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Student/Alumna: Zakita N. S. Bethel

Comparative Quality and Production effects of Spectrum conversion Films as double roofs in cucumber (*Cucumis sativus* L.)

Tutors:
Diego Luís Valera Martínez
María de los Ángeles Moreno Teruel

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Comparative Quality and Production effects of Spectral conversion Films as double roofs in cucumber (*Cucumis sativus* L.)

Zakita N. S. Bethel[1]

[1]Contact: zb922@ual.es, Máster HMI 7078, The University of Almería

Abstract

In mild-winter climatic zones such as the southern Mediterranean where plastic-film greenhouse production is concentrated, climate control during the autumn-winter production cycle is essential in the production of tropical or sub-tropical origin horticultural plants. The use of passive techniques such as plastic double roofs, can modify microclimatic variables such as temperature, humidity, the concentration of carbon dioxide, and the incidence of condensation falling on the crop. When its optical properties are modified, the plastic double roof can also modify the quality and quantity of radiation intercepted by plants. As few studies exist on this subject, this experiment was conducted to evaluate the qualitative and productive effects of spectrum conversion films (SCF) when used as double roofs in cucumber (*Cucumis sativus* L.). Six treatments of four plastics (2 SCFs and 2 industry standards: experimental blue, experimental pink, French-industry standard, Almería-industry standard) were installed in three multi-tunnels where fruit quality (average fruit weight, length, diameter, firmness, total soluble solids, and pH) and fruit production (total and commercial yields) variables were collected from three replications per treatment throughout the growing cycle. No significant difference was exhibited between both the experimental blue and pink SCFs in comparison to the Almería-standard among all the quality parameters. The French-standard plastic type, in at least one of its replications obtained the highest levels of average fruit weight, length, diameter, soluble solids and pH, with at least one of the two replications being statistically different from the Almería plastic. One of the experimental pink replications yielded the highest fruit firmness, although this result was not statistically different from the Almería-standard. Plants under the experimental blue film double roof treatment and under one of the French-replications- both of which were located within the same multi-tunnel greenhouse- experienced the highest rates of total and commercial yields and growth.

Keywords: Spectral conversion film, Mediterranean greenhouse, yield, fruit quality, cucumber.

Efectos comparativos de calidad y producción bajo plásticos conversores de espectro como dobles techos en un cultivo de pepino (*Cucumis sativus* L.)

Resumen

En zonas climáticas con inviernos leves como en el Mediterráneo, donde se concentra la mayor producción de cultivo bajo invernadero, el control del clima durante el ciclo de producción otoño-invierno es esencial en la producción de plantas hortícolas de origen tropical o subtropical. El uso de técnicas pasivas, como los dobles techos de plástico, puede modificar variables microclimáticas como la temperatura, la humedad, la concentración de dióxido de carbono y la incidencia de condensación en el cultivo. Cuando se modifican sus propiedades ópticas, el doble techo de plástico también puede modificar la calidad y la cantidad de radiación interceptada por las plantas. En este estudio se compararon 4 tipos de plásticos usados como doble techo (2 experimentales que modifican el espectro (PCE) y dos plásticos estándar, uno de Francia y otro de Almería) colocados en tres invernaderos tipo multitúnel con un cultivo de pepino. Se analizó la producción del cultivo y la calidad de los frutos (peso promedio de la fruta, longitud, diámetro, firmeza, sólidos solubles totales y pH), se recolectaron en tres repeticiones por tratamiento a lo largo del ciclo de crecimiento. No se exhibió una diferencia significativa entre los PCE (azul y rosa experimentales) en comparación con el estándar de Almería entre todos los parámetros de calidad. El tipo de plástico francés estándar, en al menos una de sus repeticiones obtuvo los niveles más altos de peso promedio de fruta, longitud, diámetro, sólidos solubles y pH, y al menos una de las dos repeticiones es estadísticamente diferente del plástico de Almería. Una de las repeticiones realizadas con el plástico experimental de color rosa produjo la mayor firmeza de la fruta, aunque este resultado no fue estadísticamente diferente del estándar de Almería. Las plantas bajo el tratamiento experimental de color azul y en una de las réplicas del estándar de Francia, ambas ubicadas dentro del mismo invernadero, pero en diferentes sectores, experimentaron las tasas más altas de rendimiento total y comercial.

INTRODUCTION

Plastic-film greenhouse crop production represents an important economic activity in the Mediterranean basin (countries of Africa, Asia, and Europe bordering the Mediterranean Sea, 30-46°N) and in other mild-winter climatic areas (Castilla and Abou-Hadid, 2004). With more than 70,000 hectares of greenhouse production in the Southern European Union alone, (Sigrimis, 2010), these sites of crop production are generally characterised by low-cost infrastructure and low levels of technological and energy input for active climate control (Castilla and Abou-Hadid, 2004). However, in comparison to crop production in the open field, protected crop production systems can facilitate more precise management of yield-influencing factors such as incoming radiation levels, pests and diseases, adverse climatic conditions, and key resources such as fertilizers, water, and labour (Pardossi et al., 2004).

Similar to other agroecosystems, the growth, development, and productivity of plants grown within the greenhouse is highly influenced by the microclimate, the levels of and the interaction between radiative factors, temperature, and the relative concentration of atmospheric gases distinct to a particular location (Castilla, 2007) among others. In the plastic-film greenhouse, changes to this non-uniform microclimate is dependent on external conditions, the properties of the enclosure materials, ventilation levels and the form, dimension, and orientation of the greenhouse, among other factors (Berninger, 1989). The primary climatic parameters that affect the growth and productivity of crops grown in protected systems are temperature, relative humidity, and radiation. From a temporal perspective, in the short-term, the microclimate is influential on the production of assimilates (the results of the photosynthetic process), and in the long-term, the status of the microclimate determines the growth of the foliar area and spatial structure of the plant, factors which are key to the absorption of incoming radiation (Lorenzo, 2012).

Of particular focus is the management of the microclimatic parameter of temperature. As it is a determining factor in the rate of cellular metabolism and wider biochemical processes, temperature is a key factor in plant development, growth, fruit quality, the relative rates of evapotranspiration, and the development of diseases within the greenhouse agroecosystem (Lorenzo, 2012). In temperate regions which engage in the commercial production of tropical or subtropical-origin crops (such as tomatoes, peppers, cucurbits among others), the management of temperature is key to the maintenance of levels of production, productivity, and fruit quality of these crops. For example, van de Vooren and Challa (1981) and von Zabeltitz (1992) proffered a threshold minimum night-time temperature of 12°C required in order to maintain normal metabolic levels in a cucumber crop, below which rates of growth and development cease, and heating is required.

In the south-eastern Mediterranean basin region, where average night-time temperatures can drop below 12°C and thus below the threshold night-time temperature between November-April (EuroWeather, 2019), low-cost and low-tech plastic-film greenhouse growers utilize various techniques and materials in order to passively maintain or increase greenhouse night-time temperature at or above minimum threshold levels and by extension, exert further control of the greenhouse microclimate, namely the relative humidity level (and the associated presence of water dripping and accumulating on plants from condensation) (Vargues et al., 1992), the carbon dioxide (CO_2) concentration, and the behaviour of longwave radiation emitted from the soil at night. These techniques involve the individual (or popularly combined) use of sand or plastic mulches on the soil surface, plastic curtains, micro-tunnels, doubled lateral walls, inflated double plastic coverings, thermal screens, and double roofs (Salvador, 2015).

Central to this investigation and due to the availability of specialized plastics in the south-eastern Mediterranean region, the use of plastic film as a double roof for passive heat control in the low-cost greenhouse has grown in popularity among growers in recent years, particularly in cucumber crops yet has extended to other horticultural crops (Salvador, 2015). Such plastic, as it modifies the parameters of temperature, humidity and levels of incoming and outgoing radiation functions directly in the modification of the greenhouse microclimate. The plastic double roof as described by Salvador (2015), Hernandez et al., (2017), and Vargues et al., (1992) is extolled as an effective means of increasing night-time air temperatures, increasing night-time soil temperature, increasing plant internode distance, eliminating the presence of water droplets on the plant and by extension increasing the control of humidity-related diseases such as Botrytis or mildew, and cracking on the surface of fruits.

However, despite the previous, there are challenges in the use of the plastic double roof in the plastic-film greenhouse. These include a reduction in the amount of intercepted radiation, a reduction in the volume of air (namely in the relative CO_2 content) in the daytime hours and related reduced ventilation around the plant - all of which can give rise to the amplified incidence of fungal diseases due to increased relative humidity rates, reduced ventilation, and lowered rates of transpiration (Baptista, 2007; Hernandez et al., 2017; Salvador, 2015). Additionally, as seen by Vargues et al., (1992), the changes in the character and quantity of light intercepted by plants can decrease plant productivity and overall yield by approximately 4.6%.

In consideration of the challenges associated with the double roof, solutions such as retracting the double roof during the daytime hours to facilitate increases in the ventilation rate, the concentration of CO_2, and available radiation to the crop (Hernandez et al., 2017) can be employed in addition to the modification of the properties of the double roof plastic film. Key plastic film parameters such as its thickness and its total light transmittance, or transmissivity, determine the amount (%) and character of visible light (PAR, 400-700nm) transmitted through the plastic to reach the crop (Epsi et al., 2006; Castilla, 2007). Photoselective greenhouse plastic coverings which modify red/far-red incoming radiation, block certain wavebands (in the case of UV-blocking plastics), transform direct incoming radiation to scattered light for inner canopy penetration, or limit the near-infrared energy load, may serve to affect plant morphogenesis, reduce crop diseases, influence fruit quality and secondary metabolite production, or modify insect behaviour (Orzolek, 2017; Stamps, 2009; Ilić and Fallik, 2017). The use of photoselective coverings as evaluated by Ilić et al., (2017) in a lettuce crop, improved light conditions to significantly increase total yield from 252g in the control to 331g (an increase of up to 13.1%) and 319g under pearl and red nets, respectively. In the specific case of cucumber, the increased production of assimilates under aluminized, pearl, blue, and red nets concurrently led to a 6.9 to 8.7% increase in the average fruit weight, and an overall increased yield of 71.1% under pearl nets and 48% under red nets (Ayala-Tafoya et al., 2015). Spectral Conversion Films (SCFs), which further modify the quality of radiation encountered by plants, convert the wavelength of absorbed light into other wavelengths, targeting those sections of the visible spectrum that directly affect plant physiological processes, (Hidaka et al., 2008, Nishimura et al., 2012). These red or blue SCFs can change blue-green light (450-550nm) into red light (600-700nm, which is the most effective region for photosynthesis); or ultraviolet (UV)-violet light (350-450nm) into blue-green light, respectively, which are then intercepted by various plant photoreceptors (Hidaka et. al, 2008, Nishimura et al, 2012). In the case of radishes grown under these films, both leaf photosynthesis and seed germination were accelerated (red film) while leaf elongation was accelerated (blue film). Such parameters are key to plant productivity during the growth cycle and can function in increasing the amount of assimilates produced (via photosynthesis) and stored in fruits. In the specific case of cucumber as highlighted by

Nishimura et al., (2012), SCFs can increase yield, growth (of thicker leaves, main stems, and lateral branches), and fruit dry matter.

Given the influence of the double roof and the modifying qualities of spectral conversion films, this present investigation was conducted to determine the influence exerted by four (4) types of plastics (2 SCFs, 2 industry standards), used as a double roof in an autumn-winter cycle cucumber crop, in respect to production (total and marketable yields) and fruit quality (average fruit weight, length, diameter, firmness, total soluble solids, and pH).

MATERIALS AND METHODS

A. Characteristics of Experimental Greenhouses

This investigation took place in three (3) multi-tunnel-type greenhouses at the Experimental Farm of the University of Almeria (Finca Experimental Universidad de Almeria – ANECOOP, 36°51'52.4''N, 2°16'58.5'' W) which is located in Paraje de Los Goterones in Retamar, Almeria. The greenhouses utilized (U9, U11, U12), were oriented in a NW-SE direction and were located at an altitude of 90m. Each greenhouse in this study (U9, U11, U12), was divided by a fixed polyethylene sheet affixed to a stainless-steel structure, creating two (2) East (U9E, U11E, U12E) and West (U9W, U11W, U12W) sections per greenhouse.

The greenhouses of the investigation were constructed with rigid polycarbonate sides and tri-layer cover of low-density polyethylene plastic with a high EVA (ethylene vinyl acetate) content in the intermediate layer. In terms of its properties, this intermediate layer is the generic copolymer EVA 3C, colourless, diffuse, thickness of 200μm, visible light transmissivity of 88%, diffuse light transmissivity of 25%, and infrared radiation transmissivity of 17%. In the outer layer, a low-EVA content copolymer is present.

In greenhouses U9 and U11, the roof was constituted of three (3) symmetrical, curved roof arches, each 8m in height with three (3) zenith window openings. In U9, however, the northern side wall has installed an air extractor and on the southern side wall, an evaporator panel (cooling system) is installed. In U11, the northern and southern side walls have window openings for ventilation. In U12, the roof is constituted by two (2) curved roof arches, each 9m in height, with two (2) zenith window openings. Additionally, U12 contained side-wall window openings, on both the northern and southern sides. In each greenhouse, the roof arch zenith openings were protected by an anti-insect mesh of 10x20 cm^2, with a porosity of 35%.

Table 1. The Proportions (m), Area (S_c, m^2), Area of side wall ventilation openings (S_{vSIDE}, m^2), Area of roof ventilation (S_{vROOF}, m^2), and Total Greenhouse Ventilation Proportion (S_v/S_c,%) of greenhouse sectors utilized

Sector	Treatment	Proportions[m]	S_c [m^2]	S_{vSIDE} [m^2]	S_{vROOF} [m^2]	S_v/S_c [%]
U9E	Experimental Blue	24×25	600	-	67.5	11.3
U9W	French standard	24×20	480	-	52.5	10.9
U11E	Experimental Pink	24×25	600	126.4	67.5	32.3
U11W	Almería standard	24×20	480	29.2	52.5	17.0
U12E	Experimental Pink	18×25	450	40.5	45.0	19.0
U12W	French standard	18×20	360	31.5	35.0	18.5

The plastic double roof treatments utilized in this investigation, is presented above (Table 1). Both the French-standard and the Almería-standard plastics were transparent, while the SCFs presented a pink and blue hue (Experimental Pink and Experimental Blue).

The French-standard plastic presented a greater transmissivity in the green zone of the solar spectrum (between 500-570nm) in addition to a reduced transmissivity in the red zone of the spectrum (between 618-780nm) in comparison to the Almería-standard. This modification seems to have a thermal influence as it presents several peaks in which its transmissivity of infrared radiation is reduced around 1250, 1350, 1450 and 1750nm.

The blue hues of the Experimental blue SCF produced a reduction of the transmissivity with respect to the French-standard in the blue-cyan zone of the light spectrum (427-497nm). In terms of the Experimental Pink SCF, there was a pronounced increase in the red zone (618-780nm) of the visible spectrum. Both SCFs also produced an increase in the transmissivity in several peaks of the infrared zones (around 1250, 1350, 1450 and 1720nm), a contrast to the reduced thermicity of the French-standard. In spite of this, its transmissivity is lower in that area of the spectrum than the Almería-standard.

B. Cultivation System

An autumn-winter cycle cucumber (*Cucumis sativus* L.) crop of the commercial variety Manglar from the seed company Rijk Zwaan was transplanted on 5 October 2018 in polystyrene coconut fibre channels of 30:1 volumetric relation at a density of 1 plant/m^2. For the first 11 days after transplanting (5-15th October 2018), the crop was irrigated by drip irrigation once daily for 7-9minutes. After which, the irrigation rate increased to twice daily for a duration of 7-9 minutes until the end of the crop cycle. Standard trellising and pruning techniques were undertaken twice per week, with lateral suckers eliminated and the vine stabilized on a vertical twine. The harvest of the crop began on 23 November 2018, 50 days after transplanting. Data of the parameters under consideration was collected from 3 replications per treatment.

Figures 1a, b, c, and d. Experimental Blue, Experimental Pink, French-Standard, and Almería-standard plastics, respectively, installed in experimental Multi-tunnel greenhouses.

C. Experimental Design

There were two primary agronomic categories investigated in this experimental work: Production parameters and Quality parameters. These parameters evaluated contained sub-parameters that were measured throughout the course of the growth cycle, as shown below (Tables 3 and 4). All measurements were taken every week, once per week, for the length of the growing cycle, including and after the first harvest.

Table 3. Measured Production parameters (Total, Commercial, and Non-marketable fruit Weight) were measured by weighing the fruits collected from each of the 3 replications of each treatment.

Parameter Category	Measurement(s)	Equipment utilized	Unit of Measurement
Production	✓ Total production ✓ Commercial production ✓ Non-marketable production	Auto-calibrated Electrical Scale	Weight ($kg\ m^{-2}$)

Table 4. Measured Quality parameters listed below were collected from 10 fruits per treatment each week throughout the length of the production period.

Parameter Category	Measurement(s)	Equipment utilized	Unit of Measurement
Quality	✓ Fruit Weight	EKS Electrical Balance Scale	Weight (g)
	✓ Fruit Length	Metric Measuring Tape	Length (cm)
	✓ Equatorial Fruit Diameter	Digital Vernier Calliper	Diameter (mm)
	✓ Fruit Firmness	Digital PCE-FM Penetrometer	Exerted pressure (kg/cm)
	✓ Total Soluble Solids	Atago PAL-1 Refractometer	Brix degrees (°)
	✓ Acidity Level	Crison pH Meter	pH (-2 -16; ±1)

D. Statistical Analyses

Each of the quality and production parameters of the six treatments were analysed statistically with the software Statgraphics Centurion XVIII (Statgraphics, 2017). The mean of each parameter was compared using an Analysis of Variance (ANOVA, with significance determined at p-value ≤0.05) and Fisher's Least Significant Difference (LSD). Under these analyses, if there was a statistically significant difference between the standard deviations, parametric analysis was not available to analyse the variance between treatments. Verification of similar variances was done by the Cochran, Bartlett, and Hartley tests.

RESULTS & DISCUSSION

Four (4) impermeable plastics (2 SCFs, 2 industry standards) used as double roofs, are expected to exert a modifying and varying influence on the microclimate and by extension, plant productivity under individual greenhouse treatments. This investigation serves to comparatively and statistically quantify that effect through various fruit quality and fruit production parameters in an autumn-winter cycle cucumber crop grown in Almería, Spain. Each quality and production parameter will be evaluated in addition to the determination of how significantly different the treatments were.

1. **Fruit Quality**

Below, the results of the quality parameters measured in each greenhouse sector under the respective plastics that which were used as a double roof, and the statistical significance that existed between them are shown (Table 5).

Firstly, in regard to the average fruit weight, values ranged from 393.18g to 430.29g in U11W and U9W, respectively. The experimental pink plastic replications (U11E and U12E), were similar to each other, while the French standard type (U9W and U12W) did show a statistical difference between its replications. Five of the six treatments, inclusive of the experimental plastics showed no significant differences between them. Sector U9W (a French-standard plastic replication), exhibited the greatest fruit weight and a significantly different, 9% greater weight than those under the standard Almería plastic.

Table 5. Analysis of Quality Parameters (Fruit Weight, Length, Diameter, Firmness, Total Soluble Solids [Brix], and pH). Different letters indicate significant differences at the 95% (LSD Fisher) for each parameter and respective treatment.

Greenhouse Sector (Treatment)	**Quality Parameter**					
	Weight (g)	Length (cm)	Diameter (mm)	Firmness (kg/cm)	Soluble Solids (°Brix)	pH
U9E (Blue)	407.70 ab	30.01 a	45.15 ab	2.85 a	4.46 bc	5.27 abc
U9W (French Std)	430.29 b	30.99 b	46.53 b	2.79 a	4.24 ab	5.27 ab
U11E (Pink)	418.20 ab	31.02 b	45.45 ab	2.93 a	4.38 abc	5.25 a
U11W (Almeria Std)	393.18 a	30.83 ab	44.95 a	2.90 a	4.51 c	5.25 a
U12E (Pink)	403.53 a	31.12 b	44.87 a	2.86 a	4.18 a	5.33 c
U12W (French Std.)	397.40 a	31.19 b	44.46 a	2.90 a	4.52 c	5.33 c

The average fruit length of all treatments ranged from 30.01cm (U9E) to 31.19cm (U12W). Statistical similarities were seen within both sets of French-standard and the pink SCF replications. There was no significant difference between both the experimental blue and pink films with the Almería-standard. Similar to the fruit weight, one of the French-standard plastics (U12W), exhibited the greatest average length, although this was not significantly different than the Almería-type.

The average fruit equatorial diameter ranged from 44.46cm (U12W) to 46.53cm (U9W), both of which contained the French-standard plastic type. Although of the same plastic double roof plastic type, these values are significantly different from each other. Concurrent to the results of fruit weight and length, there was no significant difference between either the experimental plastics with that of the Almería-standard. In addition, treatment U9W (French-standard plastic) a 3% greater diameter than that of the Almería-standard, although this was not significantly different.

The average fruit firmness under all the double roof plastics ranged from 2.85 – 2.93 kg/cm and were all statistically similar, with no substantial differences between plastic treatment types, although one of the pink SCF plastic types yielded the highest level of firmness in comparison to the others.

The average fruit total soluble solids, which are denoted in Brix degrees, ranged from 4.18 to 4.52° Brix in U12E and U12W, respectively. There was a significant difference between the French-standard replications (4.24 and 4.52° Brix in U9W and U12W respectively), yet statistical similarities or overlaps occurred between the pink SCF replications (4.38° Brix in U11E and 4.18° Brix in U12E). The greatest Brix level was seen under one of the French-standard plastics (U12W), although this result was not statistically different from the Almería-type nor one of the pink SCF treatments. Both pink and blue experimental films yielded no significant difference in comparison to the Almería-standard.

In terms of the average pH, values ranged from 5.25 (U11E and U11W) to 5.33 (U12E and U12W). Under both pink SCF and French-standard plastic replication sets, each yielded a fruit pH that was significantly different from the other in addition to one of the French-standard replications showing the greatest pH value.

This experiment was undertaken in Almeria, located on the southern Spanish Mediterranean coast. Like other contexts, this area has its own set of climatic specificities that one can assume can make the materials deemed to be “Almería-Industry standards” more applicable here than other industry standards originating from elsewhere. As such, it is necessary to make an evaluation of the quality parameters between the Almeria-standard and the French standard plastics used as a double roof in this study.

In consideration of the average fruit length and the average firmness, there was no significant differences between both treatments of French-standard plastic and that of the Almería-standard, although there was a slightly greater length under one of the French-standard replications. In the other quality parameters, there existed at least one (of the two French-standard replications) encounter of a significant difference between the French and Almería standards. In the cases of the average weight (where there was nearly a 10% difference between the French and Almería types), diameter, and soluble solids (Brix), this difference occurred in the U9W greenhouse, while in terms of the pH, a greater and significant difference was seen in the U12W greenhouse treatment. In five of the six quality parameters, at least one of the French-standard replications, yielded a significantly different value in comparison to the Almería-type, as well as the greatest value among the treatments.

2. Fruit Production

The Commercial and Total fruit Production (kg m^{-2}) recorded for each treatment sector in the investigation is depicted below (Figure 2). As seen from the values and their respective LSD letters, significant differences existed between greenhouses (U9/U11/U12) at the 95% LSD Fisher level rather than between plastic treatments.

Greenhouse U9 recorded statistically similar total production values of 5.73 kg m^{-2} and 5.97 kg m^{-2} (U9W: Experimental Blue and U9E: French-standard plastics, respectively). Contrastingly and with a significant difference, Greenhouse U11 recorded total production values of 4.59 kg m^{-2} in U11W and 4.67 kg m^{-2} in U11E, which represents the Experimental Pink and Almería-standard plastics, respectively. Lastly, Greenhouse U12, whose total yield was statistically distinct from the other greenhouses and treatments, recorded production values of 4.44 kg m^{-2} and 4.09 kg m^{-2} in greenhouses U12W and U12E, both additional replications of the French-standard and Pink SCF double roof coverings, respectively. A similar occurrence was also reflected in the values of Commercial Production between greenhouses with U9, U11 and U12 showing statistically different results from each other. Additionally, the blue SCF yielded more than 23% greater total production than the Almería-standard while one of the French-standard plastics (U9W) and a pink SCF replication yielded approximately 20% greater yield and 12% lower yield, respectively, than the Almería-type.

The statistical similarity of the total production values of treatments within the same greenhouse could illuminate more strongly the effect of the management of the specific microclimate in this investigation on the yield of the crop, rather than the presence or absence of a specific plastic type as the double roof.

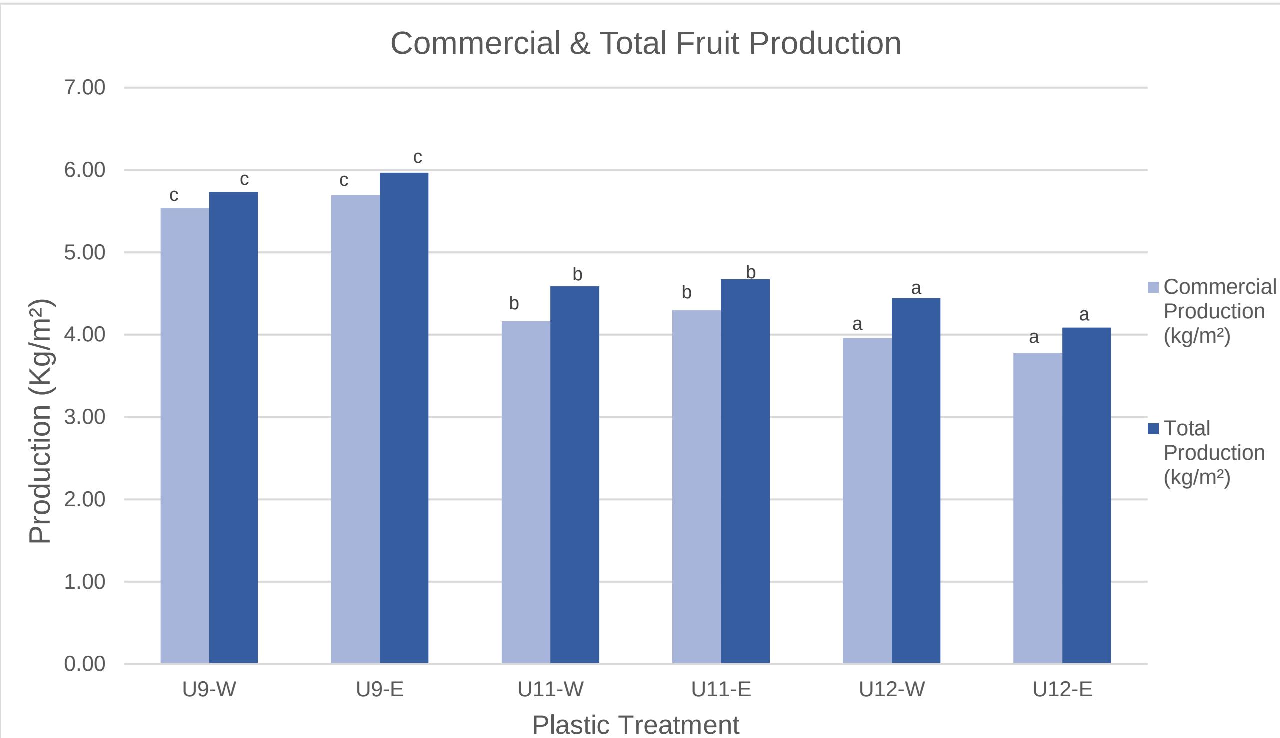

Figure 2. Commercial and Total fruit Production (kg m^{-2}) in each greenhouse sector. Different letters indicate significant differences at the 95% (LSD Fisher) for each parameter and respective treatment

As also reflected below, the evolution of the productivity of the cucumber crop during the growth cycle was strongly related to the greenhouse rather than the plastic double roof treatment (Figure 3). Greenhouse U9 (U9W: French-standard; U9E: Experimental Blue SCF) both accumulated more than 5 kg m^{-2} whereas Greenhouse U11 and U12 both acquired approximately 4 kg m^{-2}, a substantial difference as previously highlighted. Productivity rates followed similar, nearly-linear trends throughout the growth cycle, yet between 24-12-18 and 31-12-18, there was an increased rate of productivity in all treatments, an occurrence which could be due to sudden, external climatic factors such as temperature increase or increased solar radiation during these days which may have influenced the rate of nutrient absorption, biomass accumulation, and subsequent increase in the fruit production per m^2.

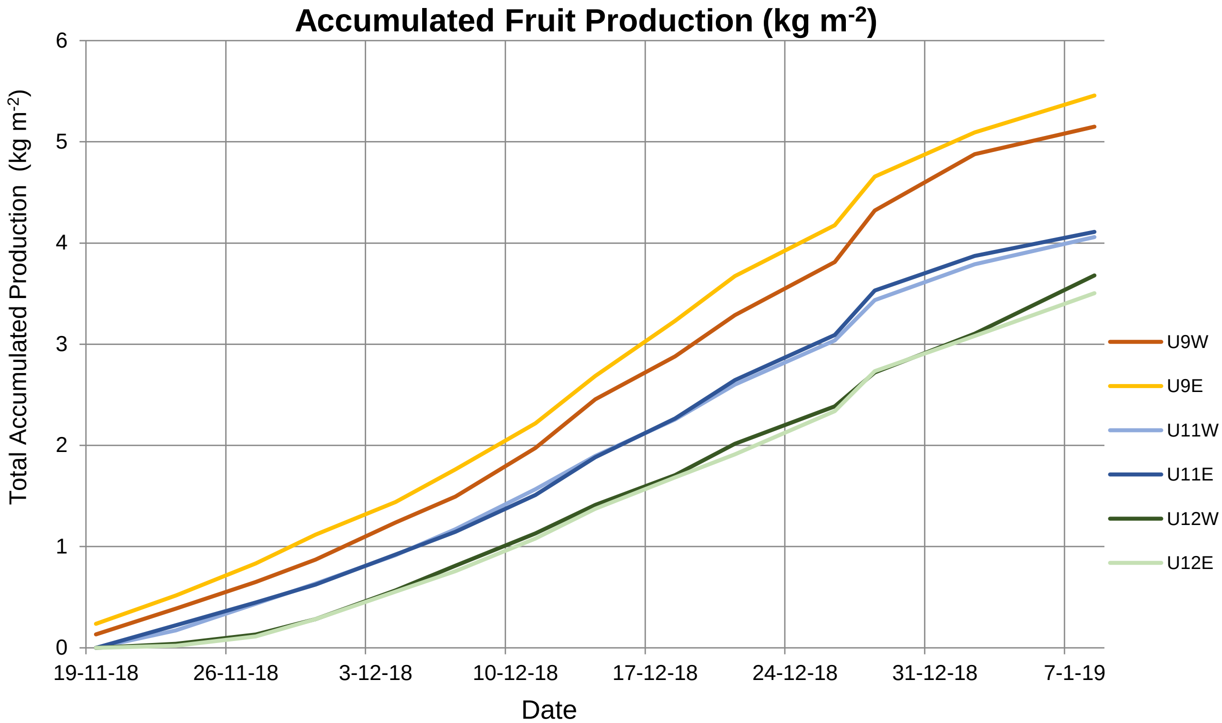

Figure 3. Accumulated Fruit Production kg m^{-2} over the growth cycle

Given the challenges associated with the double roof in the greenhouse, it is prudent to find solutions that can mitigate these while maintaining or increasing the productivity rate and fruit quality parameters. On one hand, as presented by Vargues et al (1992), Baptista, (2007), Hernandez et. al (2017), and Salvador, (2015), the direct modification of the primary microclimatic parameters of temperature, humidity, ventilation rate, and the quality and quantity of incoming radiation through the installation of the double roof could decrease yields by more than 4%. On the other hand, the modification of the transmissive character of the respective plant covering (such as shade nets used in lettuce and cucumber as highlighted by Ilić et al. (2017) and Ayala-Tafoya et. al 2015)), can offset these decreases and turn them into net gains of more than 40%. In the case of this investigation, it was seen that the neither the pink nor blue SCFs influenced substantially the quality or yield of the fruits evaluated throughout the growing cycle. Although the blue SCF (U9E), had the highest total production rate in comparison to all other treatments and experienced a 20% increase in production as compared to the Almería-standard, its presence in only one greenhouse begs for further replication in subsequent experiments, like the pink SCF and French-standard.

CONCLUSIONS

1. The French-standard plastic type, in at least one of its replications obtained the highest levels of average fruit weight, length, diameter, soluble solids and pH, with at least one of the two replications being statistically different from the Almería plastic. One of the experimental pink replications yielded the highest fruit firmness, although this result was not statistically different from the Almería-standard.

2. There was no significant difference exhibited between both the experimental blue and pink plastic films in comparison to the Almería-standard throughout all the quality parameters.

3. Over the length of the growing cycle, plants under the experimental blue film double roof treatment and under one of the French-replications- both of which were located within the same multi-tunnel greenhouse- experienced the highest rates of total and commercial yields and rates of growth that were statistically significant at the 95% LSD Fisher level.

4. Statistically significant differences in production and rates of growth over the production cycle was seen between greenhouses, more clearly than between plastic treatments in this investigation.

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