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Impact of Innovative Optically Active Greenhouse Films on Melon, Watermelon, Raspberry and Potato Crops

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Key words: Light spectrum, optical active dyes, photosynthesis, vegetable, yield, fruit quality ***Abstract***

Adaptation of the light spectrum to the greenhouse cultivated crops is considered as a one way to improve plant production. Light quality might be increased by the incorporation of optically active light shifting dyes in the greenhouse plastic films which adapt the photosynthetically active radiations (PAR) to photosynthesis and consequently might improve plant growth and yield. This present study aims to evaluate the effects of an increase in the Blue (400-500nm) and in the Red (600-700nm) wavelengths induced by the registered "Light Cascade®" technology (LC®) on the low and high tunnels cultivated crops i.e. Charentais melon, watermelon, raspberry and early potato. The experiments have been performed in different experimental farms and in growers' farms located in France and Spain and qualitative and quantitative parameters have been evaluated. The results obtained for the melon and watermelon crops showed globally (i) an increase up to 10% of the yield at the first harvests, (ii) an increase of the fruit size or weight (iii) and a maintained even an increase of the sugar content in comparison to the standard film. It was observed that the effect of the LC® is more significant in unfavourable weather conditions (reduced sunlight) on melon. The raspberry showed underneath the LC® films an increase of both fruit production at the first harvests and the sugar content. Concerning the early potato crop, the results showed an early harvest time reaching 8 days and an increase of 12% of the final net yield especially for desired small sized tubers. These results suggest that the efficiency of the LC® films appeared to be optimal on periods when the sunlight and temperature are insufficient (winter and spring). Further research is ongoing to evaluate the effect of the LC technology on other crops (red fruits, tomato & cut flowers), in relation with additional parameters (temperature regulation, plant disease management and use efficiencies of water and nitrogen).

INTRODUCTION

Light is one of the most important factors that regulates plant growth and development (Smith, 1982). Two functions of light are classically described for plants: (i) the visible sunlight, referred to as the photosynthetically active radiation (or PAR 400-700nm), provides energy for photosynthesis and (ii) specific wavelengths, i.e. far-red (FR) wavelength, constitute a signal that gives information on the environmental surrounding conditions (composition, duration and direction of the light) which induces some morphological and physiological changes referred as photomorphogenesis. Photosynthesis involves specific pigments in higher plants i.e. chlorophyll a and b and carotenoids which absorb in the blue (B: 400-500 nm) and red spectral regions (R: 600-700 nm) while the photomorphogenesis process relies on range of photoreceptors (phytochromes, cryptochromes,

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phototropins and zeitlupe, flavin-binding kelch and lov kelch proteins) which absorb near UV and in far red wavelength (Demotes-Mainard et al., 2016; HuchéThélier et al., 2016).

The discovery and development of the polyethylene polymer in the late 1930s and its subsequent introduction in the early 1950s in plastic films revolutionised the vegetable and horticulture crop production. According to Lamont (2005), the use of plastic films provides many benefits to the producers, such as earlier crop production, increased yield per unit area, better quality of produced fruits, vegetables and flowers and a potential decrease of plant diseases. Different crops such as tomato (*Solanum lycopersicum*), eggplant (*Solanum melongena*), pepper (*Capsicum annnum*), cucumber (*Cucumis sativus*), melon (*Cucumis melo*), watermelon (*Citrullus lanatus*) and potato (*Solanum tuberosum*) showed substantial increases in earliness, yield and/or vegetable/fruit quality (Lamont et al., 2005).

Moreover, the spectral modifications by the incorporation of fluorescent dyes in the cover films might be an interesting tool to improve crop production and quality (Rajapakse and Shahak, 2007). The studies related to the spectral modulations induced by the cover films mainly focused on the effect of the R/FR (Red / Far Red) ratio on different ornamental and vegetable crops. However, to our knowledge, relatively few studies evaluated the impact of the increase of the gains in R and B wavelength on different crops cultivated below low and high tunnels.

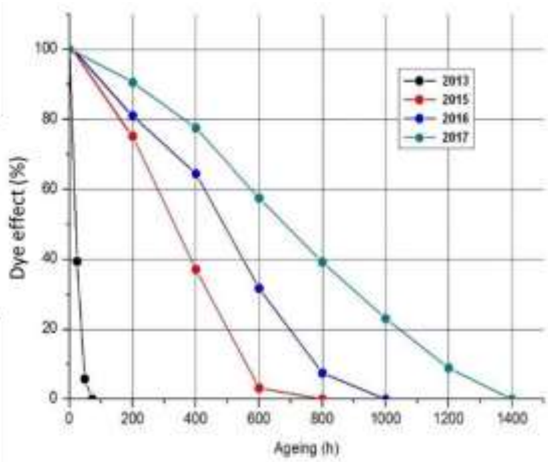
In this context, the French CASCADE company has elaborated different dye formulations (registered as "Light Cascade" or LC®) which, when incorporated into plastic cover films, induce gains in the R and B wavelengths. The effect of the corresponding optically active films has been evaluated on low and high tunnels crops as the Charentais melon, watermelon, raspberry and early potato crops in France and in Spain. This study shows the different agronomic results obtained with the LC® technologies on different parameters as flowers production, first and final cumulated yields, fruits and tubers quality (size or weight, sugars content and acidity).

MATERIAL AND METHODS FORMULATIONS AND FILMS

The principle of the registered LC® technology aims to enhance in the Blue (420-480 nm) and in the Red (620-680 nm) range respectively. Four formulations designed by the CASCADE company have been tested and improved since 2013 based on their colorant composition, concentration and their life time when incorporated into the films. The formulations have been optimised in collaboration with the IRHS institute (Institut de Recherche en Horticulture et Semences, France) based on the agronomic results. In 2016, two formulations have been tested (ORCA M1 and ORCA M2). As the agronomic results were globally better with the "ORCA M2" formulation, the 2017 formulation (referred as to "ORCA PTM17") was improved mainly for the durability. For confidential reasons, the details of the formulations tested cannot be revealed in this article. However, it is worth to mention that the durability of the formulations has been substantially increased for some of the dye formulations (from 100 to 1400 hours for one of the dyes, Figure 1).

The tested films composition was in ethylene–vinyl acetate copolymer (EVA) and have been produced by the TRIOPLAST (Pouancé (49), France) and AGRIPOLYANE companies (Saint Chamond (49), France). In the different trials, the corresponding standard reference film has been always included. The size and the thickness of the films are specified below for each crop.

Figure 1 Evolution of the stability of one of the components in the LC® formulation from 2013 to 2017. The effect of the dye is characterised as a function of the residence time in an accelerated light ageing chamber (Atlas Suntest). Fine-tuning of the formulation resulted in a longer lifetime of this component during artificial ageing.



MELON TRIALS

The effect of the different formulations has been tested on 3 early growing varieties of melon (*Cucumis melo* Charentais) in France and in Spain from 2013 to 2017 (Figure 2A and Table 1). The trials have been carried out at experimental farms or at growers' farms: GDM ("Groupement de Développement des maraîchers", Pétosse (85) and in Vouillé-les-Marais (85), France), SUDEXPE ("Station de Recherche appliquée Fruits et Légumes, Marsillages (34) France) and IMIDA ("Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario", Murcia, Spain). According to the geographical location of the trials, the films were applied in late winter or early spring (February to April) and covered the melon crop for 57 to 93 days. The duration of the culture varied from 97 to 125 days. The length of the low tunnels varied from 9m (experimental farm) to 5000m (growers' farm) and the film thickness was 49µm. The effect of the different formulations has been evaluated on the (i) first harvest and the cumulated final gross or net yield, and (ii) on the fruits quality (fruit weight(g) and sugar content determination by the Brix index on a minimum of 4 fruits)).

Table 1. Summary of the Charentais melon trials done in France and Spain from 2013 to 2017. Abbreviation: NA=not available.

Year	Variety	Location	Experimental or growers' farm	Film tested	Experimental crop surface	Beginning and the end of the trial	Duration of film application (days)	Harvests period (days)	Crop cycle (days)
2013	SILVIO	Petosse (85) (France)	GDM	Standard ORCA MM21M	100m of low tunnel per type of film, 5 measures done per tunnel	At 19/04/13	93	NA	NA
2015	SILVIO	Petosse (85) (France)	GDM	Standard ORCA MM21M	100m of low tunnel per type of film, 4 measures done per tunnel	From 07/04/15 to 20/07/15	68	21	103
2016	ESCOBAR	Petosse (85) (France)	GDM	Standard ORCA M1 ORCA M2	100m of low tunnel per type of film, 4 measures done per tunnel	From 06/04/16 to 11/08/16	68	28	125
2017	ALONSO	Marsillargues (34) (France)	SUDEXPE	Standard ORCA PTM17	9m*6 low tunnels per type of film, 1 measure per tunnel	From 09/03/17 to 16/06/17	68	17	97
2017	ALONSO	Vouillé-les-Marais (85) (France)	GDM	Standard ORCA PTM17	5000m of low tunnel per type of film, 1 measure per tunnel	From 16/03/17 to 05/07/17	76	16	109
2017	ALONSO	Murcia (Spain)	IMIDA	Standard ORCA PTM17	10m of low tunnel per type of film, 1 measure per tunnel	From 15/02/17 to 20/06/17	57	32	125

WATERMELON TRIALS

One watermelon (*Citrullus lanatus,* 'Bengala' variety) trial has been carried out in 2017 and took place in Spain at the IMIDA experimental farm (Figure 2B). The experiment design consisted on 4 low tunnels (2.1mx10m, thickness: 49µm) with 5 plants per low tunnel. In this trial, the control and the 2017 "ORCA PTM17" formulation films were tested. It started on 20th March 2017 and ended 3rd July 2017. The different covers remained for 36 days and the duration of the culture was 110 days. Fruits were harvested on the 26th of June and the 3rd of July 2017. The following parameters have been evaluated: number of female flowers per replicate (52 days after the beginning of the trial), fruit size and quality (sugar content on a minimum of 4 fruits and acidity (g of citrate per 100 ml)), fruit weight (kg) and the gross yield obtained at the first harvest and at the final cumulated gross yield ($t.ha^{-1}$).

RASPBERRY TRIALS

The effect of the ORCA PTM17 formulation has been evaluated in the experiment farm ADESVA (Centro Technologico de la Agroindustria, Spain) on the non-repeat flowering raspberry (*Rubus idaeus*) variety 'San Rafael' in 2017 (Figure 2C). The one-year old plants were planted on the 21st of February under 2 high tunnels of 264m² (one tunnel per type of film, 8.5mx50m, thickness: 150µm, 4 measures per tunnel) and the harvests occurred from the 17th of May 2017 until the 15th of June 2017. The crop was covered permanently until the end of the trial. The following measurements have been carried out: number of flowers per plant (done on the 24th of April 2017), the mean net yield on the 7 first harvestings (in g/plant, from 17th of May to 31th of May) and on the next harvestings, the sugar content calculated on 3 harvests (24th of May, 26th of May and 29th of May) and citrate quantification (in g per 100ml) realised on the harvest of 8th of June.

POTATO TRIALS

The effect of the 2016 ORCA film formulations (M1 and M2) has been evaluated on the early ("primeur") potato (*Solanum tuberosum*) 'Sirtema' in 2016 in Noirmoutier en l'Ile (France) (Figure2D). The experimental design consisted on two different low tunnels (150mx2.1m, thickness: 80µm) per type of film. The beginning of the trial was on the 19th of January 2016 and ended on the 13th of April 2016. The harvest tubers have been calibrated in 2 categories: below 35 mm and between 35mm-55mm and the total weight per low tunnel have been measured.

Figure 2. Illustration of the different trials on melon (A), watermelon (B), raspberry (C) and early potato (D) crops.

RESULTS AND DISCUSSION EFFECT OF THE FLUORESCENT FILM ON MELON AND WATERMELON

The effect of the 4 different formulations has been assessed on the melon crop in France and Spain from 2013 to 2017 (Table 2). The results showed that an average of 23% of the final cumulated yield was reached at the first harvest under the CL® films in comparison to the standard reference films (14,8%). Consequently, the LC® films favoured precocity to the melon crop. Although no differences have been noticed between the two films at the first harvest in 2015, a gain of +11% in the final cumulated yield has been recorded. An important gain, especially with the ORCA M2 formulation, has been highlighted in 2016 both at the first and final cumulated yield (+10% and +52% more respectively). These results might be explained by the non-optimal weather conditions in 2016 and consequently underlined an enhancement of the films effects. The trial carried out in Spain did not show any substantial effects on the yields but only an increase of fruit weight; this might be explained by the relatively late application of the films on the crop (in the middle of February 2016 instead of the beginning of January). According to the trials, the melon quality was almost not changed by the LC® films and the weight of fruits was slightly increased.

Table 2. Effect of the 4 different formulations on the melon crop evaluated from 2013 to 2017 in France and Spain.

Year	Variety	Location	Film tested	Yield at the first harvest (t.ha-1)	Final cumulated gross or net yield (t.ha-1)	% of reached total yield at the first harvest	% Difference between the films at the final yield	Sugar content (°Brix)	% Difference between the films for the sugar content	Mean weight of harvest fruits (g)	% Difference between the films for the fruit weight
2013	SILVIO	Petosse (85) (France)	Standard	1,58	24,9	+6,4	**-4,1**	13,1	**+4,6**	NA	**NA**
			ORCA MM21M	4,79	23,8	**+20,1**		13,7			
2015	SILVIO	Petosse (85) (France)	Standard	0,4	22,4	+1,8	**+11,0**	13,00	**+8,5**	NA	**NA**
			ORCA MM21M	0,44	24,9	**+1,8**		14,1			
2016	ESCOBAR	Petosse (85) (France)	Standard	3,23	11,2	+28,8		15,3		651	**+0,8**
			ORCA M1	3,85	14,0	**+27,4**	**+25,2**	14,0	**-8,5**	656,0	
			ORCA M2	6,57	17,1	**+38,6**	**+52,0**	15,6	**+2,0**	709,0	**+8,9**
2017	ALONSO	Marsillargues (34) (France)	Standard	0,56	22,5	+2,5	**-6,6**	13,3	**+1,5**	981,0	**+4,8**
			ORCA PTM17	4,86	21,0	**+23,2**		13,5		1028,0	
2017	ALONSO	Vouillé-les-Marais (85) (France)	Standard	8,5	24,85	+34,3	**-3,4**	NA	**NA**	NA	**NA**
			ORCA PTM17	10,9	24	**+45,3**		NA			
2017	ALONSO	Murcia (Spain)	Standard	6,2	41,5	+15,0	**+1,9**	13,0	**-3,8**	713,0	**+28,3**
			ORCA PTM17	2,5	42,2	**+6,0**		12,5		915,0	

With regards to the watermelon field trial, only the effect of the ORCA PTM 17 formulation has been evaluated in Spain on flowers production, fruit size and weight, fruit quality and on gross yield at the first harvest and last final cumulated yield (Table 3). The LC® films increased slightly the number of female flowers produced (+15%) per low tunnel and the size (from +7 to +11 %) and weight of fruits (especially at the first harvest, +34%). The sugar content of the fruits and acidity were almost similar or slightly increased below the LC® films in comparison to the standard film. The gross yield at the first harvest showed a double increase using the LC® films and the final cumulated yield was +38% higher. These results suggest a positive impact of the LC® films on watermelon production (both yield and quality). The fact that a higher yield was obtained at the first harvest did impair the fruit quality (same size, sugar content and acidity). Further trials are currently carried out in Spain and France to confirm and improve these effects.

Table 3. Effect of the ORCA PTM 17 formulation on the watermelon crop (Spain, 2017).

Evaluated parameters	Measures	Mean value under the "Standard" film film	Mean Value under the "CASCADE" film	%Difference
Flowers production	Number of female flowers/low tunnel (52 days after the cover application)	20,75	24	**+15,7**
Fruit size	Length (cm) at the first harvest	20,57	22,11	**+7,5**
	Width (cm) at the first harvest	19,71	21,91	**+11,2**
	Mean Fruit weight (kg) at the first harvest	3,93	5,28	**+34,3**
	Mean global fruit weight (kg)	4,57	5,00	**+9,4**
	Mean sugar content (°Brix)/replicate at the first harvest	11,2	10,92	**-2,6**
Fruit Quality	Mean global sugar content (°Brix)/replicate	11,06	11,98	**+8,3**
	Acidity (g citric acid in 100ml) at the first harvest	0,09	0,1	**+11,1**
	Global acidity (quantity of citric acid (g)/100 mL)	0,08	0,085	**+6,3**
Yield	Gross Yield at the first harvest ($t.ha^{-1}$)	3,5	7,8	**+122,9**
	Final cumulated gross yield ($t.ha^{-1}$)	29,6	41,1	**+38,9**

EFFECT OF THE LIGHT SHIFTING FILM ON RASPBERRIES

The effect of one LC® formulation has been evaluated on flowers production, yield and quality of the fruits of the high tunnel cultivated non-recurrent blooming raspberry variety 'San Rafael' in Spain in 2017 (Table 4). After two months since the start of the trial, the results showed an increase of flowers production (+19%) under the LC® film in comparison to the standard film. An increase on the quantity of produced fruits (+16%) at the 7 first harvests has been observed with the LC® formulation and almost no effect on the next harvests. With regards to the fruit quality, the sugar content measured on 3 different harvests (from the 24th to 29th of May, corresponding to the middle of harvests period) was substantially higher under the LC® films (from +24% to +62%) and the acidity was lower (-22%). These results suggest that the LC® films improves at least raspberry quality and potentially improves the yield of the first harvests. According to these results, it might be suggested that the LC® technology improved the effect of light especially during winter on raspberries fruit ripening. Further investigations are needed to evaluate the effect of the LC® films on winter cultivated red fruits (from October to March-April) in order to observe whether the yields and the quality are substantially improved.

Table 4. Effect of the ORCA PTM 17 formulation on the raspberry crop (Spain, 2017).

Evaluated parameters	Measures	Mean value under the "Standard" film	Mean Value under the "ORCA PTM17" film	% Difference
Flowers production	Number of opened flowers/plant (27/04/2018)	27,7	32,9	**+19%**
Fruit Yield	Mean net fruit yield (g/plant) on the 7 first harvests	345,8	402,4	**+16,4%**
	Mean net fruit yield on the next harvests (g/plant)	737,7	755,3	**+2,4%**
Fruit Quality	Sugar content (°Brix measured at 24/05/2017)	8,88	11,08	**+24%**
	Sugar content (°Brix measured at 26/05/2017)	6,36	10,33	**+62%**
	Sugar content (°Brix measured at 29/05/2018)	6,78	10,43	**+62%**
	Acidity (g of citric acid per 100ml) measured at 08/06/18 (mean of 30 fruits)	2,07	1,6	**-22%**

Effect of light shifting films on early potato

The production of the early potato crop in France aims to harvest small sized potato tubers in the beginning of the spring (middle of April). The two 2016 LC® formulations have been tested on this crop by measuring the size of harvested tubers and the mean of the total weight produced per low tunnel (Table 5). The results showed that the mean weight per tunnel of the 35 to 55mm sized tubers was almost 3-4 times higher than the <35mm sized tubers. Interestingly, the two formulations tested have induced an increase in yield of +11% to +13% of the <35mm sized tubers. Only the ORCA M2 formulation increased the yield of the 35-55mm sized tubers by +7% in comparison to the standard film. The same trial has been carried out in 2017 (data not shown) and the results showed similar yield gains. At the beginning of the trials, an acceleration of the vegetative potato plant growth cultivated with the LC® films has been observed. Besides, the harvest of tubers occurred 8 days before under the LC® films in comparison to the standard film (pers. commun., 2017). These observations of precocity might explain the size reduction of the tubers under the LC® formulation.

Table 5. Mean potato tubers yield (size below 35 mm and between 35-55mm) obtained per low tunnel covered with the standard film and the two LC® films harbouring the formulations ORCA M1 and ORCA M2.

Type of film	Tubers size (mm)	Mean total weight per tunnel	Difference (%)
Transparent film	<35	1,77	
Fluorescent film 1	<35	2,04	**13,0**
Fluorescent film 2	<35	1,99	**11,0**
Transparent film	35-55mm	7,21	
Fluorescent film 1	35-55mm	6,42	**-12,3**
Fluorescent film 2	35-55mm	7,80	**7,6**

CONCLUSIONS

This research highlighted a positive effect of the LC® light shifting technology on low and high tunnels cultivated crops such as melon, watermelon, raspberry and early potato. Concretely, a gain has been noticed on the first harvest yields showing precocity of up to a week while the quality (sugar content, fruit weight and size) was at least maintained, even improved in certain cases. Yield gains have been measured in difficult weather conditions that can help secure yields for growers. Positive effects of Red and/or Blue spectrum modulation have been noticed on other species as roses and tomato (Novoplansky et al., 1990), strawberries (Hemming et al., 2006), radish and welsh onion (Hidaka et al., 2008), cucumber (Nishimura et al., 2012) and lettuce (Minich et al., 2011). Interestingly, the effect of the LC® films appeared to be larger during difficult growing conditions (limited sunlight) and seems to be used in early, late winter and early spring crops in France and Spain. New trials are underway this year to confirm and improve these effects and to test on other genotypes of the previously tested crops and on new crops such as rose, tomato and strawberries. Further investigations in controlled conditions are needed to understand the effect of these spectral modifications and thereby to allow the CASCADE company to define the best formulations and use of LC® films for each targeted crop.

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