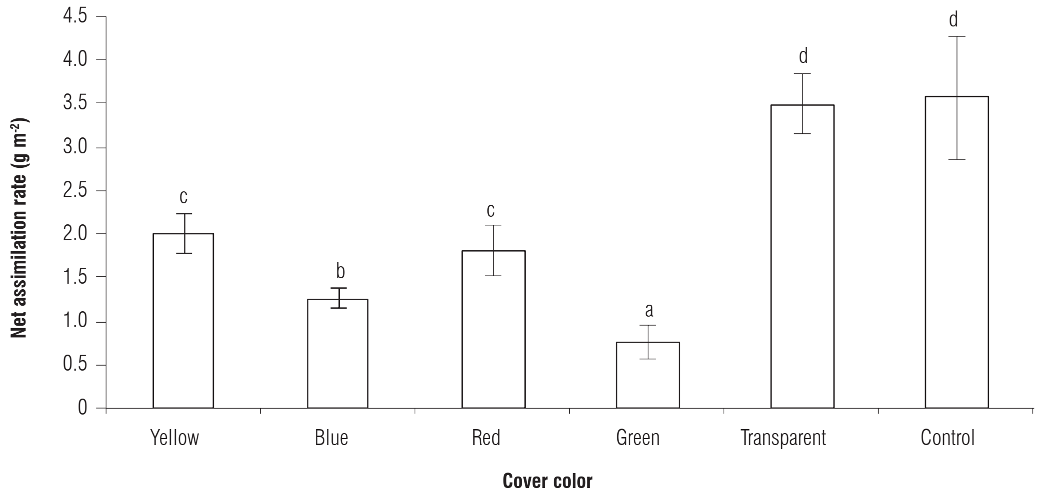

FIGURE 1. Net assimilation rate in strawberry plants (*Fragaria* sp.) exposed to colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar over each column indicates standard deviation.

films had NAR 64.52, 49.32, 78.66, and 43,76% lower than control plants grown with no colored cover (Fig. 1).

It should be pointed out that maximum absorption ranges for chlorophyll occur in the blue-violet range (400-500 nm) and the orange-red range (600-700 nm) of the visible spectrum (Mc Donald, 2003), which would explain the behavior of NAR in plants grown under yellow, blue, and red films as compared to green films. Plants exposed to these colors would be favored by a higher absorption of quanta by chlorophyll.

When radiation intensity is low, plants invest little in production of photosynthesis-related enzymes (Lambers *et al*., 1998). Hence in low light conditions, as in the case of plants developing under colored films, morphology and architecture of aerial plant parts become relatively more important; according to Evans *et al.* (1988) leaf area ratio is maximized in such conditions, but there are limitations to maximizing net assimilation rate. However, this general tendency does not explain the difference in NAR between green and red films, which were almost equally opaque.

Svenson (1993) placed strawberry plants in either green or white pots and exposed them to differing degrees of shade. He found that the reflection of light from different pot colors alone did not influence dry weight of crowns and leaves, but that a 60% shading combined with white pot color notably reduced dry weight of aerial plant parts and fruits, as compared to the same shading level in green pots. It can be inferred then that the extremely low NAR value in the present study for plants grown under green film was due to the combined action of the shading caused by the film (73.70%) and low absorption of green light by plants, given that the majority of photons in this wavelength range are reflected as diffuse radiation (Lazo and Ascencio, 2010). Furthermore, if we consider that net assimilation rate is a measure of average efficiency of plant leaves, or an indirect measurement of the net gain of assimilates per unit of leaf area over time (Brown, 1984), then treatments with higher light levels such as the control and the transparent film should trigger higher assimilate production than in plants grown under the colored covers. In the present study control plants without plastic film or those grown under transparent film presented higher NAR values, which agrees with this affirmation. However, the results of an experiment carried out by Casierra-Posada and Rojas (2009) showed that broccoli plants exposed to red covers showed better results in terms of total dry matter production. This implies that photomorphogenic responses differ according to plant species.

Root to shoot ratio

The root to shoot ratio of plants under green cover presented significantly higher values (86.77% higher) as compared to control plants with no cover. All other cover colors showed no significant difference with the control treatment (Fig. 2).

Increased assimilate allocation towards leaves as a response to shading normally coincides with a reduction in root dry matter (Björkman, 1981). This was not the case in the present study's green cover treatment, given that root to shoot ratio rose as compared to the other treatments, despite the

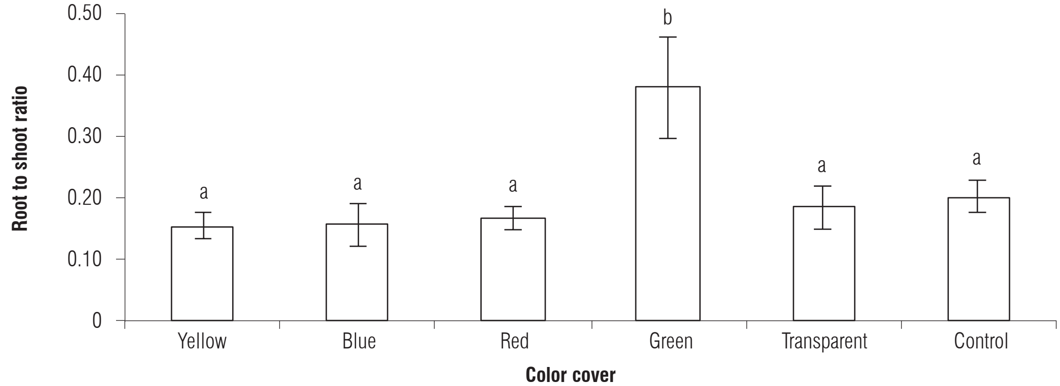

FIGURE 2. Root to shoot ratio in strawberry plants (*Fragaria* sp.) exposed to colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

green polyethylene film's shading 73.70% of incident light. The red film, which had an opacity of 71.01%, similar to the green film, did not however demonstrate the same increase in root to shoot ratio. This suggests that this parameter was more influenced by light than by shading.

As a point of comparison, Antonious and Kasperbauer (2002) placed colored panels on the soil surface in a carrot crop and measured changes in root to shoot ratio as a result of light reflected from the panels onto leaves. They found differences only in plants exposed to white panels as compared to the other panel colors (blue, green, and red), which contrasts with the present experiment, in which the green treatment was that which showed differences as compared to all others. The use of mulches on the soil surface obviously modifies the physico-chemical conditions in the soil by raising temperature, but mulches also trigger morpho-physiological changes in plants, due primarily to the reflection of certain light wavelengths from the mulch onto leaves, which can in turn increase root proliferation and thus improve growth and development (Solaiman *et al.*, 2008).

Plants must balance biomass assignation to leaves, which increases the capacity to capture light and carbon dioxide and hence improves growth rate, and assignation to roots, which allows increased water and nutrient capture from the soil at the expense of aboveground growth. From an ecological viewpoint, a plant with more biomass allocated to its roots, as was the case in the strawberry plants growing under green cover in the present experiment, would exhibit slower growth but would possess certain survival advantages in a resource-limited environment (Castro-Diez, 2002).

Leaf area ratio (LAR)

Compared to control plants, plants exposed to yellow, blue, red, and green covers showed significantly higher LAR values 73.12, 169.89, 96.05, and 320.60%, respectively (Fig. 3).

The productive capacity of a plant depends among other things on leaf expansion and the distribution of photosynthetically active versus inactive tissues (Puntieri and Gómez, 1988). The maximization of leaf area relative to biomass (LAR) can be achieved by increased leaf expan-

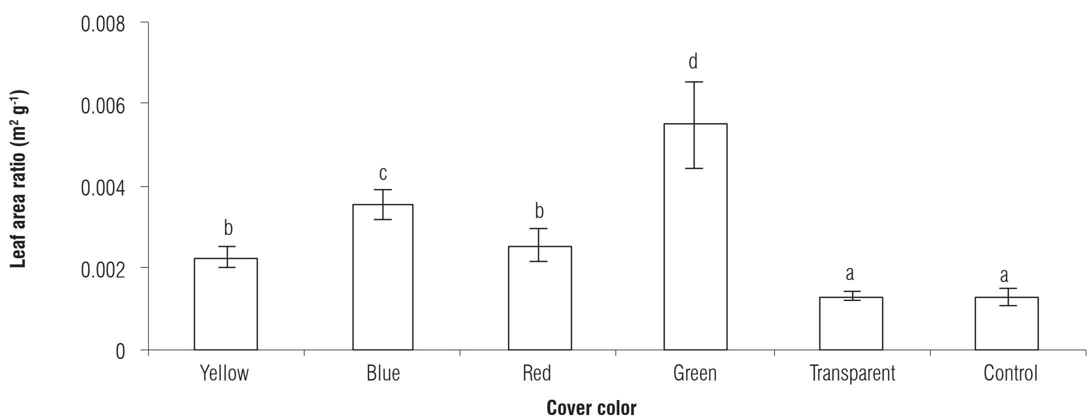

FIGURE 3. Leaf area ratio in strawberry plants (*Fragaria* sp.) grown under colored films. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$) at the level. The bar above each column indicates standard deviation.

sion in space, an almost universal mechanism (Björkman, 1981). Different results in different environments, as seen in the present study, could be due to different shading levels among treatments (Tab. 1), but nevertheless the differences in the present study are striking between strawberry plants grown under red and green films. These films exhibited 71.01 and 73.70% shading, respectively, which is surely too minor a difference to explain the large contrast in LAR values under these two treatments, especially considering that the much less opaque yellow film gave similar results to the red film in this parameter. Without totally discounting the possibility of different shading levels influencing results, film color must be considered as the primary factor explaining the differences in LAR.

As mentioned before, under low-light conditions plants do not maximize production of photosynthetic enzymes, so to increase photosynthesis they must rely on changes in aboveground morphology and architecture (Lambers *et al.* 1998). In other words, LAR is maximized under low light, but NAR cannot be. This would explain why plants show high LAR and low NAR grown under very opaque green cover, though it fails to account for the different results under almost equally opaque red film.

Leaf weight ratio

As occurred with LAR, LWR showed highly significant differences ($P \leq 0.05$) between the control treatment and all other treatments save the clear plastic. Compared to control plants, those exposed to yellow, blue, red, and green covers showed values 23.29, 59.43, 33.89, and 113.32% higher, respectively, for this parameter (Fig. 4).

Many plant species exhibit an increase in leaf weight ratio as one type of adaptation response to shaded conditions (Björkman, 1981). In the present study, LWR increased under light-excluding plastic films as compared to control plants grown without film. In other words, biomass was increasingly allocated to the formation of assimilatory surface. This was especially true in the case of the green cover, which again indicates the importance of light quality in addition to light quantity in different growth parameters.

Harvest index (HI)

The green cover induced a 91.34% reduction in HI (the value of harvestable dry matter) as compared to control plants grown without colored filters (Fig. 5).

Regarding this parameter, Waterer *et al.* (2001) evaluated the response of different horticultural crops such as pepper, tomato, squash, and melon exposed to transparent, red, blue, yellow, silver, white, and black mulches and found that plant response to the light reflected from mulches varied widely with the species and the moment of measurement. In 2000, red and blue mulches promoted growth and yield as compared to other mulch colors. In 2001, on the other hand, the more reflective mulches (blue and silver) induced higher yields. Franquera (2011) affirms that colored plastic mulches affect soil temperature, but that they also serve to reflect red and far-red light that influence phytochromes to increase plant growth and yield. With respect to the results of the present study, the photomorphogenic response of plants in terms of harvest index depends on the quality of incident light. However, the effect of light quantity should not be ignored. Together these factors would produce modifications in crop yield, given that plant morphogenesis (the form in which plants grow and develop) varies according to the spectrum and total quantity of light, which change due to environmental factors (Bonser and Aarssen, 2003).

Absolute growth rate (AGR)

Absolute growth rate showed significant differences between control plants and those grown under yellow, blue, and green filters, which respectively presented values

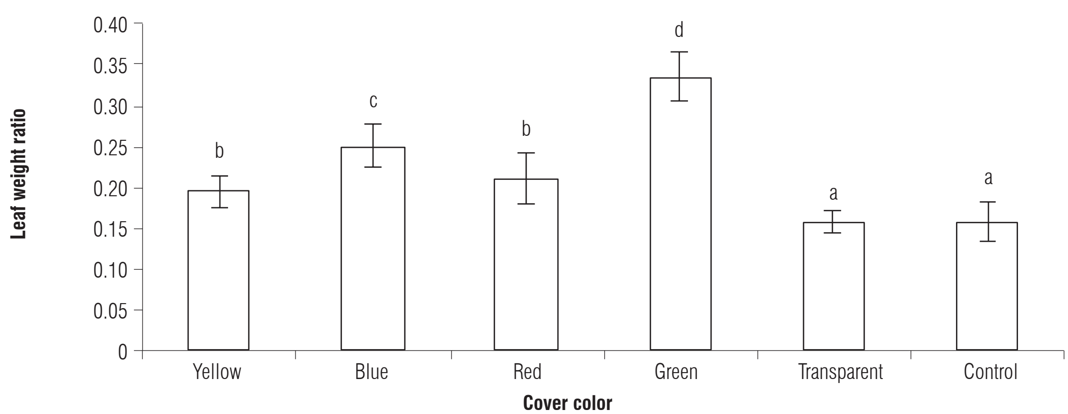

FIGURE 4. Leaf weight ratio in strawberry plants (*Fragaria* sp.) exposed to colored films. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

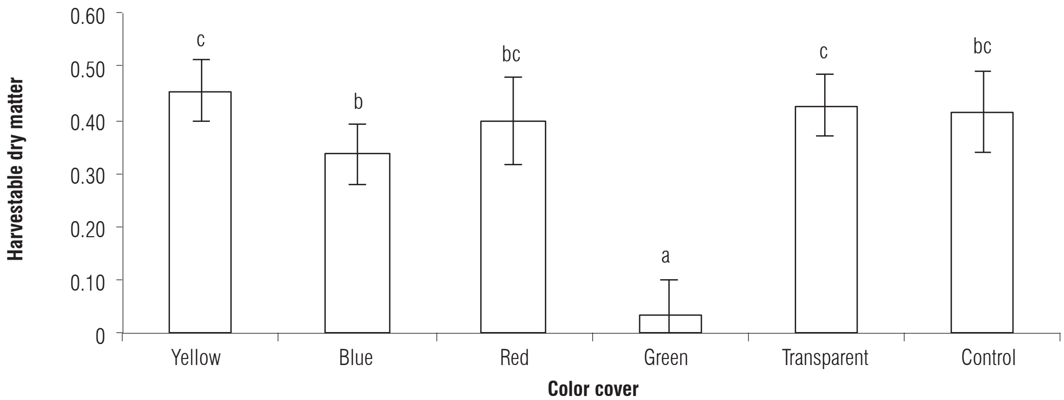

FIGURE 5. Harvest index or harvestable dry weight in strawberry plants (*Fragaria* sp.) exposed to different colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

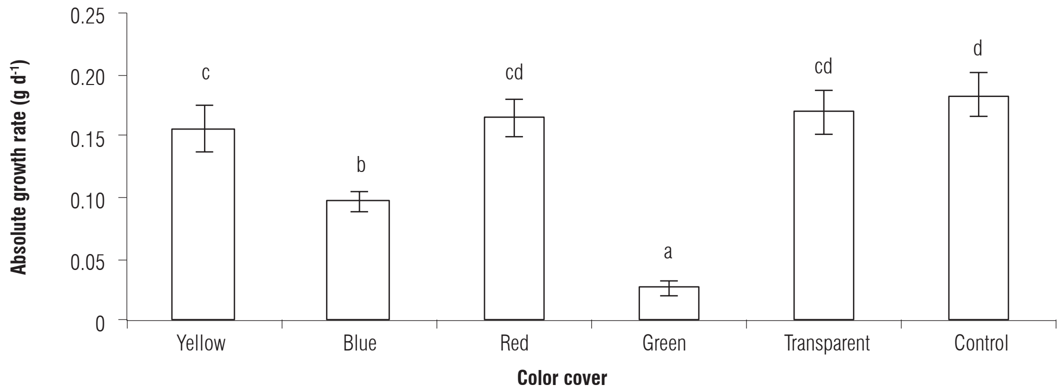

FIGURE 6. Absolute growth rate in strawberry plants (*Fragaria* sp.) exposed to colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

15.11, 47.06, and 85.63% lower than control plants grown without plastic covers (Fig. 6).

The behavior of AGR can be explained by the fact that plants absorb photons in the red and blue range of the spectrum, while absorption of light in the green and far-red ranges is weaker, and much of these photons are reflected by plants as diffuse radiation (Lazo and Ascencio, 2010). Furthermore, a low level of photosynthetically active radiation and a low proportion of red to far-red light promote apical dominance and in some species promote internode lengthening (Casierra-Posada *et al*., 2012).

Relative growth rate (RGR)

Plants grown under blue and green films showed RGR values 18.03 and 47.37% lower, respectively, than control plants without cover (Fig. 7).

Regarding the AGR and RGR values found in the present study, Rikvin (1989) and Senger (1987) described faster growth and higher protein and chlorophyll content in plants exposed to blue light as compared to those grown under white light. Nevertheless, other authors suggest that light level is more important than spectral composition, and that after acclimatization plant responses depend on available light quantity and not quality (Gostan *et al*., 1986; Morel *et al*., 1987; Humbeck *et al*., 1988). The present study would support the first affirmation as opposed to the second, since red and green films allowed through roughly equal amounts of light, but growth rates were very different between these two treatments.

Specific leaf area (SLA)

Plants exposed to yellow, blue, red, and green filters showed SLA values 40.29, 70.04, 46.24, and 97.57% higher than control plants (Fig. 8).

Research reported by Björkman (1981) shows that plants can adjust to low-light environments by increasing SLA, which is to say that they increase leaf area per unit of leaf weight, making for thinner, larger leaves. Despite this, in some species the increase in dry matter allocated to leaves (leaf weight ratio) is less pronounced than the effect on specific leaf area (Páez *et al*., 2000). This was not the case

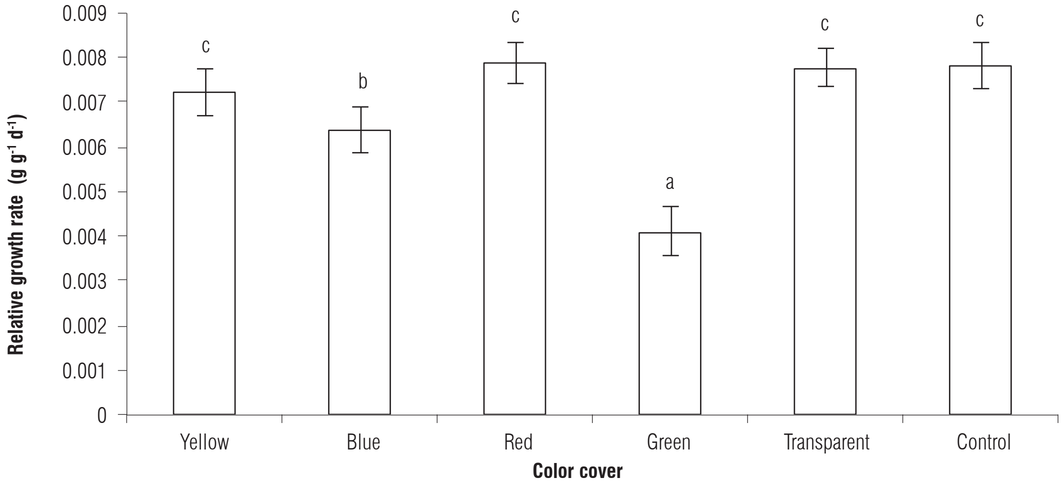

FIGURE 7. Relative growth rate in strawberry plants (*Fragaria* sp.) exposed to colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

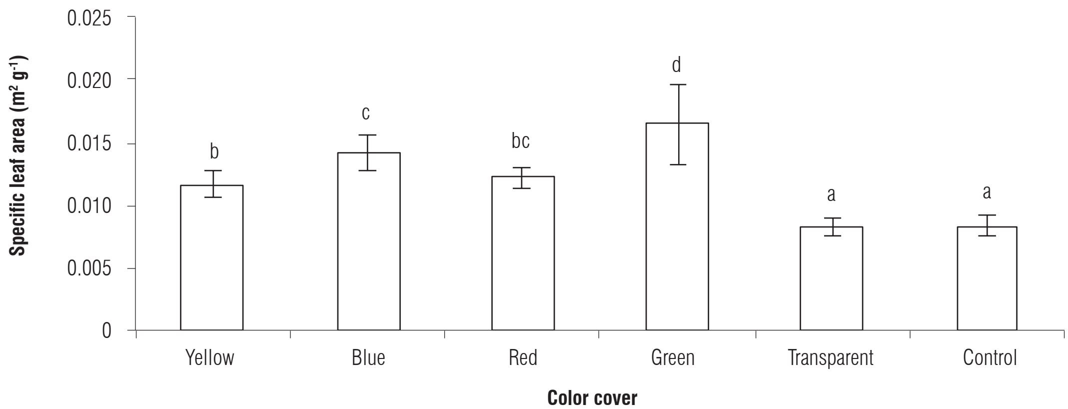

FIGURE 8. Specific leaf area in strawberry plants (*Fragaria* sp.) exposed to colored covers. Different letters indicate significant differences according to Tukey's test ($P \leq 0.05$). The bar above each column indicates standard deviation.

in the present study, since both SLA and LWR increased in a proportionally similar manner.

Conclusions

Most plant species respond to differences in light quality (color or wavelength) and light quantity (density of photon flux or irradiance), as well as to combinations of these two factors (Lazo and Ascencio, 2010).

Miranda and Williams (2007) evaluated photochemical efficiency of photosystem II (PSII) *in vitro* in strawberry leaves, and found an increase in this parameter from 0.64 under white light to 0.80 under yellow light. Furthermore, leaves developed under blue light were similar to those grown under white light in many parameters related to chlorophyll fluorescence, except for the initial fluorescence level. Casierra-Posada and Peña-Olmos (2012) exposed strawberry plants to different colored covers and found that different light quality influenced chlorophyll content. They also found that chlorophyll *a* concentration was higher in leaves growing under green and red light, followed by leaves in the blue, transparent, and yellow treatments. Wang *et al.* (2009) exposed *Cucumis sativus* to different colors of light, and found that all plants grown under monochromatic light showed reduced growth, CO_2 assimilation rate, and PSII quantum yield (ΦPS II) as compared to plants grown under white light. The reduction in these parameters was most pronounced in plants grown under yellow, red, and green light. Furthermore, the reduction in ΦPS II was due primarily to a reduction in photochemical quenching.

The present study confirmed the importance of both light quantity and light quality in plant growth. The blue and far-red ranges of the light spectrum are known for their important roles in genetic expression and in morphogenesis

(Reymond *et al*., 1992; Kaufman, 1993; Short *et al*., 1994; Gupta and Tripathy 2010), but the present study clearly showed the important, often negative effective of green light on growth in strawberry.

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