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The Effect of New Developed Fluorescent Greenhouse Films on the Growth of *Fragaria* x *ananassa* 'Elsanta'

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Summary

In order to optimise light quality and quantity for plant growth, new photoselective greenhouse covering materials were developed containing different fluorescent pigments (Blue, Red1, Red2, Red3) in different concentrations. Excitation of all fluorescent pigments took place around 365 nm. Blue pigments showed fluorescence between 410–480 nm, Red1 and Red2 pigments between 610–630 nm and Red3 pigment between 600–690 nm, while also major parts of the blue and green part of the spectrum were absorbed. Fluorescence effects of the plastic film prototypes were rising with increasing pigment concentration. However, fluorescent effects were small. While Blue pigments increased total PAR transmission with 1–3 %, Red pigments were found to lower PAR transmission. Only pigment Red3 was able to increase the red:far-red ratio with 10 %.

The effect of the different film prototypes on strawberries 'Elsanta' was investigated in two experimental periods in 2002 and 2003. Blue fluorescent films seemed to be favourable for strawberry fruit production. Whether this was due to the higher PAR transmission of the films or to a light quality effect cannot be concluded from the experiments. Blue fluorescent films caused strawberry production to increase with 11 %, mainly because of an increased fruit number. On the other hand Red3 fluorescent film delayed fruit production significantly. Total yield under Red3 was 10 % lower than under the Reference film. This effect was due to the lower PAR transmission of the film and the increased red:far-red ratio.

Fruit colour was only slightly influenced by the different film prototypes. Fruits grown under Blue fluorescent films were slightly brighter but more saturated than fruits grown under the Reference film, which were darker but paler. Fruits grown under Red3 fluorescent film were apparently brighter but more saturated than fruits grown under the Reference film. In experiments in 2002, that was also observed for fruits grown under the Red1 and Red2 fluorescent film.

Furthermore, dry matter and ash content of the fruits were determined, as well as the electric conductivity (EC) and sucrose concentration in the fruit sap. However, no significant differences could be detected. Fruits grown under Blue films were found to be slightly more acid (lower pH) than fruits grown under the Reference film, fruits grown under the Red films were found to be less acid. Since the sweetness to sourness ratio can be used as quality index, which fairly correlates with the taste quality, we can conclude that fruits grown under the Blue films taste less sweet than fruits grown under the Reference, Red1 and Red2 films.

Several vegetative growth parameters were measured such as number of leaves, total leaf area, mean leaf area, leaf fresh weight, leaf dry weight and dry matter content of leaves, but no significant differences were detected. No correlation between vegetative growth parameters and fruit production was found.

From these results it can be concluded that newly developed greenhouse films containing blue fluorescent pigments have good potentials to affect growth and development of *Fragaria* x *ananassa* 'Elsanta' positively, whereas red fluorescent films are less promising

Key words. blue light – fruit colour – fruit quality – light quality – light intensity – PAR – photoselective materials – plant growth – red:far-red ratio – spectral transmission – strawberry

Introduction

Natural light is an important factor in horticultural production. Light provides energy for photosynthesis, the process by which plants produce carbohydrates and oxygen from carbon dioxide and water. For photosynthesis light with the wavelengths from 400–700 nm is necessary. This part of the global radiation is called photosynthetically active radiation (PAR) (CIE 106/8 1993). Light also acts as an informational medium for plants such as identifying surrounding environmental conditions. Photoreceptors that function as light sensors provide information on changes in light composition in the growing environment, so the plant can react with a photomorphogenetical response. Photomorphogenesis is the process that determines the form, colour and flowering of plants. For morphogenetical responses wavelengths from 300–800 nm are important (CIE 106/5 1993). Several photoreceptors are developed by higher plants, phytochromes absorb light in the red (600–700 nm) and the far-red part of the spectrum (700–800 nm) (SMITH 1982), chryptochromes and phototropines absorb in the blue part of the spectrum (400–500 nm) and in UV-A (320–400 nm) (CHRISTIE and BRIGGS 2001), other photoreceptors absorb UV-B (BROSCHE and STRID 2003).

Since the optimum light intensity and light spectrum are essential for optimum plant growth and development, much effort is focussed on the development of transparent greenhouse covering material with improved optical properties (PEARSON et al. 1995; MURAKAMI et al. 1997; KITTAS and BAILLE 1998; HOFFMANN 1999; GONZÁLEZ et al. 2003; RAJAPAKSE et al. 2000; SONNEVELD et al. 2002; FLETCHER et al. 2003; HEMMING et al. 2004). Plastic films containing fluorescent pigments seem to have potential to increase light transmission of greenhouse covering and / or change the red:far-red ratio.

There are different fluorescent pigments available. In the past fluorescence plastic films were developed, which shift green light into red light since it was assumed that green light is less effective for photosynthesis and a higher amount of red light was assumed to increase photosynthesis (ZARKA and ZARKA 1985). However, total PAR transmission of those films was reduced (PEARSON et al. 1995; KITTAS and BAILLE 1998). Recently films are developed, which absorb parts of the ultraviolet, blue and green region of the spectrum and shift it to red light with the aim to change red:far-red ratio. Also these films reduce total PAR radiation (GONZÁLEZ et al. 2003). Another option is the development of fluorescent plastic films, which only absorb ultraviolet radiation and shift that into PAR with the aim that the total amount of PAR is enlarged and light quality is optimised for several plant processes. The effects of these types of films are described in the research done.

The objective of this research was to develop new fluorescent greenhouse covering materials containing different fluorescent pigments, which shift ultraviolet radiation into blue or red light. The optimum concentration for the fluorescent pigments had to be found. Technical aspects of fluorescent films were investigated, such as spectral light transmission, fluorescent effect and stability. It was investigated whether it is possible to increase PAR transmission of the films and simultaneously improve the light spectrum meeting the needs of the plants produced under these films.

In The Netherlands, strawberry is one of the largest crops grown in plastic greenhouses. In 2003, in total 1915 ha strawberries were grown, of which 133 ha in greenhouses and 59 ha in plastic tunnels (CBS STATLINE 2004). In 2001, from a total strawberry production of 34 million kg, 15 million kg was grown in greenhouses and tunnels. In this research it is investigated whether the new developed fluorescent film prototypes are able to improve fruit production and quality of *Fragaria* x *ananassa* 'Elsanta'.

Materials and Methods

Plastic films and experimental greenhouses

For the experiment, 6 greenhouse tunnels of 4 m by 5 m with a height of 2.10 m were placed in two rows with 3 greenhouses with a space of 4 m in between the greenhouses and the rows. The tunnels were covered with different experimental plastic films containing fluorescent pigments. Plastic films were arranged on the experimental greenhouses by coincidence.

Two types of fluorescent pigments were used, one type of pigment absorbing ultraviolet radiation and transforming it into blue radiation, here referenced as "Blue pigment" or "Blue", the other type of pigment absorbs ultraviolet radiation and transforms it into red radiation, here marked as "Red pigment" or "Red". Since three different Red pigments were used from different producers, they are here labelled as Red1, Red2 and Red3.

Fluorescent measurements were carried out with an Avantis Fibreoptic Spectrometer at TITK (Thüringisches Institut für Textil- und Kunststoff-Forschung in Rudolstadt), Germany. Excitation takes place at 365 nm (ultraviolet-A radiation, UVA), and then spectral radiation intensity was measured. Maximum fluorescence of the Blue pigment was found at ca. 450 nm (blue radiation), maximum fluorescence of both Red1 and Red2 pigment was found between 610–630 nm and around 705 nm (red radiation). Maximum fluorescence of the Red3 pigment was found between 600–690 nm (red radiation); however, a significant part of the radiation of 400–600 nm was absorbed.

With these pigments different experimental plastic films were produced by blow extrusion technique from compounds giving a monolayer LDPE film of around 200 μm. The films contained a HALS (hindered Amine light stabilizer) to protect the polymer carrier against UV degradation, Chalk as light diffuser and Clay as filler. The films contained the Blue and the Red1 pigment in three different concentrations here coded as "a", "b" and "c", Red2 in the concentrations a and c and Red3 is only used in one concentration slightly higher than the concentration c. Another film contained a combination of the Blue pigment (b) and the Red1 pigment (a). All films looked transparent, except Red3, which had an orange colour.

Experiments were carried out in 2002 and 2003. During the first year low pigment concentrations were used in the plastic films advised by the pigment producers. Since fluorescent effects were low higher concentrations were used in the second year trials.

The spectral transmission of all films with wavelengths of 300 to 800 nm was measured with an "Ulbricht integrating sphere" at A&F, Wageningen. This "Ulbricht integrating sphere" contains a diode array spectrophotometer measuring the spectral light transmission for the wavelength of 300 nm$<\lambda<$1100 nm. The internal diameter of the sphere is 0.75m, the entrance aperture is 0.48 cm^2. The inner surface of the sphere is coated with $BaSO_4$ (KODAK). Standard materials were used for calibration purposes.

Greenhouse climate

In all tunnel greenhouses the inside climate was recorded every second by a datalogger 'dataTaker DT600'. Mean values were stored every 15 minutes. PAR radiation was measured with Deka quantum sensors DK-PHAR 2.0,01S2000VP, air temperature and relative humidity were measured by Rotronics HygroClip to characterise inside climate. Of the outside climate PAR radiation, air temperature and relative humidity were measured. Additionally global radiation was measured with a Kipp & Zonen pyranometer CM21. Wind velocity, wind direction and sky temperature were recorded. Only calibrated sensors were used.

Plant materials and growing techniques

Plants of *Fragaria* x *ananassa* cv. 'Elsanta' were kept at −1 °C (waiting bed). After defrosting plants were potted in Libra containers filled with potting soil, especially developed for strawberries and fertilized with slow release Osmocote (16-11-11 NPK). Potting took place on 8th of May 2002 and on 7th of April 2003. The containers were placed in a multi-span Venlo greenhouse for 6 days to adapt to the warm outside climate before they were transferred to the experimental tunnel greenhouses covered with different fluorescent plastic films. In each tunnel 15 containers with 10 plants each were placed, of which 9 containers contained examination plants, the other contained border plants. The plant density was 9.5 plants m^{-2}. Water was supplied by drippers, giving up to 0.5 l water per plant per water supply. EC in the substrate was 0.8 mS cm^{-2}, pH was 5.7 and the drain was approximately 25 %. For pollination, a beehive was placed in the vicinity of the tunnels.

Harvests and analyses

Strawberry fruits were picked two to three times per week. Harvest took place between 17th of June and 26th of July for experiments carried out in 2002 and between 6th of June and 7th of July for experiments in 2003. For each container of each tunnel, the harvested fruits were separated into three size classes, namely A, B and C (>40 mm, 26–40 mm, <26 mm) according to the rules of the Dutch auction. For each class, total weight and number of fruits were recorded, as well as the number of deformed and diseased fruits.

At several harvests 10 non-deformed class B fruits were randomly chosen of which the colour was determined. Images were recorded with an image acquisition system consisting of a colour CCD-camera (Hitachi HV C-20), a framegrabber for image digitisation (Matrox Meteor) and a standard PC running Windows NT4. The acquired images had a resolution of 768x576 pixels per colour channel. The camera was mounted on top of a closed illumination box. The inside of the white box is diffuse illuminated by neon tubes. The fruits were positioned on a blue background to enable a good segmentation of fruit and background. Before the colour measurements took place, the system was calibrated. A special colour segmentation algorithm was used to segment the fruits in the image. Per single fruit the mean colour value of all pixels belonging to the fruit was recorded as red, green and blue (R, G, B) values. Because the R, G, B values were unsuitable to compare different colours, they were transformed to the L*a*b* colour space using the standard D65 Illuminant and the 2° observer as defined by the CIE in 1931.

The L*a*b* space is typified by the lightness parameter L* of which the scale ranges from no reflection (L*=0, black) to perfect diffuse reflection (L*=100, white) and the colour co-ordinates a* and b*. The a* scale ranges from negative values for green to positive values for red, and the b* scale ranges from negative values for blue to positive values for yellow.

In experiments in 2002, further analyses of strawberry fruit were carried out. After colour determination, the 10 fruits were homogenised with a home-mixer. Dry matter was measured after 24 h drying at 105 °C and ash content subsequently after 4 h at 550 °C. Acidity (pH) and conductivity (EC) of each mixed sample were determined. Refraction index (Brix index) of fruit sap was determined with a refractometer using juice clarified by centrifugation (4500 rpm for 5 min). The refraction index was recalculated to the percentage sucrose in the strawberry fruits.

Table 1. PAR transmission of several new developed plastic films containing different fluorescent pigments in different concentrations and average day and night temperatures (°C) measured under these films over the experimental period of 15th of May until 22nd of July 2002 and 7th of April until 2nd of July 2003.

Plastic film	PAR transmission	Difference in PAR transmission to Reference film	Red:Far-red ratio (655–665 nm: 725–735 nm)	Day temperature (°C)	Night temperature (°C)
Experiments 2002					
Reference	79.8 %		1.07	22.3	15.0
Blue-a	80.0 %	+0.2 %	1.08	22.8	15.0
Blue-b	80.5 %	+0.7 %	1.08	21.6	15.1
Red1-a	78.8 %	−1.1 %	1.08	22.2	15.0
Red1-b	79.2 %	−0.6 %	1.08	21.8	14.8
Red2-a	73.0 %	−6.8 %	1.07	22.4	14.9
Experiments 2003					
Reference	82.0 %		1.08	20.5	12.4
Blue-c	83.1 %	+1.1 %	1.08	21.4	13.7
Blue-b & Red1-a	81.4 %	−0.6 %	1.08	21.9	13.5
Red1-c	80.0 %	−2.0 %	1.08	21.6	13.7
Red2-c	80.8 %	−1.2 %	1.09	20.1	12.3
Red3	57.3 %	−24.7 %	1.17	21.3	13.6

In experiments in 2003, further analyses of strawberry plants were carried out. Total leave area per plant and total number of leaves per plant were measured of 10 plants per tunnel. Dry matter of these leaves was measured after 72 hours drying at 70 °C.

Results

Spectral transmission of greenhouse films

The spectral transmission of the newly developed fluorescent greenhouse films averaged over the PAR region (photosynthetically active radiation) of 400–700 nm is given in Table 1. Total PAR transmission of the experimental films in 2003 seemed to be improved towards the films produced in 2002. PAR transmission varied slightly between 78.8 % and 80.5 % in 2002 and between 80.0 % and 83.1 % in 2003. Exceptions were Red2 in 2002 and Red3 in 2003, which both showed a reduced PAR transmission compared to the Reference film.

The spectral transmission of the newly developed fluorescent greenhouse films is shown in Fig. 1. It can be observed that the blue pigments showed fluorescence between 410–480 nm, while maximum fluorescence of both Red1 and Red2 pigment was between 610–630 nm. Maximum fluorescence of the Red3 pigment was found between 600–690 nm, while major parts of the blue and green part of the spectrum were absorbed. In general, fluorescent effects were rising with increasing pigment concentration. All measured fluorescent effects were small. Effects of the Blue pigment were relatively higher than effects of the Red pigments.

The Blue fluorescent pigments slightly increased PAR radiation under the film and at the same time they also increased the amount of blue radiation with ca. 1–3 %. On the other hand Red fluorescent pigments lowered PAR transmission and simultaneously lowered red radiation. In other words, the amount of total PAR, which was absorbed by the pigment, was not transformed into the same amount of red radiation. There was no profit by adding the Red pigments concerning light quantity.

None of the pigments altered the red:far-red ratio (R:FR 655–665 nm:725–735 nm;) (Smith 1982), except the film containing Red3. This film increased the red:far-red ratio with almost 10 % (Table 1). The amount of UV (ultraviolet) radiation under the several films did not differ much, except Red3 absorbed most of the UV so only 13 % were transmitted.

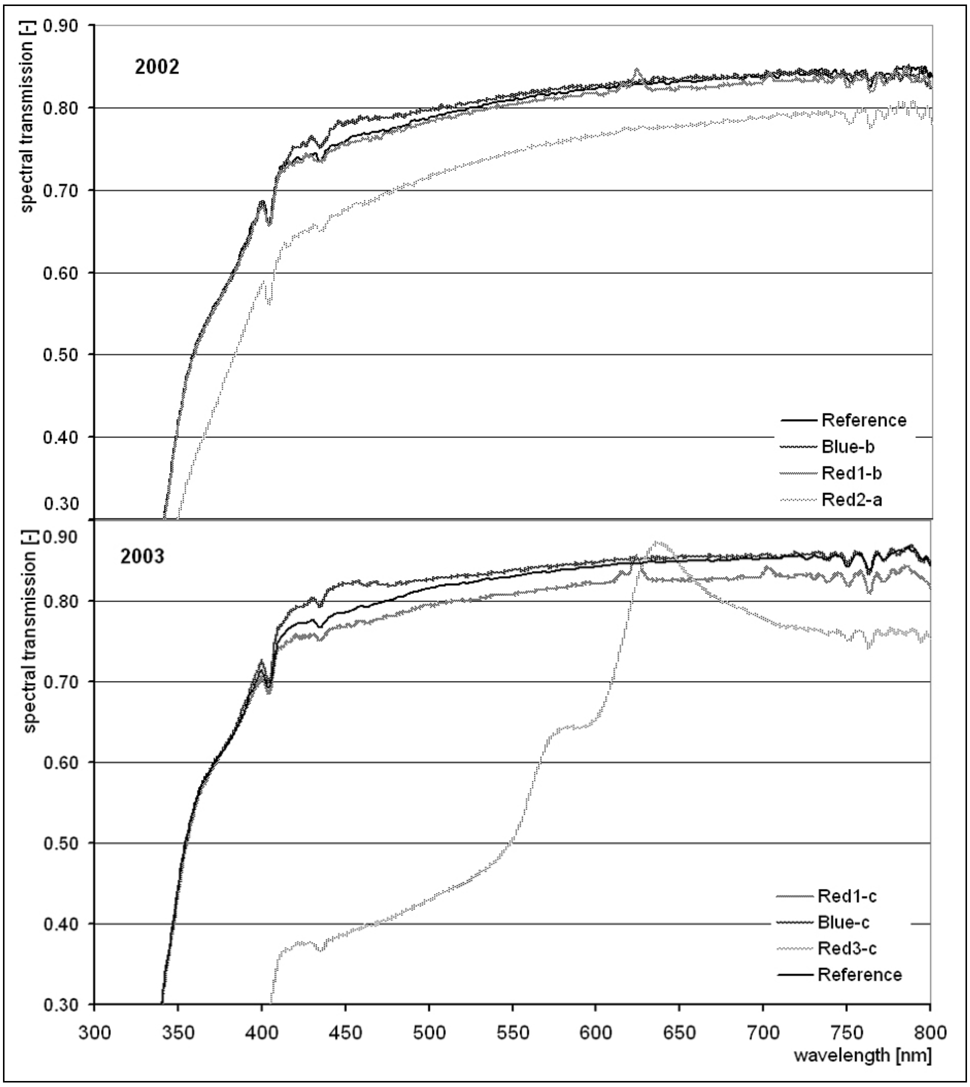

Fig. 1. Spectral transmission from 300–800 nm of some new developed fluorescent greenhouse films used in experiments in 2002 and 2003.

Table 2. Effect of fluorescent films on the total cumulative total fruit weight (g), total fruit number and mean fruit weight (g) of *Fragaria* x *ananassa* 'Elsanta' in 2002 and in 2003 (± standard deviation).

Pigment	Total fruit weight (g)	Total fruit number	Mean fruit weight (g)
Experiments 2002			
Reference	22332±325	2361±26	9.4±0.4
Blue-a	22848±226	2414±25	9.5±0.4
Blue-b	25390±281	2569±35	9.9±0.6
Red1-a	26296±283	2469±24	10.7±0.5
Red1-b	23260±473	2199±37	10.5±0.6
Red2-a	26331±208	2461±11	10.7±0.7
Experiments 2003			
Reference	28820±316	2188±32	13.2±0.6
Blue-c	31940±195	2447±15	13.4±1.0
Blue-b & Red1-a	29656±268	2357±23	12.6±0.6
Red1-c	26642±454	2129±39	12.5±0.5
Red2-c	29296±373	2369±31	12.4±0.5
Red3	25810±327	1906±25	13.6±0.5

The stability of the pigments differed. While Red3 showed strong migration effects, so that the life-time of the pigment was limited to two years, Blue and Red1 fluorescence pigment did not show any migration effects at any time of the trials even after 3000 h Xeno Test and 2000 h QUVA-Weather test assuming a very long lifetime.

Greenhouse climate

In Table 1 mean day and night temperatures averaged over the total period of the experiments in 2002 and in 2003 is given.

In experiments in 2002, mean day temperature was comparable for all 6 greenhouses. It is 0.5 °C higher under Blue-a than under the Reference, 0.7 °C lower under Blue-b and 0.5 °C lower under Red1-b than the Reference. Night temperatures were identical. Temperature inside the tunnels was approximately 4 °C higher than outside during daytime and 0.5 °C during night time.

In experiments in 2003, mean day temperature was 0.8–1.4 °C higher for Blue–c, Blue-b & Red1-a, Red1-c and Red3 than the Reference. It was 0.4 °C lower for Red2-c than the Reference. Temperatures during night times were also lower for the Reference and Red2-c compared to the other films.

Fruit production

Cumulative fruit weight, cumulative number of fruits and mean fruit weight of *Fragaria* x *ananassa* 'Elsanta' is given in Table 2.

In 2002, the number of fruits averaged for the Red films was approximately identical to the Reference film, whereas the Blue films increased the number of fruits produced with 5 % (Table 2). In time, mean fruit weight at the start of the fruit harvests was high, since the first fruits that were harvested were the top ones from a truss, which were significantly larger than the following fruits. Thereafter average fruit weight decreased gradually from approximately 10–12.5 to 5–7.5 g (data not shown). The mean fruit weight in 2002 was higher for Red films than for Blue films and the Reference film (Table 2).

Also in 2003, the newly developed fluorescent greenhouse films affected fruit production of *Fragaria* x *ananassa* 'Elsanta'. Cumulative fruit production was highest under Blue-c and lowest under Red3. In Fig. 2 cumulative fruit weight was shown for the whole harvesting period from 6 June until 7 July, when almost no fruits were left on the plants. Strawberry fruits under Red3 ripened later than under the Reference and under the other fluorescent films. However, fruit production under Red3 increased at the end of the harvesting period, so that total cumulative fruit weight was only 10 % less than under the Reference. Cumulative fruit weight was 8 % less under the Red1-c film, but 13 % higher under Blue-c than under the Reference film. Total fruit weight under Red2-c and the combination film Blue-b & Red1-a were comparable to the Reference film. The film containing Blue-b & Red1-a in 2003 combined the properties of the Blue and the Red1 film.

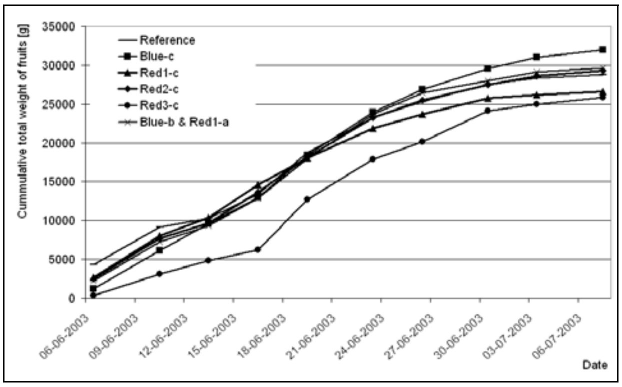

Fig. 2. Cumulative total weight of harvested fruits of *Fragaria* x *ananassa* 'Elsanta' grown under different fluorescent films in experiments in 2003.

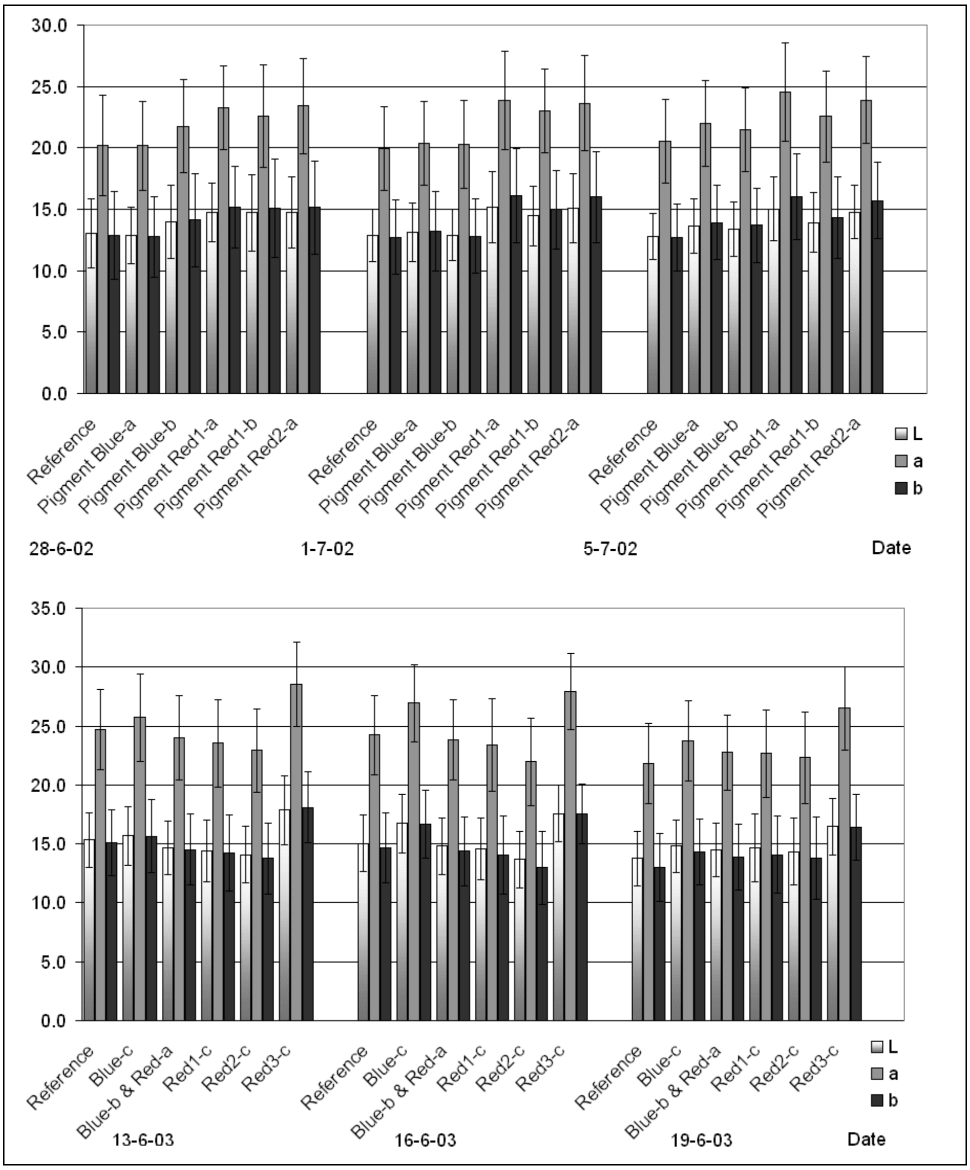

Fig. 3. Mean colour values and standard deviations in the L*a*b* space of *Fragaria* x *ananassa* 'Elsanta' fruits grown under different fluorescent greenhouse films in 2002 (figure above) and in 2003 (figure below) on three different harvesting dates.

As in 2002, cumulative number of fruits was increased by the Blue film with 8–12 %, whereas the number of fruits averaged for the Red films was comparable to the Reference film. Cumulative number of fruits was 13 % lower under Red3 compared to the Reference.

Mean fruit weight was higher in 2003 than in 2002. As in 2002, it varied during the harvesting period. While it was 20–23 g per fruit at the beginning, it dropped to 12.5–14.5 g per fruit in the middle of the harvesting period down to 4.5–9.0 g per fruit at the end (data not shown). Mean fruit weight was at the beginning of the harvesting period higher for the Red fluorescent films compared to the Reference and slightly higher for the Blue fluorescent film. In the middle of the harvesting period mean fruit weight was higher for the Blue fluorescent film and only slightly higher for the Red fluorescent films. At the end mean fruit weight was still high for Red3 but significantly smaller for the other Red fluorescent films compared to the Reference (data not shown).

Fruit quality differed between the fluorescent films. While the number of deformed fruits was highest under Red3, where in average 17 % of the fruits were deformed, under the other films only 6 12 % of the fruits was deformed.

Fruit quality

In order to compare colour measurements of fruits grown under the various films, the mean colour values of the 10 individual fruits per sample per harvesting date were calculated using the methods described before.

No significant differences in fruit colour could be observed by fruits grown under the different fluorescent greenhouse films. In tendency fruits grown under Red pigments showed at the beginning of the experiments in 2002 higher values in all three colour channels, in L* a* b* colour space compared to fruits that had grown under Blue pigments and the Reference. That means that fruits grown under Red pigments were slightly brighter but more saturated than the Reference fruits. Fruit colour under the Blue pigments and the Reference was darker but paler. Above all, this could be noticed on 1st and 5th of July 2002 (Fig. 3).

Table 3. Effect of fluorescent films on dry matter content, ash content and sucrose concentration of fruits of *Fragaria* x *ananassa* 'Elsanta' grown under films with different pigments (± standard deviation).

Pigment	Dry matter ($g\ kg^{-1}$)	Ash ($g\ kg^{-1}$) ($g\ kg^{-1}$)	Sucrose concentration (%)	EC ($mS\ cm^{-1}$)
Reference	82.2±3.2	4.1±0.8	8.4±0.3	3.6±0.3
Blue-a	84.4±1.6	3.5±0.9	8.5±0.2	3.2±0.4
Blue-b	80.0±3.2	3.2±0.7	8.1±0.4	3.1±0.5
Red1-a	77.8±3.2	3.1±0.7	7.9±0.4	3.0±0.4
Red1-b	80.1±1.4	5.2±1.2	8.3±0.2	3.8±0.2
Red2-a	79.6±1.8	3.9±1.3	8.2±0.3	3.3±0.3

Table 4. Effect of fluorescent plastic films on average number of leaves, total and mean leaf area and dry matter content of leaves of *Fragaria* x *ananassa* 'Elsanta' (± standard deviation).

Pigment	Number of leaves	Leaf area [cm^2]	Mean leaf area [cm^2]	Dry matter content [%]
Reference	18.2±4.4	3735±834	209.1±38.3	19.8±2.8
Pigment Blue-c	18.3±4.2	4029±853	222.6±28.5	21.0±2.3
Pigment Blue–b & Red1-a	19.4±6.3	3388±767	181.2±34.3	21.3±1.2
Pigment Red1-c	17.1±6.0	3257±702	200.3±38.0	21.7±1.4
Pigment Red2-c	16.5±5.9	3164±757	202.2±45.5	21.4±1.1
Pigment Red3-c	17.0±5.0	3767±934	227.7±49.6	18.3±2.7

In 2003, again no significant differences in fruit colour could be observed. It can be noticed that fruits grown under the Red3 pigment showed at the beginning of the experiments in tendency higher values than the Reference in all of the 3 channels, but mainly in the a* channel, which represents a more saturated red colour. On most harvesting dates, the fruits grown under the Blue pigment also showed a light increment in colour intensity compared to the Reference.

In general, fruits that had grown under the Red3 pigment were brighter but more saturated than the Reference fruits, fruit colour under the Blue pigment was also slightly brighter but more saturated and fruits grown under the Reference were darker but paler. Above all, this could be noticed on 13th, 16th and 19th of July 2003.

In 2002, dry matter, ash content, sucrose concentration, electric conductivity and pH of fruit sap were determined on fruits at 6 dates of harvest. Dry matter and ash content were found to be approximately constant in time (data not shown). Since standard deviation was high no differences in dry matter and ash content were observed (Table 3). Electric conductivity of the fruit sap decreased slightly in time. In tendency fruits grown under the Blue film seemed to have a lower EC than the average of fruits grown under Red films (Table 3). Sucrose concentration is a major part of the sweet taste of strawberry fruits, and therefore an important quality characteristic. Sucrose content was found to remain approximately constant in time (data not shown). No significant differences in sucrose content were found (Table 3). PH of the fruit sap was found to increase slightly in time. In tendency fruits grown under Blue films were found to be more acid than fruits grown under the Red or Reference films.

The ratio of sweetness (sugar) to sourness (acid) is an important quality trait of strawberry fruits. Therefore, the sucrose data (%) were related to the pH results. Since sucrose concentrations did not differ between the different films and the fact that fruits grown under Blue films were more acid causes the sweetness to sourness ratio of fruits grown under Blue films to be slightly lower and of those grown under Red films to be slightly higher than under the Reference film.]

Vegetative growth

In Table 4 the effect of fluorescent plastic films on several vegetative growth parameters of strawberries was described. Number of leaves, total leaf area, mean leaf area and dry matter content of leaves did not differ significantly.

Discussion

Photoselective films

In the experiments as described in this report, the effect of fluorescent films on fruit production and quality of *Fragaria* x *ananassa* 'Elsanta' is determined. The assumption before the start of the experiment was that the films would not differ in transmission for PAR radiation, but only in the spectral composition of the light within the tunnel. However, transmission of the films for PAR radiation is found to differ. For experiments carried out in 2002 the transmission of the Reference film, Blue films and Red1 films varies between 79.2 and 80.2 %, but

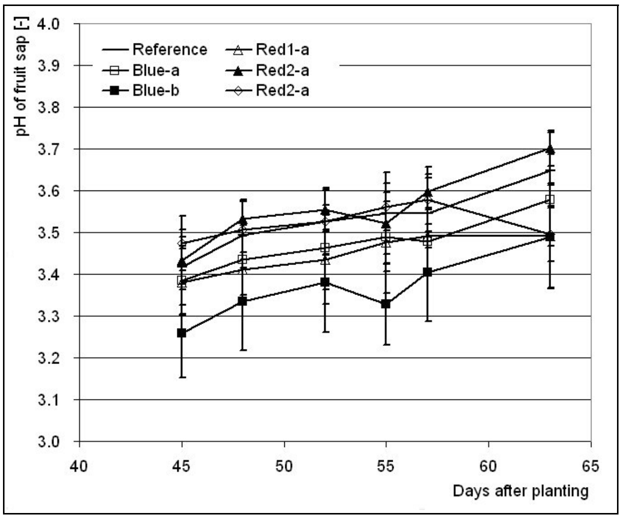

Fig. 4. Evolution of pH of fruit sap of *Fragaria* x *ananassa* 'Elsanta' grown under different fluorescent greenhouse films in 2002 (mean values ± standard deviation).

transmission of the Red 2 film is found to be only 73.0 %. Differences are even higher for experiments carried out in 2003. The PAR transmission of the Reference film, Blue, Red1, Red2 and Blue & Red1 films varies between 80.0 % and 83.1 %, transmission of Red3 is found to be only 57.3 %.

Furthermore, the transmission data show disturbances in the production process of the films. Total PAR transmission is low compared to commercial films and pigments within the prototype films are not uniformly distributed.

In the past several fluorescent films were developed. Some fluorescence pigments absorb parts of the green radiation and emit it again in the form of red radiation. Such fluorescence pigments were inserted in PVC plastic films (Zarka and Zarka 1985) and in PE plastic films. However, the fluorescent property disappeared after 6–8 months. Some vegetables and some cut flowers showed a 5–10 % increase of yield under these films under the high light intensity in Israel (Zarka and Zarka 1985). Both Pearson et al. (1995) and Kittas and Baille (1998) point out that the transmission of PAR of those films is reduced compared to standard polyethylene films. Recently films are developed, which absorb parts of the ultraviolet, blue and green region of the spectrum. González et al. (2003) investigated those films. One film is comparable to Red3. They found the same reduction in PAR transmission as in the measurements described here.

Some fluorescence pigments also absorb ultraviolet radiation and emit it in the form of visible light, comparable to the pigments investigated in the experiments described here. Pearson et al. (1995) investigated two UV-fluorescent films. They found no fluorescent effect in one film a slightly increased light transmission in the other. These results are in line with our measurement results of spectral transmission described here.

It has to be considered that the increase in PAR is dependent on the amount of pigment in the polymer and the amount of UV in global radiation. In winter on average <1 W m^{-2} UV-B and ca.7 W m^{-2} UV-A are available in Middle European Countries by an average global radiation of ca. 100 W m^{-2}. In summer the average amount of UV radiation rises up to 2 W m^{-2} UV-B and ca. 40 W m^{-2} UV-A by an average global radiation of 600 W m^{-2} (Cie 85 1989). So the potential of fluorescent effects is limited. Fluorescent effects are enlarged by increased pigment concentrations. We can conclude from our measurements and experiments that total PAR transmission can be increased by some pigments (Blue pigments) by 1 to 3 %, while other pigments absorb more light than they emit again in the PAR region of the spectrum (Red pigments). Due to small changes in total PAR transmission also effects on plant growth due to changes in photosynthetic activity can be expected to be small.

In our measurements we only found small changes in light quality under the different new developed greenhouse films. Only the film containing Red3 pigment increased the red:far-red ratio with ca. 10 %. Due to minor changes in light quality under the films photomorphogenetic effects can also be expected to be small.

Fruit production

In general, a higher fruit production of *Fragaria* x *ananassa* 'Elsanta' could be observed in experiments carried out in 2003 than in 2002. However, cumulative number of fruits produced is slightly lower in 2003. So higher production is due to an increased mean fruit weight, which is about 10 g in 2002 and about 13 g in 2003. This could be due to a higher temperature sum or a higher irradiation sum during the cropping period. Avigdori-Avidov (1986) found that average fruit weight is inversely proportional to the temperature during the day, whereas night temperature had no effect (Avigdori-Avidov 1986). However, in our experiments average day temperature is only 1–2 °C lower in 2003 than in 2002, whereas night temperatures are in average 2–3°C lower. So we conclude that also night temperatures contributed to the higher mean fruit weight in 2003. Wang and Camp (2000) found that strawberry fruit production is in general positively affected by temperatures that do not exceed 18/12°C day/night.

Experiments in 2003 are also characterized by a longer production period. While the last harvesting took place 91 days after planting in 2003, it was only 73 days in 2002, though the harvesting period in 2003 is 2 weeks shorter than in 2002. This is probably due to temperature effects. In 2003, strawberries are planted begin of April when outside temperatures were low, so total cropping period is delayed, compared to 2002 when strawberries are planted in May with higher outside temperatures. These results are comparable to Le Miere et al. (1998), who showed that cropping duration of *Fragaria* x *ananassa* 'Elsanta' is longer when plants are grown at low temperatures.

In 2002, total fruit weight of *Fragaria* x *ananassa* 'Elsanta' under the plastic films containing the pigments Blue-b or Red1-a is increased compared to the Reference film. Whereas fruit production under Blue–a and Red1-b is comparable to the Reference film. This tendency can also be found in 2003, when fruit production is increased by Blue-c but reduced by Red1-c. It seems that in tendency a higher concentration of the Blue pigment has a positive influence on strawberry fruit production and the higher concentration of the Red1 pigment has a negative influence. From our experiments it cannot be distinguished whether this is due to light quantity or light quality effects since both total light transmission and light quality are changed by the different prototype films. We assume that the higher yield under the Blue films with raising pigment concentration is due to an increased total PAR transmission compared to the respective Reference film. Also FLETCHER et al. (2002) found strawberry yield to be highest under plastic films with high light transmission. They found cumulative fruit number and fruit fresh weight to be increased with increased PAR transmission of the films. Plants grown under lower light transmission films produced the lowest fruit fresh weight per plant (FLETCHER et al. 2002). AWANG and ATHERTON (1995) found additionally a reduction in marketable fruit of strawberries under low light conditions. In our experiments Blue fluorescent films with a higher PAR transmission increased the number of fruits produced, while the Red1 fluorescent film with a lower PAR transmission slightly reduces the number of fruits. Apparently a high PAR transmission and a blue enriched environment seem to increase strawberry fruit production.

If total PAR transmission and red:far-red ratio of a film is low, fruit production of *Fragaria* x *ananassa* 'Elsanta' is significantly delayed. This is shown for plants grown under Red3 in 2003. The results are consistent to the results of FLETCHER et al. (2002), who found cropping duration to be affected by a changed light quality under photoselective plastic films. Films with high red:far-red ratio delayed cropping duration significantly. In our experiments fruit production accelerates towards the end of the experiment, though, so that total fruit production in kg is only 10 % less than under the Reference, while it is 70 % less at the beginning of the harvesting period. The same tendency could be seen by the low transmission film Red2-a in 2002. While strawberry fruit production is 70 % less at the beginning of the harvesting period, it is even higher at the end compared to the Reference.

Fruit quality

Fruit quality is determined by appearance (colour, size, shape, absence of physiological disorders and decay), flavour, firmness, texture, dry matter and organoleptic properties (balance between sweetness (sugars) and sourness (acids) (MONTERO et al. 1996; DORAIS et al. 2001). In the experiments described here, some of the quality traits were determined.

FLETCHER et al. (2002) showed that films with high light diffusing properties result in higher fruit quality due to higher light interception. The films used in the experiments described here all had light diffusing properties. In 2002, more fruits grown under the Red fluorescent films with a lower light transmission are classified in class A and B and less are classified in class C compared to the Reference. Again this is not found in 2003 when the percentage of marketable fruits (class A and B) is comparable under all films. Only fruits grown under Red3 are less classified in class C. Apparently the lower light transmission seems to improve fruit classification. This is in contrast with AWANG and ATHERTON (1995), who found a reduction in marketable fruit of strawberries under low light conditions. In our experiments total marketable fruit under Red3 is decreased since the number of deformed fruit was higher. Since it is observed that bees fly worse in the greenhouse tunnel covered with Red3, the increased number of deformed fruit may have been caused by a bad orientation of bees under this film. Red3 transmits almost no UV and less blue radiation so that bees are disorientated and are not able to pollinate the strawberry flowers sufficiently, which can lead to fruit deformations. The disorientation of insects is described by many authors.

Fruit colour is determined. No significant differences could be found. In 2003, *Fragaria* x *ananassa* 'Elsanta' fruits grown under the Red3 fluorescent pigment are in tendency brighter but more saturated than the Reference fruits, fruit colour under the Blue fluorescent pigment is also slightly brighter but more saturated and fruits grown under the Reference were darker but paler. In 2002 additionally strawberry fruits are found to be brighter and have a more saturated red colour, if they are grown under the other Red fluorescent films compared to the Reference. This could not be observed in 2003.

Furthermore, dry matter and ash content of the fruits are determined, as well as the electric conductivity and sucrose percentage of the fruit sap. In general, no significant differences in fruit quality of fruits grown under the Blue, Red or Reference films could be detected. Fruits grown under Blue films are found to be slightly more acid than fruits grown under the Reference film, while fruits grown under Red films are found to be slightly less acid. In general, sweetness to sourness ratio is used as a quality index (MONTERO et al. 1996). AVALOINE and CROCHON (1989) showed that the refractrometric index seems to fairly correlate with the taste quality. Given that sucrose concentrations hardly differ between the different films, the acidity results indicate that fruits grown under Blue films taste less sweet than fruits grown under the Reference.

Vegetative growth

Number of leaves, total leaf area, mean leaf area and dry matter content of leaves do not differ significantly. There is no correlation between vegetative growth parameters and fruit production. This was also found by FLETCHER et al. (2002).

From these investigations it can be concluded that new developed greenhouse films containing blue fluorescent pigments have good potentials to affect growth and development of *Fragaria* x *ananassa* 'Elsanta' positively.

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