

# Diffuse Greenhouse Covering Materials – Material Technology, Measurements and Evaluation of Optical Properties

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## Abstract

At high irradiation levels, diffuse greenhouse coverings result in better light distribution, lower crop temperature, decreased transpiration, and increased photosynthesis and growth. Various greenhouse coverings (plastic films, glass panes and temporal coatings) can be used to transform direct light into diffuse light. However, light diffusing properties of materials are hardly known. Optical properties of a wide range of materials are being currently investigated, including direct light transmission under different angles of incidence, transmission for hemispherical light and haze. The potential of diffusing greenhouse covering materials is estimated by analyzing the global radiation data for different climatic regions: marine winter climate (The Netherlands), Mediterranean mild winter climate (Italy) and semi-arid climate (Arizona). The required optical properties differ for the various climates. With modern material technology, the optical properties (haze and light transmission) can be altered to meet the requirements for different climatic regions in order to optimize crop performance in the future.

## INTRODUCTION

Diffuse light is able to penetrate deeper into a plant canopy in comparison to direct light (Farquhar and Roderick, 2003; Gu et al., 2003). Hemming et al. (2006, 2008a), demonstrated production increases of 8–10% for greenhouse cucumber by applying diffusing materials, indicating the advantages of diffusing natural light in greenhouses.

Various greenhouse coverings (plastic films, glass, temporal coatings) can be used to transform direct light into diffuse light. However, light diffusing properties of materials are hardly known. Optical properties of traditional, non-diffusing covering materials were published by, Giacomelli and Roberts (1993), Kittas and Baille (1998), Papadakis et al. (2000), Waaijenberg et al. (2004). In the present paper, the possibilities to improve diffusing materials were investigated. In addition, the potential of diffusing greenhouse covering materials in various climates is estimated by analyzing the global radiation data for different regions: marine winter climate (The Netherlands), Mediterranean climate (Italy) and semi-arid climate (Arizona).

## MATERIALS AND METHODS

The global radiation data for The Netherlands and Italy were extracted from the SEL-year (Breuer and Van de Braak, 1989) and University of Bari data (Hemming et al., 2008b), respectively. The diffuse radiation was calculated from the ratio between the measured global radiation and maximum theoretical global radiation at a special moment for the given location (de Jong, 1980). The data for Tucson, Arizona were extracted from Kania and Giacomelli (2008). A conversion factor of 2.3 was used to transform  $\text{mol m}^{-2}$  PAR to  $\text{J m}^{-2}$  global radiation (McCree, 1981).

The optical properties of different light diffusing materials were also investigated. The total transmission for photosynthetic active radiation ( $\tau_{\text{PAR}}$  400–700 nm) was measured on large samples of 0.5 by 0.5 m materials using a large integrating sphere (radius 1 m and opening of 0.4 m diameter), coated on the inside with barium sulphate

(Fig. 1). A halogen lamp light bundle perpendicular to the sample was used as direct light source to determine PAR transmission for perpendicular light, at  $0^\circ$  incident angle ( $\tau_p$ ). The PAR transmission for hemispherical light, diffuse incident light ( $\tau_h$ ) was determined by illuminating a hemispherical sphere as a sky vault above the large integrating sphere (Fig. 1). Data were gathered by means of a diode-array spectrophotometer, with a resolution of 1 nm. Haze ( $\eta_{PAR}$ ) as the percentage of scattered PAR, following ASTM D1003, was measured in 0.1 by 0.1 m material samples with a small integrating sphere (0.5 m radius and 0.1 m diameter opening) (Fig. 2) using a xenon lamp as a direct light source in the range of 300–1100 nm.

## RESULTS AND DISCUSSION

### Natural Light Conditions in Different Climates

The natural radiation regime has to be known in order to estimate the potentials of diffuse greenhouse covering materials. Three different climatic regions are considered: the marine winter climate of The Netherlands, the Mediterranean mild winter climate of Southern Italy, and the semi-arid climate of Arizona. Their radiation characteristics given in Table 1 differ especially in the annual irradiation, the differences between winter and summer and in the direct and diffuse components. Hemming et al. (2008a) showed that cucumber production could be potentially increased by 8–10% under a diffuse covering material (50% haze). This result was realised in The Netherlands with about 1080 MJ m<sup>-2</sup> direct radiation sum (20–40% of total radiation) (Table 1). In mild winter climates the direct radiation sum would be 3000 MJ m<sup>-2</sup> (40–60% of total radiation), and in semi-arid climates even 5200 MJ m<sup>-2</sup> (70–85% of total radiation); so diffusing covering materials have high potentials in those regions. Moreover, the aspect of light loss is less important for climates with less variation in radiation throughout the year, since in The Netherlands summer to winter irradiation ratio is 10, while this ratio is only 3.5 for the Mediterranean region or 2.5 for Arizona as can be deduced from Table 1.

### Measurement Methodology

Many diffusing covering materials are available. When judging the optical properties of the materials, two factors are especially important: the light diffusing property (haze) and the light transmission for photosynthetic active radiation (PAR 400–700 nm). Often the international norm ASTM D1003-07 is used to determine the haze of a material. For light transmission, all available norms (e.g., EN410, DIN 5036-3, NEN 2675) describe the light transmission for perpendicular light. Since perpendicular light almost never occurs on greenhouse roofs, hemispherical light transmission is more appropriate to characterise a covering material as it correlates well with the average light transmission of a covering under practical conditions inside the greenhouse. This was demonstrated with the light transmission of the films F-Clean clear and F-Clean diffuse, which we measured in the lab and in two greenhouses covered with these films. The measured perpendicular light transmission of both materials in the lab is about 93%, the hemispherical light transmission differs by 5%, in favour of F-Clean clear (Table 2). Measuring the light transmission in the greenhouse, the difference is again 5% (Fig. 3). Therefore we can conclude that the hemispherical light transmission  $\tau_h$  is the most appropriate factor for characterising transmission of greenhouse covering materials.

### Light Diffusing Covering Materials

Measurements of the haze  $\eta$  and the hemispherical light transmission  $\tau_h$  were carried out for a great number of clear and diffusing coverings (Table 2). Standard greenhouse glass has almost no haze, whereas clear plastic films (e.g., Rovero Solar EVA 5 clear) show already a haze of 25–30%. Only the AGC F-Clean clear film has a haze lower than 10%. Haze and light losses are dependent on the addition of pigments or on surface structure. For example, the diffuse glasses Centrosol diffuse and Centrosol HiT have an irregular wavy microstructure on the surface. Both show a small haze of about

13%. Hogla/Vetrad Vetrasol 502, 504 and AGE/Glaverbel Glamatt diffuse also have an irregular wavy microstructure, with a relatively low haze and minor light loss. On the other hand, the sandblasted or chemical treated glass V&V diffuse and AGE/Glaverbel Crepi diffuse show higher light diffusion, but higher light losses as well. The same surface structure can be observed with the AGC F-Clean diffuse film. Since the initial light transmission is very high, the light loss is relatively low compared to regular greenhouse glass. With all AGE/Glaverbel and Hogla/Vetrad glasses we can observe that a higher haze results in a higher light loss. Vetrasol 503 seems to show the best performance since it combines a very high haze of 74% with a relatively high hemispherical light transmission of about 80%. This is realised with a micro-pyramided surface structure. Another positive example is Centrosol HiT; it has a 6% higher light transmission since the surface is additionally coated with a nanostructure resulting in an anti-reflection effect. This technology should be used on other surface structures as well to reach a high haze simultaneously with increased light transmission.

Haze and light loss seem to be connected (Fig. 4). Material development is necessary to combine high haze and high hemispherical light transmission. Regular surface structures and additional nano-coatings seem to have potentials.

Temporal diffusing coatings during high irradiation periods are also being applied. Traditional white wash coating reduces light intensity on cloudy days with low irradiation level as well. The currently developed Hermadix temporal coating at low concentration (1:7) (Table 2) shows a high haze when dry and a low haze when wet. Thus, the grower can alter the properties of his greenhouse covering: on cloudy rainy days it is transparent, or the grower can turn on the roof-spraying when he wants to make it transparent. Here too, more material development is needed to further optimize the optical properties.

## CONCLUSIONS

Diffuse light is favourable for crop production and can result in a production increase of 8–10% for cucumber (Hemming et al., 2008a) under Dutch conditions. However if combined with lower light transmission it may be compensated by production losses during periods when light is the limiting factor in winter. From a crop point of view, we do not yet know the ideal haze characteristic of a covering. This is presently under investigation and we hope to present the results in the near future. In general, the potential for diffuse covering materials is much higher for semi-arid climates than for marine winter climates; the direct irradiation in South Italy is almost three and in Arizona it is almost five times higher than in The Netherlands, as shown in this paper.

Several light diffusing materials (plastic films, glass, temporal coatings) are available. It can be concluded that the light transmission of covering materials is characterised well by the hemispherical light transmission  $\tau_h$ . Together with the haze  $\eta$  this describes the optical properties of a diffusing covering. For current materials higher haze results in higher light loss (Fig. 4). Materials combining high haze with high hemispherical light transmission should be developed. Regular surface structures and additional nano-coatings seem to have potentials. The optimal combination of properties has to be found for different climatic regions in order to optimise crop performance.

## ACKNOWLEDGEMENTS

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## Tables

Table 1. Average global radiation in De Bilt (Bilt), The Netherlands (based on data from KNMI and the SEL-method described by Breuer and van de Braak, 1989), Bari (Bari), South of Italy (based on measurements from the University of Bari UNIBA in 2000, Hemming et al., 2008) and Tucson (Tucs), Arizona, U.S. (based on data published by Kania and Giacomelli, 2008).

Days	Month	Global radiation									
		Total [ $\text{MJ m}^{-2}$ ]			Direct [ $\text{MJ m}^{-2}$ ]			Diffuse [ $\text{MJ m}^{-2}$ ]			
		Bilt	Bari	Tucs	Bilt	Bari	Tucs	Bilt	Bari	Tucs	
1	31	Jan	62.6	202.4	342.3	12.8	86.7	247.4	49.7	115.6	94.9
32	59	Feb	104.7	211.2	383.5	15.8	103.2	265.9	89.0	108.0	117.6
60	90	Mar	314.6	418.4	570.1	95.0	245.6	439.3	219.6	172.8	130.8
91	120	Apr	299.1	494.0	690.0	41.5	281.1	523.3	257.6	212.9	166.7
121	151	May	568.0	648.5	793.9	162.2	353.1	664.8	405.8	295.4	129.1
152	181	June	551.5	708.6	782.6	159.0	413.3	673.3	392.5	295.3	109.3
182	212	July	597.4	736.3	703.6	244.7	443.1	556.9	352.8	293.2	146.7
213	243	Aug	502.5	670.9	655.0	148.1	425.3	489.5	354.4	245.5	165.5
244	273	Sep	342.3	446.5	581.7	124.0	260.4	453.3	218.3	186.1	128.4
274	304	Oct	163.7	332.8	501.4	37.9	173.4	384.8	125.8	159.4	116.6
305	334	Nov	89.9	237.0	367.8	26.0	108.8	269.7	63.9	128.2	98.1
335	365	Dec	54.0	222.2	315.4	14.4	81.9	230.3	39.7	140.3	85.1
1	365	Total	3650	5329	6687	1081	2976	5198	2569	2353	1489

Table 2. Optical properties of several clear and diffuse materials (glass, film, temporal coating).

Type	Product	Haze $\eta$	Perpendicular PAR transmission $\tau_p$	Hemispherical PAR transmission $\tau_h$
glass	Standard horticultural glass clear	0.0043	0.8938	0.8219
glass	Centrosol HiT diffuse	0.1262	0.9639	0.8983
glass	Centrosol HiT clear	0.0025	0.9520	0.9098
glass	Centrosol diffuse	0.1317	0.9178	0.8380
glass	Centrosol clear	0.0026	0.9075	0.8382
glass	Hortilight 91 plus clear	0.0043	0.9107	0.8391
glass	Hortilight 91 plus diffuse	0.5261	0.9163	0.7615
glass	V&V diffuse	0.8608	0.9215	0.7312
glass	Holga/Vetrad Vetrasol 502	0.2748	0.9191	0.8327
glass	Holga/Vetrad Vetrasol 503	0.7444	0.9269	0.7984
glass	Holga/Vetrad Vetrasol 504	0.1581	0.9164	0.8313
glass	AGE/Glaverbel Satinbel diffuse	0.0434	0.8968	0.8111
glass	AGE/Glaverbel Crepi diffuse	0.4594	0.8928	0.7817
glass	AGE/Glaverbel Glamatt diffuse	0.2007	0.9053	0.8160
film	AGC F-Clean clear	0.0887	0.9362	0.8579
film	AGC F-Clean diffuse	0.7427	0.9382	0.8099
film	Rovero Solar EVA 5 clear	0.3116	0.8918	0.7917
film	Rovero Solar EVA 5 HD diffuse	0.7437	0.8766	0.7346
film	BPI Luminance THB diffuse	0.8108	0.8549	0.6921
coating	Hermadix coating (1:3) dry	0.8716	0.4945	0.4187
coating	Hermadix coating (1:3) wet	0.5589	0.8180	0.7042
coating	Hermadix coating (1:7) dry	0.6849	0.7166	0.6058
coating	Hermadix coating (1:7) wet	0.1724	0.8802	0.7936

## Figures

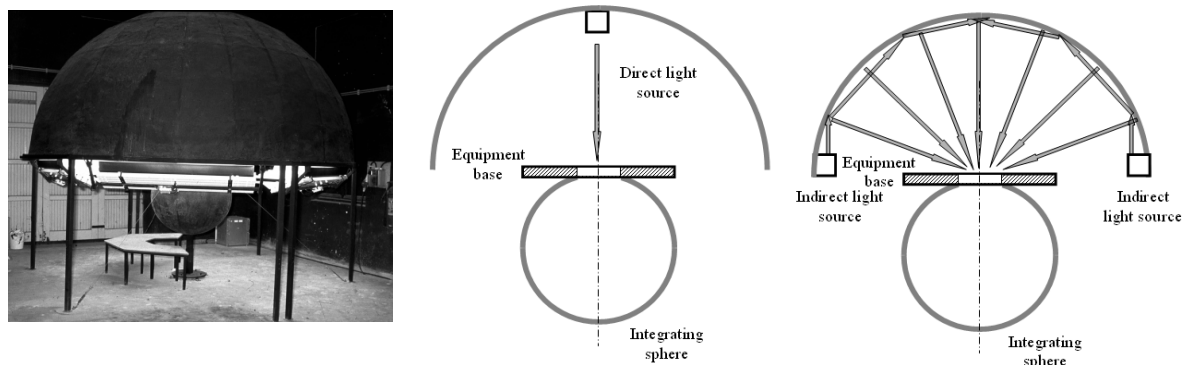


Fig. 1. Measurement principle for light transmission of transparent materials (large integrating Ulbricht sphere), left: perpendicular light transmission  $\tau_p$ , right: hemispherical light transmission  $\tau_h$ .

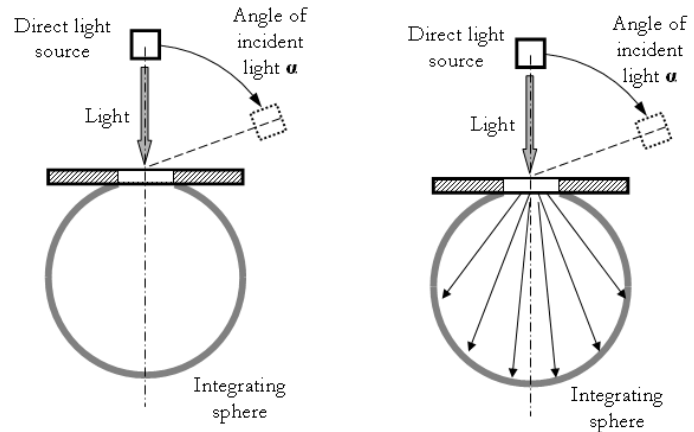
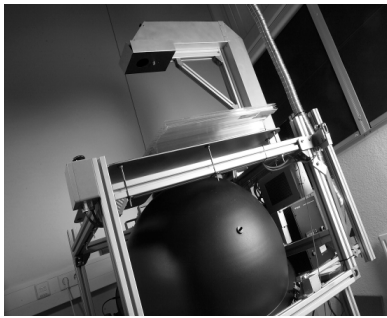


Fig. 2. Measurement principle for light transmission and haze of transparent materials (small integrating Ulbricht sphere), left: measurement of light transmission under different angles of light incidence, right: measurement of haze  $\eta$ .

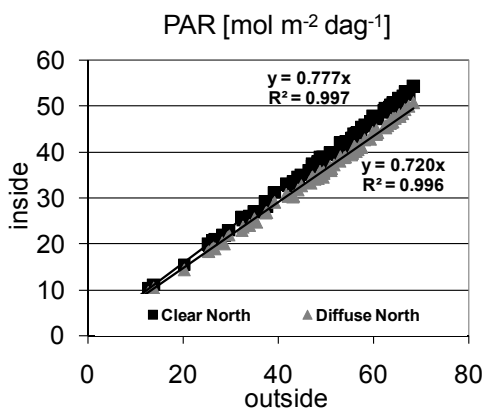


Fig. 3. Measurements of daily PAR integral in- and outside experimental greenhouses covered with diffuse and clear covering, Apr.-Sep. 2006 in NL.

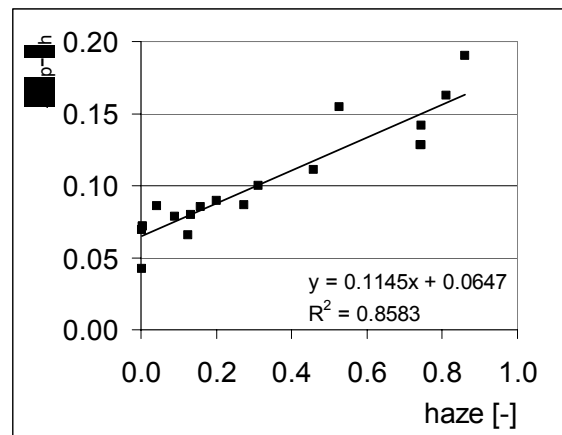


Fig. 4. Correlation of haze  $\eta$  and light loss of a material (perpendicular light transmission  $\tau_p$  minus hemispherical light transmission  $\tau_h$ ).

