Light Use Efficiency at Different Wavelengths in Rose Plants

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Abstract

Current knowledge about the spectral dependence of leaf light use efficiency of leaf photosynthesis (LUE; rate of leaf photosynthesis per unit incident light energy) is based on investigations of mostly arable crops. The leaf LUE depends on the optical properties of the leaf (light absorption), on the fraction of light energy absorbed by photosynthetically active pigments and on the excitation balance of the two photosystems. These properties have hardly been investigated on modern vegetable and especially ornamental greenhouse crops. In this research we investigated the action spectrum of leaf photosynthesis and related leaf optical properties of reddish young leaves and green middle aged leaves of rose 'Akito'. The crop was grown in a heated greenhouse in Wageningen (The Netherlands, latitude 52°N). The green and reddish leaves had similar total absorptance of 87% on average in the PAR range (400 to 700 nm). In the green leaves, however, leaf absorptance around 550 nm was lower than in the reddish leaves, but slightly higher at longer wavelengths. Red light of 680 nm was found to be the most effective for leaf photosynthesis in the short term. Leaf LUEs were calculated for supplemental light by HPS and 645 and 680 nm LEDs based on their emission spectra and the measured action spectra of leaf photosynthesis. These calculations showed that a 645 nm LED light yielded more improvement in LUE compared to HPS light than 680 nm LED light. This is because the 680 nm LED also emits light >700 nm at which the LUE is much lower. If these calculated improvements in leaf LUE for red LED-light compared to HPS-light are sustained at the crop level during prolonged illumination, substantial energy savings may be realized in rose by supplemental lighting with red LED light.

INTRODUCTION

In many greenhouse crops (e.g., rose), supplemental lighting is often used in northern countries during fall and winter. The lighting enhances plant growth which results in year round high production and good quality. This practice is, however, relatively expensive and the most common lighting systems (High Pressure Sodium - HPS lamps) may neither spectrally nor energetically be optimal (Heuvelink et al., 2006; Marcelis et al., 2006).

Recently, commercial growers have started experiments with Light Emitting Diodes (LEDs) for supplemental lighting. Lighting systems based on LEDs have a variety of advantages over traditional systems of lighting in horticulture: small size, long lifetime,

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low heat emission and potentially a high energy conversion efficiency in near future (Massa et al., 2008; van Ieperen et al., 2008). Narrow-band lighting devices are available in several colours, giving the opportunity to select the light spectrum that is photosynthetically the most favourable for the crop. Selection of an LED type that combines both efficient LED operation and efficient photosynthesis of the crop requires that more information is needed about the spectral dependence of photosynthesis and leaf acclimation to different spectra (Hogewoning et al., 2007).

Current knowledge about spectral dependence of photosynthesis in higher plants is mainly based on early observations on arable crops (Balegh and Biddulph, 1970; McCree, 1971/1972; Inada, 1976, 1977; Evans, 1987). The action spectrum of photosynthesis (expressed as µmol of CO_2 per mJ of incident light) and the spectral quantum yield (µmol of CO_2 per µmol absorbed photons) have hardly been investigated in ornamentals and only on a small selection of greenhouse vegetables. Furthermore, little is known on the effects of growth conditions and leaf ontogeny on these parameters in greenhouse crops. Moreover most experiments were carried out on (parts of) cut leaves, while only a few studies have been performed on intact leaves (e.g., Balegh and Biddulph, 1970).

Potential benefits of this knowledge are optimization of the spectral energy distribution of lamps (Brazaitytė et al., 2006; Moore et al., 2006), optimizing lighting strategies and reducing energy inputs. Note that, however, these studies only provide information on instantaneous spectral effects on photosynthesis. Spectral effects of long-term illumination on leaf functioning and LUE also do need to be unravelled, in order to be able to optimize the plant-growth spectrum in practice. The aim of this research was to investigate the action spectrum of leaf photosynthesis in a modern rose cultivar grown in a modern greenhouse. The source leaves included young leaves with red pigments and green middle-aged leaves of upright shoots.

MATERIALS AND METHODS

Plant Material and Growth Conditions

The experiment was carried out in Wageningen (the Netherlands, latitude 52°N) in July 2008. Rose plants ‘Akito’ were grown on rockwool slabs, in a heated experimental greenhouse (transplant February 2008), in double rows, at a plant density of 6.5 plants m^{-2}. Water and fertilizers were supplied via a drip-system, automatically controlled by a fertigation computer.

The night temperature inside the greenhouse was 17.2 to 21.5°C (set point: 18°C) while the day temperature was between 23.7 and 34.9°C. Relative humidity was kept around 70% and the CO_2 concentration around 500 ppm. Supplemental lighting by High Pressure Sodium lamps (Philips 600 W) provided a minimum photon flux density of 150 µmol m^{-2} s^{-1} at the crop level extending the natural day length to 16 hours (3:00 till 19:00).

Photosynthesis, transmission and reflection measurements were carried out on 6 plants, placed in a climate chamber 1 to 2 days prior to the measurements, at the following conditions: day/night temperature 20/18°C, photon flux density 100 µmol m^{-2} s^{-1} (Philips TLD 50 W 840 HF), 16 hours long day, relative humidity 65% and ambient CO_2 concentration.

Photosynthesis and Leaf Optical Properties

The following types of leaves were compared: i) leaves with red pigments (2^{nd} to 5^{th} leaf from the top of the stem), and ii) green leaves (5^{th} to 8^{th} leaf from the top of the stem). All leaves were penta-foliate and fully expanded from stems with 13 to 16 leaves, in the vegetative stage or with a barely visible flower bud.

Photosynthesis measurements were done on the top leaflet with a LICOR 7000 (CO_2/H_2O gas analyzer) connected to a custom made leaf chamber (area: 4.52 cm^2). The conditions inside the leaf chamber were kept constant (temperature 26°C, CO_2 concentration 380 ppm, O_2 concentration 2%, RH 72%, air flow rate 204 µmol s^{-1}).

Photosynthesis was measured at 18 wavelengths in the interval 406-740 nm. The leaf was illuminated by two custom 250 W halogen light-sources via a 4-armed fiber optics light guide. Continuous white background light (40 µmol m^{-2} s^{-1}) was provided by lamp 1, of which the halogen spectrum was filtered with a heat filter and a filter which converts tungsten to day-light (Lee filters, Hampshire, UK). Narrow band light was obtained by placing a narrow band interference filter between lamp 2 and an arm of the fiber optics. The light from the two light-sources was projected fully mixed on the leaf surface. At each wavelength, photosynthesis was measured at background light plus 0, 30 or 60 µmol m^{-2} s^{-1} narrow band light, after a 3-min exposure to 100 µmol m^{-2} s^{-1} of white light. Using the calculated net photosynthesis data, the quantum efficiency for CO_2 fixation was calculated by linear fitting of the incident light-net CO_2 fixation relationship. All values are expressed as a fraction of the maximum value (varied between 640 and 680 nm).

After the photosynthesis measurements the top leaflet was removed from the plant and leaf transmission (Tr) and reflection (Ref) spectra were measured (between 400 and 740 nm) with a spectrophotometer (Perkin Elmer Lambda 950 UV/NIR). For transmission measurements, the leaf was clamped to the input port of the integrating sphere with the bottom facing the sphere. For reflection measurements, the leaf was clamped to the exit port with the upper side facing the integrating sphere. In all measurements the leaves were illuminated from the top (adaxial) side and the direction of the collimated light was perpendicular to the leaf plane. Measurements were randomly carried out on leaves of 4 different plants per developmental stage (green or red). Leaf absorption (Abs) at the used wavelengths was calculated as Abs=100-(Ref+Tr). Details of the photosynthesis measurement procedure will be published elsewhere (Hogewoning et al., in preparation).

In order to calculate the potential short-term differences in Light Use Efficiency (LUE; rate of leaf photosynthesis per unit incident light energy), in terms of photosynthesis under different light sources, the normalized spectral power of three types of commercial lamps (HPS: Philips Green Power 600W-400V; LED 645 nm: Roithner LED type 645-66-60; LED 680 nm: Roithner LED type 680-66-60) were multiplied with the light use efficiency (LUE) at each light source wavelength. The LUE at a given light source wavelength was calculated from the LUE data by linear interpolation.

RESULTS

The green and red leaves had a similar total (400-700 nm) leaf absorption of 88% on average, but they showed some differences in the different bands (data not shown). Green leaves showed higher values of transmission and reflection than young red leaves between 520 and 560 nm. As a consequence, absorption of green leaves was lower than that of red leaves in this region (72.1 vs. 77.1% on average in the range 520-560 nm), but slightly higher at longer wavelength.

In both green and red leaves, the LUE showed a broad plateau in the blue and the green regions (Fig. 1). From there LUE increased with wavelength and reached the highest values under red light with a maximum near 680 nm, then it declined rapidly above 680 nm, with hardly any photosynthesis at 740 nm.

The average LUE was not significantly different in the green and young red leaves. Small differences were found at green light (520-560 nm), with the higher LUE values in the green leaves (Fig. 1).

The spectral distribution differed distinctly for the different lamps used in the calculations on short-term spectral effects on LUE (Fig. 2). The most conspicuous difference is the broader spectral distribution of the HPS lamp compared to the LEDs. The HPS lamp has the highest light output in the green, yellow and orange regions and very low levels in the blue, red and far red bands.

Based on the LUEs recorded at the different wavelengths and the spectral distribution of the lamps, the LUE of the lamp/leaf combination was calculated (Table 1). With HPS light (used for the supplemental lighting in our greenhouse) the red leaves reached a lower LUE than the green ones. Both types of LED light yielded a higher LUE compared to HPS, independent of the leaf type. The 645 nm LED showed a higher calculated LUE than the 680 nm LED at leaf level.

DISCUSSION AND CONCLUSIONS

In this research we evaluated the spectral dependence of leaf reflection, transmission and photosynthesis in intact rose leaves differing in developmental stage.

Both red and green leaves of rose 'Akito' absorb more than 90% of the incident radiation in the violet and blue regions and from 80 to 90% in the orange and red light. It is known for most plant species that almost all of this absorption is due to the chloroplast pigments (Gates et al., 1965).

The young red and green leaves differed in the optical properties, particularly in the green region of the spectrum. Normally, leaf absorption in the green waveband is lower in pale than in dark green leaves (Inada, 1977). Similar to our results in red leaves, purple leaves of flowering kale and perilla had a higher absorption and a lower photosynthesis efficiency in the green region (Inada, 1977). This was attributed to a higher content of anthocyanins. These pigments absorb light energy but do not contribute to photosynthesis (Salisbury and Ross, 1992).

In terms of photosynthesis, in the short term red light is the most effective in rose 'Akito' in both mature green and young red leaves. Previous papers showed similar action spectra for a number of species (McCree, 1971/1972; Inada, 1976). Particularly, the comparison of our results to the relative action spectrum of the "average plant" (from 20 plant species grown in growth chamber; McCree 1971/1972) showed similar values in the blue and deep red bands, but a distinct difference in the 540-640 nm region The relative LUE in this region was 0.68 in our studies on rose leaves, while the average value of McCree (1971/1972) was 0.78 (525-650 nm).

Common strategies of artificial lighting in greenhouse are frequently based on the "rule of thumb" that a 1% increment of light results in a 1% yield increase at the crop level. Recent studies demonstrate that for most greenhouse crops a 1% increment of light results in a 0.5 to 1% increase in harvestable product, with a tendency to a smaller and more variable effect in cut flowers and pot plants (Marcelis et al., 2006). This "rule of thumb" does not take into account several internal physiological and external environmental factors at the leaf level: leaf photosynthesis saturates at high light, shows acclimation to the light level and is dependent on e.g., leaf age and position in the canopy; local environmental conditions, e.g., CO_2 concentration, temperature also affect leaf photosynthesis (Demitriades-Shah et al., 1994).

The results of the effect of different wavelengths on the instantaneous LUE at leaf level presented in this paper suggest a significant potential beneficial effect of optimizing the spectral output of assimilation light sources in rose at the crop level. Whether this in practise will result in comparable benefits depends on the extent at which the short-term effects on leaf photosynthesis will sustain on the long term and how differences in spectral distribution of assimilation light applied by LEDs further influence crop physiology and morphology on the long term. These factors were not taken into account in the present research and may affect photosynthesis on crop level.

It is known that light quality affects morphogenesis and overall appearance of rose plants. For instance, an increased red/far red ratio reduced plant height while leaf chlorophyll content (McMahon and Kelly, 1990) and the number of flowers (Roberts et al., 1993) increased. These effects are probably phytochrome-mediated, as are lateral branching in other species (Mortensen and Stromme, 1987). In this respect, further investigations are needed in order to evaluate potential spectral effects on more factors than photosynthesis alone.

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Tables

Table 1. Calculated relative light use efficiency in the short-term (<1 hour) on a single leaf layer (photosynthesis per incident light energy) as a function of the lamp type (HPS: Philips Green Power 400W; LED 645 nm: Roithner LED type 645-66-60; LED 680nm: Roithner LED type 680-66-60) and the leaf developmental stage (green and red).

Lamp type	Light use efficiency (%)	
	Green leaf	Red leaf
HPS	100	96
LED 645 nm	136	136
LED 680 nm	128	126

Figures

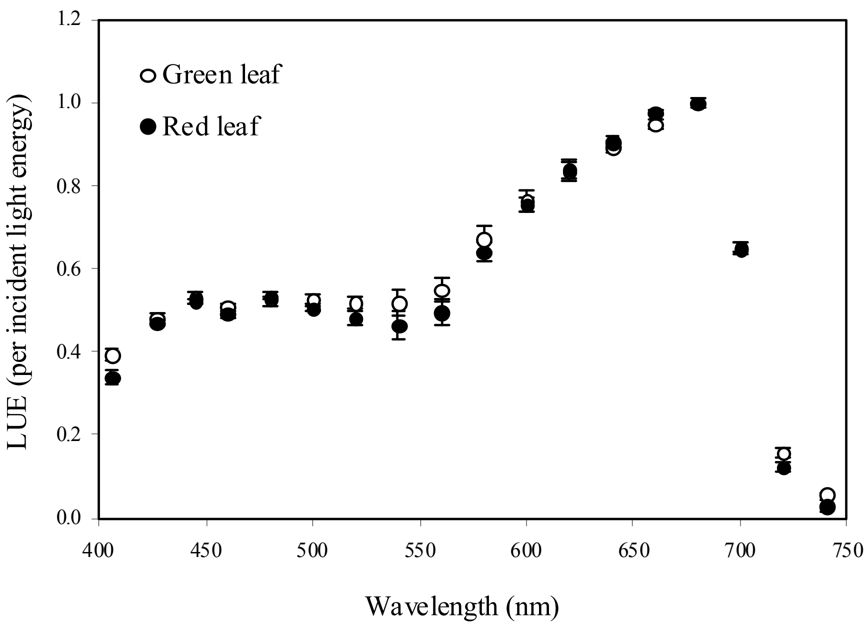

Fig. 1. Measured light use efficiency spectra (photosynthesis per unit of incident light energy) in green and red leaves of rose ‘Akito’ (relative values; n=4; Average± s.e.m.).

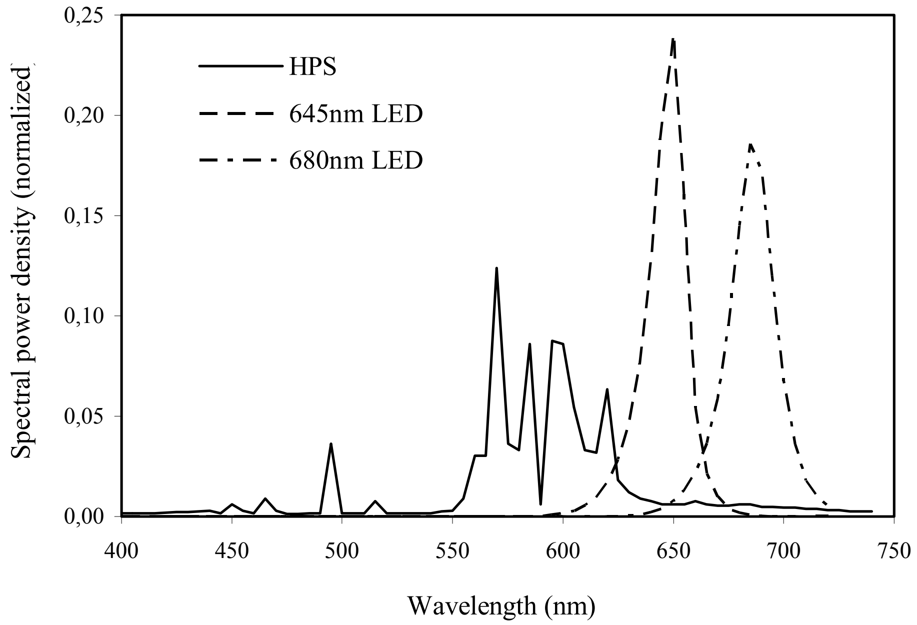

Fig. 2. Normalized power density spectra (in W m^{-2} nm^{-1}) as a function of the lamp type (HPS: Philips Green Power 400W; 645nm LED: Roithner LED type 645-66-60; 680nm LED: Roithner LED type 680-66-60).