Design, Construction and Maintenance of Greenhouse Structures

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Abstract

In this paper a review is given about the effects of different parts of the solar radiation and its importance for plant growth in greenhouses. Besides the most important visible part of the light (PAR), ultraviolet (UV), near infrared (NIR) and far infrared (FIR) are discussed. The strength of the greenhouse structure can be calculated following the new European Standard for Greenhouses EN 13031-1. The orientation and the roof inclination at the greenhouse have limited influence on the light transmittance. The most important material properties of greenhouse cladding materials are presented for glass, plastic sheets (PMMA and PC) and plastic films (PE, PVC and ETFE). These properties can be modified in the different materials, which leads to improvements of the materials with respect to light transmission, heat transfer, condensation behaviour, etc. Some recent results of research of greenhouse cladding materials and structures are described, like 'floating greenhouses', 'closed greenhouses', ETFE membrane, a greenhouse for tropical lowland, zigzag-shape double PC-sheet and microstructural coated glass.

INTRODUCTION

A greenhouse system must protect plants against low temperatures, wind, rain, hail, birds and insects to promote plant growth and to increase production and quality and allow modern work routines and logistics. The components of a greenhouse design are: the shape, the orientation, the structure, the foundation, the cladding material and the ventilation facilities together with the technical equipment needed to control the climate inside the greenhouse. The greenhouse design must deal with the local outdoor circumstances, like minimum, maximum and average temperature, humidity, solar radiation, clearness of the sky (clouds), precipitation (rain, hail and snow) and average wind speed and wind direction.

The greenhouse system is widely spread all over the world to produce vegetables, fruits, plants, herbs or ornamentals. In Europe the largest greenhouse areas are concentrated in the Mediterranean countries, like France, Italy and Spain (Elsner et al., 2000a). Greenhouses covered with glass are mainly located in the countries of Northern Europe, like The Netherlands. In The Netherlands the total area of greenhouses is 10,500 ha (98% is glass-covered). The application of plastic films for covering greenhouses and tunnels however, is dominant worldwide e.g. for example in Southern Europe, the Arab countries, Israel and Northern Africa, namely the total greenhouse area there is estimated at 190,000 ha; of this area 168,000 ha are covered with plastic films; the others with glass or plastic sheets. In three countries in Asia the estimation is 380,000 ha (!) for China, 60,000 ha for Japan and 2,200 ha for Korea (Zabeltitz, 2001). The percentage of plastic film-covered greenhouses of this area is almost 100%.

The main objective of this paper is to describe the present situation of greenhouse technology by analysing the design requirements, the standards and the factors influencing climate for plant growth in greenhouses, like the local global radiation, temperature, wind and ventilation. More in particular the aspects of natural light and their influence to the greenhouse environment will be discussed. Also a review will be given about the available greenhouse cladding materials with their specific properties.

MATERIALS AND METHODS

Light in Greenhouses

Global radiation are electromagnetic waves emitted by the sun and reaching the earth surface. The global radiation can be separated in: UV-radiation (ultraviolet), visible light PAR (violet, blue, green, yellow, orange and red), NIR (near infrared) and FIR (far infrared).

1. PAR. For crop production photosynthesis as well as crop development are important. For photosynthesis the light level in the **photosynthetically active radiation** (PAR, 400-700 nm) is mostly decisive following the sensitivity curve of the crop (the red part is the most effective; the green part the less effective). For crop development the spectral criteria like the relation red/far red and the quantity of blue light are important. The blue light contributes to the photosynthesis but also to the photomorphogenesis.

In Table 1 an overview is given of the spectral distribution of the optical radiation characterised by the wavelength, which is given in nanometers (nm) (1,000 nanometer is 1 micrometer).

For the PAR radiation it is important to distinguish diffuse and direct radiation. With direct radiation is meant the radiation, which reaches the earth directly from the sun without being reflected. On cloudy days however most of the sun radiation is scattered by small water droplets in the atmosphere and then reaches the earth as diffuse radiation. In Western Europe the transmittance for diffuse light is decisive for plant growth, because during 75% of the winter season the weather is cloudy. In tropical countries the direct light transmittance is more important mostly. When the radiation is direct there are big differences between the locations in the greenhouse with and without shadow (40% compared to 85%). The transmittance for diffuse light is in general 10% lower than the transmittance for direct light (Bakker et al., 1995) but it reaches the lower parts of high plants better, which is positive for plant growth. In Table 2 the transmittances for diffuse and direct light of some greenhouse cladding materials are given for the wavelength band of 400-700 nm (PAR).

2. UV. Ultraviolet (UV) radiation can be separated in UV-A (315-400 nm), UV-B radiation (300-315 nm) and UV-C radiation (< 280 nm) and has a high energy content. UV-A and UV-B are responsible for degradation of plastics and therefore it is necessary to protect greenhouse plastic films for UV-degradation (ageing) by adding UV-stabilisers to the polymer. In combination with blue light, UV-A plays a role in some morphological processes like stem stretching and leaf development. UV-B can influence the colouring of flowers by developing pigments like flavonoids (Hoffmann, 1999).

3. NIR. The **near infrared** (NIR, wavelength 700-3,000 nm) is the part of the solar spectral that is hardly used by the plants for photosynthesis; it is mostly substituted into heat (sensible and latent) in the greenhouse. This can be an advantage in a country with a colder climate and a disadvantage in a greenhouse located in a warm country like in the tropics and subtropics. In these areas NIR radiation leads to additional heating in the greenhouse, which is mostly unwanted. To limit this process in tropical countries, special plastic films are developed, which block the NIR and in that way have a cooling effect (Hemming et al., 2006).

4. FIR. Far infrared radiation (FIR, wavelength 3,000-100,000 nm) is not caused by direct sun radiation, but it is heat radiation transmitted by each ‘heat body’ in and on the greenhouse. This radiation is very important in greenhouses; since it causes a part of the ‘greenhouse effect’. The radiation emission from a body depends on the temperature of the body. Glass and other greenhouse covering materials are transmitting this long wave radiation in a certain extent. To avoid strong radiative heat losses during cold clear nights a covering material should reflect FIR and not transmit it. In subtropical regions there is a need for thermic films, which prevent the transmission of FIR during cold nights and thereby create an insulating effect.

Different additives, coatings or surface structures can influence the transmittance or reflectance of the radiation in specific wavelength bands. The challenge of developing the optimal plastic film or sheet for greenhouses is to find a balance between thermal transmittance and light transmittance and other aspects.

A&F has unique laboratories and instruments to measure all relevant properties of greenhouse cladding materials and screens. Thereby the optical properties addressed to the specific light demands of horticultural plants, like transmission, reflection, absorption and emission can be measured adequately according internationally accepted standards. Also the interpretation of the measured data can be an important task of A&F.

Greenhouses Structure and Shape

1. Structure and Standard. Greenhouse structures differ a lot from simple and very cheap structures to high-tech multispan-structures (Elsner et al., 2000b). The reasons for the large variety of greenhouse types in the world are mostly local conditions and the availability of building materials like timber, bamboo or steel. The overall greenhouse design is strongly influenced by the climate and latitude of the location. Regulations imposed at national or international level also influence the greenhouse design. The requirements for maximum light transmittance leads to designs with smaller and fewer structural parts, which may affect the structural stability of the greenhouse. National standards give rules for the structural design of greenhouses and specify the loads caused by self-weight, wind, snow, crops (suspended to the structure), installations, thermal actions and maintenance.

Since beginning 2002 a European standard for designing greenhouses cladded with rigid or flexible covering materials is available (in English). According this European standard EN 13031-1 (EN 13031-1, 2001), greenhouses are divided into three groups based on the minimum design working life, respectively five, ten and fifteen years. Simple tunnels and shade houses for example are grouped in Class B5, the glass-covered greenhouses in Class A15 and the sophisticated plastic-covered multispan greenhouses in B15. Each group has its specific design rules. For example for a greenhouse with a cladding material, which is not tolerant for frame displacements (the A-type greenhouse) both the strength and the displacements/deflections should be checked. For type B greenhouses (tolerant for frame displacements) only the strength has to be checked. Also the wind and snow loads differ when comparing an A-type greenhouse with a B-type of the same reference period (Waaijenberg et al., 1998).

EN 13031-1 gives the rules for designing greenhouses in nineteen European countries. After a certain bridging period and after the European standard is accepted by all national governments, the standard becomes law for all nineteen European countries. This is not the case yet. Now there is a common European standard for designing greenhouses available, which also takes into account the local climate differences in a country like Finland compared to for example Greece (differences in snow and wind loading). The new European standard gives more rules for designing plastic-covered greenhouses than for example the Dutch Standard (NEN 3859, 1996), which is mostly focused on glass-covered greenhouses. A&F is active as a member of both the Dutch (NEN 3859) and the European standardisation committee (EN 13031-1).

Thanks to the standards and material research executed during recent years (Briassoulis and Aristopoulou, 2002) there are good designed plastic film greenhouses on the market now, which are designed according to specific standards and are comparable to the functionality and the reliability of the traditional glass-covered greenhouses.

2. Orientation Greenhouse and Inclination. For the quantity of light level inside the greenhouse, besides the structural parts and cladding material, also the orientation of the greenhouse has influence. When the ridge of the greenhouse is orientated East-West, the light transmittance is the highest during the winter months (see Table 3). Measured over the total year, the ridge orientation North-South is slightly favourable (Elsner et al., 2000a).

It appears that the influence of the inclination of the roof on both the diffuse and direct perpendicular light transmittance is only minor, even in the winter months at low angle of incidence of the sun. Roughly speaking: an increase of the inclination by 10°

(e.g. from 20° till 30°) gives an improvement of the light transmittance of only 1% for both diffuse and direct radiation.

Greenhouse Cladding

In general the following material properties are important for evaluating greenhouse cladding materials:

- Transmission for global radiation (UV and PAR)
- Transmission for heat radiation (NIR and FIR)
- Insulating effect
- Sensitivity to ageing (mainly UV degradation)
- Permeability for humidity (water)
- Mechanical strength (tensile and impact)
- Fire behaviour
- Investment costs
- Available dimensions

Another aspect is the light scattering by the cladding material. This is called the diffusity or the 'haze' of a material. The haze is strongly depending on the surface structure or the presence of certain pigments. The diffusity of a material is important for plant growth, because the chance of leaves getting burned by direct sun radiation is reduced, clear cast shadow will not appear and the light is better spread inside the greenhouse. Therefore the light can penetrate better lower in the crop. The haze of cladding materials differ a lot; when the haze is more than 50% the material is called diffuse.

Inside the greenhouse high humidity and differences between inside and outside temperatures induce condensation of water vapour on the film's inner surface. Condensation on the covering material can appear in two ways: forming water droplets or forming a water film. If water droplets are formed the light transmittance can be reduced up to 15% because of an increase of total reflection in the water droplets. Furthermore the plants can be damaged by water dripping off. These problems mainly appear on plastic covering materials while on glass panes film condensation occurs. By adding anti-drop additives to a plastic film or a coating to a rigid covering material condensation also results in a water film, which flows down to the sides and can be collected in a gutter. A film, with 'anti-drop' or 'anti-condensation' of 'anti-fog' treatment is highly recommended in most European regions when the relative humidity in the greenhouse is high. In tropical countries with greenhouses with much ventilation (open sidewalls) the humidity inside the greenhouses is mostly not so high; therefore the need for an AC treatment (anti condensation) of the cladding materials is not so big here.

1. Glass. There is a long experience with the covering material single glass in Western and Northern Europe. The popularity of the material glass in the colder countries is caused by the high light transmittance, the durability, the good behaviour of condensation on the surface, blocking of long wave heat radiation and the knowledge of glass as a traditional structural material that can resist wind- and snow loads when the design is adequate. Also the relatively low price growers have to pay for floatglass with a thickness of 4 mm is relevant (normal glass costs € 4.50 per m^2). Disadvantages are: the light losses caused by reflection, the brittleness (glass is breakable in case of hail) and the unsafety for the workers in greenhouses.

To improve the safety, tempered glass has been introduced for horticulture. The strength of this glass is five times better than normal glass and when it breaks it falls down in small pieces, which causes no injuries. The use of this material is not yet obliged in The Netherlands. The price of this tempered glass in 4 mm thickness is twice the price of normal glass.

The light transmittance of glass can be improved by adding antireflection coatings to the glass. These coatings give a gradual transition of the refraction index between air and glass, which leads to an increase in light transmittance (Sonneveld and Waaijenberg, 2003) (see also under heading 'Recent Developments in Greenhouse Cladding Materials').

Low iron sand glass can be produced that has a higher light transmittance and partly transmits UV-B radiation in contrast to normal glass (Waaijenberg and Hoffman, 2000).

Coatings on glass are also possible to decrease the emission of heat to the sky (in other words: less energy loss). This coated glass, called Hortiplus, has the disadvantage that energy saving in this way means light loss at the same time.

2. Plastic Sheets. As rigid plastic materials for greenhouse covering the following materials are used: polyvinylchloride (PVC), glass reinforced polyester (GRP), polymethylmethacrylate (PMMA) and polycarbonate (PC), mostly as extruded (double wall) plastic sheets. Some materials are also on the market as corrugated (single) sheets. The disadvantages of the common double plastic sheets are: the light loss (about 7 to 10% compared to glass), the costs per m^2 (4 to 5 times compared to single glass 4 mm), the impact resistance in the case of PMMA (hail resistance) and the behaviour in case of fire and smoke. The light transmittance of the common double PMMA sheets is better than PC (see Table 2), but PC has other advantages compared to PMMA: PC has a higher impact resistance (hail proof) and is less dangerous in case of fire.

The advantage of all double wall sheets is of course the energy saving compared to all single materials.

At the moment PVC is only used as corrugated (single) sheets for greenhouse claddings (brand name Ondex).

Glass reinforced polyester must have a polyvinyl-fluoride coating to protect the polyester against altering. The glass fibres in these sheets cause light loss and quick pollution of the sheets, because of the roughness of these sheets.

There are possibilities to modify the plastic sheets of PMMA (acrylic) and PC (polycarbonate) into the so-called 'double-wall zigzag sheet'. A commercial available cover was developed in a co-operation between A&F and General Electric Plastics (Sonneveld et al., 2002). For a summary of this research, see also under heading 'Recent Developments in Greenhouse Cladding Materials'.

3. Plastic Films. The most applied flexible plastics for horticultural purposes are the low-density polyethylene (LDPE) films, like polyethylene (PE) with UV-stabilisation, polyethylene infrared (PE-IR) films and the ethylenevinylacetate (EVA) films. The price of these films is relatively low (about € 0.50 till € 0.70 per m^2). The transmission for perpendicular direct light for these films is comparable to single glass (see Table 2). In Asian countries like Japan mostly PVC films are used since this film is stronger (resistant against wind) and the transmittance of FIR is lower than standard PE. So a PVC film is advantageous to use for single-clad greenhouses during cold, clear nights. The disadvantage is the disposal of PVC, which cannot be burned or recycled as easily as PE. PVC film in Japan is usually replaced after 2-3 years (Bay-Petersen, 1992).

The plastic film properties improved clearly during the last years by adding additives to the plastic material and thereby they are better tuned to the horticultural demands.

A higher light transmittance of the plastic films can be reached by using other (more expensive) fluorfilms, like ethylene tetra fluoroethylene (ETFE) and polyvinyl idene fluoride (PVDF). These films have light transmittances of respectively 95% and 94% for perpendicular direct light and combine a durability of more than 10 years with a good thermal behaviour caused by the low transmittance for long wave heat radiation. The price of a commercial ETFE film is € 10 per m^2.

In Table 4 the transmittances for long wave heat radiation (FIR) for some greenhouse cladding materials and screening materials are presented. Glass, PC and PMMA sheets are hardly or not transparent for FIR radiation. This is also valid for wet surfaces, like a sheet covered with a continuous condensation film. Normal PE without extra absorbing pigments has a high transmittance for FIR. Pigments in the film lower the transmittance for FIR, which is positive for the greenhouse climate during cold, clear nights. A material with a FIR transmittance lower than 20% is called 'thermic'.

For energy screens inside greenhouses, both the FIR reflection as the FIR transmittance play an important role. To block the heat radiation as much as possible it is necessary to keep the FIR transmittance of screening materials as low as possible.

Maintenance

Cleaning the greenhouse roofs is important in areas with high pollution, because pollution can reduce the light transmittance strongly (up to 10% per year in The Netherlands). For glass-covered greenhouses, like the standard Dutch greenhouses, washing machines are common now. These operate like a car wash and run and wash the greenhouse roofs fully automatically several times during the year. A similar system needs also to be developed for multispan greenhouses covered with plastic films, but a problem here is the lack of standardisation in span width, height, etc. This standardisation is more common in glass-covered so-called Venlo-type greenhouses. Another solution could be the application of totally inert plastic films, like the more expensive ETFE film, which do not attract dust.

Also during erection of the greenhouse mechanisation has made its appearance, because of the safety of the workers that built the greenhouses covered with glass panes. The reason for this is also that the sizes of the glass panes increased during the last years (up to 1.25 x 2.05 m) and also the height of the greenhouses (gutter height > 4.5 or 5 m). Therefore it is becoming too dangerous to put the glass panes on the roof by hand. This work is now done by a glazing machine, which lifts up the glass panes from the ground to roof level and brings the glass pane also in the correct inclination and spot. Also for repairing activities on the roof similar machines are developed.

RESULTS AND DISCUSSION

Recent Developments in Greenhouse Structures

In a small country like The Netherlands there is a growing demand for space for recreation, houses, other buildings or infrastructure and for reconstruction replacing traditional horticultural areas. Apart from that there is a need for emergency water storage, in cases of excessive rainfall, for water from the big rivers that enter the country from Germany and France. When the water level gets too high, there is a serious threat for flooding. This resulted to the idea of '**floating greenhouses**' in a lake or pond in open connection with the rivers and with changing water level. The idea is to built floating islands on which greenhouses could be built. The water under the artificial island could be used for long term heat or cold storage. Together with an engineering bureau and a contractor A&F develops the starting points, boundary conditions and the structural principles for floating greenhouses in a project.

Although these 'floating greenhouses' are more expensive than the ones built on the mainland, horticultural industry in The Netherlands is positive about this idea. A demonstration project will be realised (for more information see the Internet-site: http://www.rnw.nl/science/html/030128greenhouse.html).

During the last Hortifair exhibition in Amsterdam a so-called **closed greenhouse** was introduced. This greenhouse is designed without natural ventilation, but the ventilation is realised with an air-conditioning installation, which cools down or heats up the air that is moved through the greenhouse with artificial ventilators and air ducts. This idea came up caused by the need for energy saving and environmental friendly growing systems in greenhouses (no emission of pesticides, CO_2, etc). A&F is able to provide the basic conditions for this kind of growing system and tries to make the system more profitable for growers together with the industry.

Another innovation introduced during the Hortifair of 2003 was the first study model of a greenhouse covered with more durable plastic films, like the fluor **ETFE membrane**. Two Dutch companies (Bom and BOAL) and the Japanese producer of this membrane (Asahi Glass) will develop a complete wider span greenhouse this year with ETFE membranes in the roof (A&F advises). The brand name of this membrane is F-Clean. As mentioned before under the heading 'Plastic Films' this very promising material combines a very high light transmittance, a very good durability and good condensation properties with a good resistance against long wave heat radiation.

A special design for **greenhouses** suitable **for tropical circumstances** like in the lowland of Indonesia is developed by A&F together with two Dutch companies. This greenhouse design with a very high ventilation capacity is covered with a combination of nettings and a special PE-film that blocks the near infrared radiation (Hemming et al., 2006).

The possibilities for designing a greenhouse with very few structural elements, which cause shadow in the greenhouse, were the subject of a study for alternative greenhouses, for example A&F developed an inflated structure, which needs no structural elements like trusses and beams (Waaijenberg and Hoffmann, 2000). In this study the advantages and disadvantages of the different types of **membrane and pneumatic structures** used as horticultural greenhouses are illustrated. It can be concluded that these advanced systems offer a lot of possibilities e.g. energy saving, being more environmental friendly, having a higher light transmittance and contributing to better logistic. These designs however can only be achieved if new advanced covering materials are coming available.

One of the designs presented in the mentioned report has been worked out further as a pneumatic structure (with double inflated plastic films) in the scope of the development of a 'sustainable plant production system', called 'solar greenhouse' (Bot, 2004).

Recent Developments in Greenhouse Cladding Materials

When a light beam is incident to a flat transparent sheet, a part of this light will be transmitted, according to Fresnell law, and another part will be reflected (Fig. 1, above). For the world exhibition Floriade 2002 in The Netherlands, a greenhouse design was developed by A&F together with General Electric Plastics with **polycarbonate** double-web sheets with **a zigzag-shaped** cross-section. Intensive research was executed to develop the special zigzag shape of the plastic sheets resulting in an enhanced light transmittance and energy saving of approximately 20% over the whole year (Sonneveld et al., 2002). The optimal dimensions for the sheets with respect to light transmittance, strength and insulation is a pattern of 50 mm for the zigzag shape, a thickness of 25 mm and the inclination of the pattern is 50°. The transmittance for diffuse light of the entire greenhouse with the double-web sheets is 78.8%, which is comparable to a greenhouse with single glazing. When a light beam is incident to a flat transparent sheet, a part of this light will be transmitted, according to Fresnell law and another part will be reflected (Fig. 1, above). In the case of a flat sheet the reflected part of the light does not enter the greenhouse and therefore is not available for plant growth. In the case of a zigzag-surface the part of the light that is reflected by the sheet can hit again another part of the sheet surface and enters in that way partly the greenhouse after all (Fig. 1, below). By this effect the transmittance for diffuse light of a zigzag-shaped single sheet increases about 5% compared to a flat single sheet of PC. Calculations and measurements of single and double sheets with different pigment additives and with and without coatings were performed.

The chosen material polycarbonate (PC) has some advantages, but also some disadvantages, when comparing it to the material PMMA. PC as basic material has a very good impact resistance. Due to the high impact resistance the outer skin of the double sheets can still be sufficiently hail resistant at small thicknesses. Moreover PC is more elastic than PMMA, due to this the sides of the sheets can be applied with a click-connection system (see Fig. 2). Two sheets will be connected then only by a click-connection on the sides; glazing bars are not needed anymore. This has a positive effect on the total light transmittance of a greenhouse.

Another advantage of PC is the better behaviour during fire. With PMMA some huge, dangerous fires occurred in the past years. The material PC can indeed be ignited, but PC has a self-extinguishing property in contrast to PMMA.

Insulation by more layer systems is an obvious solution to reduce energy loss in the cold period for heated cultures with a high energy demand. The commercially available materials result in high light loss when applied as more layer applications. A possibility to improve the light transmittance is the modification of the **surface** of greenhouse cladding materials **with microstructures**, so that a multilayer system can compete with single glazing with respect to light transmission and at the same time a good heat insulation (Sonneveld and Waaijenberg, 2003).

A&F has executed a feasibility study to investigate the applicability of microstructural coated greenhouse covering material and to reach the level of needed energy saving for glasshouse horticulture. Anti reflection microstructure (ARM) coated materials (Fig. 3) have the highest light transmission of the now known materials. The measured light transmittance for ARM coated glass is 96% for direct light and 90% for diffuse light. Double ARM glass has a transmittance of 92% for direct light and 86% for diffuse light. These values are higher than those for standard glass, which are respectively 90% and 83%.

The high light transmission leads to the entrance of more sunlight in the greenhouse and so to energy saving. Besides this the extra PAR can lead to a higher production, what brings a lower energy consumption per kg of product.

A double glass covering with this type of glass gives a higher light transmission than standard single glass and an extra heat insulation, what leads to energy saving. The costs for this type of coating are still high; more applications may lead to a lower price.

The possibilities for improving plastic film coverings for greenhouses are numerous. Some of the possibilities are:

- Blocking NIR to reduce the natural warming up effect inside greenhouses in particular in tropical or sub-tropical countries (as mentioned before);
- Blocking UV radiation to limit the activity of harmful insects and in that way limiting plant diseases without spraying large quantities of pesticides (anti-botrytus film);
- On the other hand permitting UV radiation entering the greenhouse can bring improvements of certain cultures, which need UV for development (Hoffmann, 1999);
- Improvements of certain aspects of plastic film materials can be reached by several roofing materials based on the principles of absorption, reflection, interference, photo- and thermochromism (Hoffmann and Waaijenberg, 2002). Some of these techniques are still experimental or are too expensive at the moment for horticultural application. Some of them are practice now already;
- Improving the anti-fog and anti-dust properties also when looking at the durability of these properties. More in particular anti-fog is important in the colder countries of Europe;
- Improvement of the greenhouse effect; in other words: blocking the transfer of long wave heat radiation. This is important to avoid quick cooling down of the unheated greenhouse during cold, clear nights.

CONCLUSIONS

The analysis of natural light in greenhouses makes it clear that the transmittance for PAR is the most important property all over the world. In particular in countries with a colder climate the diffuse light transmittance of a material is of most importance, because during winter 75% of the days are clouded and then the light is diffuse.

A cladding material should be so that in countries with a warm climate a diffuse radiation is produced inside the greenhouse, to prevent plants from direct sun burning, to decrease the differences in locations with and without shadow in the greenhouse and to allow light to penetrate better the greenhouse, in particular with high plants and high leaves densities like tomatoes and cucumbers. The diffuse character of a cladding material should not reduce the overall transmittance for PAR of that material.

Some plants show positive effects of radiation by UV. For those specific crops the material should be transparent for UV radiation. On the other hand blocking UV radiation out of the greenhouse can reduce plant diseases in greenhouses, because harmful insects can lose their orientation. Blocking NIR out of the greenhouse by modifications of the standard PE plastic films can have a cooling effect on the greenhouse climate in tropical countries, because NIR is not important for plant photosynthesis: it only heats up the greenhouse, which is mostly unwanted.

When the climate is so that relatively cold nights occur, then a greenhouse covering material should block the FIR radiation, because in that way the long wave heat radiation is kept inside the greenhouse and is not radiated to the sky through the material. FIR radiation is transmitted to the clear, cold sky by each warm body in and on the greenhouse. With a material that blocks FIR, like glass, plastic sheets (PMMA and PC) and IR-blocking plastic film the heat is better kept in the greenhouse, so that the temperature inside the greenhouse can be kept at a safe level, sometimes without extra heating.

The European Standard EN 13031-1 can be used to design and calculate the structure of greenhouses for nineteen European countries. For a good design the climate circumstances of the relevant country should always be investigated and the greenhouse should be adapted to these circumstances, like wind, temperature (average, minimum and maximum), radiation, rain and snow loads, etc. The orientation of a greenhouse and the roof inclination has influence on the available light quantity in the greenhouse; changing the roof inclination has only minor influence.

There are many possibilities to improve the properties of greenhouse cladding materials.

Glass can be improved by modifying the raw materials (for example low iron sand) or by adding coatings or a microstructural treatment to the surface, which influences the reflection and transmittance of light.

These coatings can also be added to plastic sheets, like PMMA and PC and the cross-section of these extruded sheets can be modified to give a better light transmittance (zigzag shape of double wall PC).

At the moment the best economic possibilities exist for plastic films, because in the production process of these films additives can be added, which influence many properties. This is relatively cheap compared to other measures like zigzag and coatings on sheets and glass. Mostly PE films with additives for UV-protection, anti-condensation (no-drop), anti-dust, blocking NIR and blocking FIR are used to improve the climate and the light transmittance inside the greenhouse.

In particular for tropical and sub-tropical countries the most promising possibility is to add near infrared (NIR) blocking additives to common plastic films to limit NIR radiation entering the greenhouse. This can reduce the inside temperature. This idea is worked out in a project in tropical lowland in Indonesia.

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Tables

Table 1. Overview of the spectral distribution of the optical radiation, characterised by the wavelength (in nm).

Description	Abbreviation		Wavelength (nm)	Remark
Ultraviolet radiation	UV	UV-C	< 280	<300 nm doesn't reach the earth
		UV-B	280-315	
		UV-A	315-400	
Photosynthetically active radiation	PAR	B (blue)	400-500	
		G (green)	500-600	
		R (red)	600-700	
Near infrared radiation	NIR	FR (far red)	700-800	
		NIR	800-3.000	
Far infrared radiation	FIR		3.000-100.000	

Table 2. Transmittance for direct (perpendicular) and diffuse light of some greenhouse cladding materials (PAR, 400-700 nm).

Material	Thickness	Transmittance for direct, perpendicular light	Transmittance for diffuse light
Glass	4 mm	89-91%	82%
PE film	200 µm	89-91%	81%
EVA film	180 µm	90-91%	82%
PVC film	200 µm	87-91%	\
ETFE film	100 µm	93-95%	88%
PVDF film	100 µm	93-94%	85%
PC sheet	12 mm	80%	61%
PMMA sheet	16 mm	89%	76%
PC zigzag sheet (double)	25 mm	88%	79%

Table 3. Influence of the orientation of the greenhouse on the light sum in Wh m^{-2} d^{-1}.

	Orientation of the greenhouse	
Week number	East-West	North-South
2 (January)	379	293
4 (January)	426	322
6 (February)	578	530
10 (March)	1243	1226
14 (April)	1955	2104
20 (June)	2720	2969
Total year	588000	609000

Table 4. Transmittance for long wave heat radiation (FIR) of different greenhouse cladding and screening materials.

Material	Thickness	Transmittance for long wave heat radiation
Glass	4 mm	0%
PE film	200 µm	40-60%
PE-IR film	200 µm	20-40%
EVA film	180 µm	20-40%
ETFE film	100 µm	15-20%
PC sheet	12 mm	0%
PMMA sheet	16 mm	0%
Knitted polyester white	140 g m^{-2}	22%
Knitted polyester white	150 g m^{-2}	11%
Knitted polyester black		5%
Polyester textile white		12%
Polyester textile white		12%
Polyester textile transparent		ca. 50%
Polyester textile aluminised		3%
Black film		0%

Figures

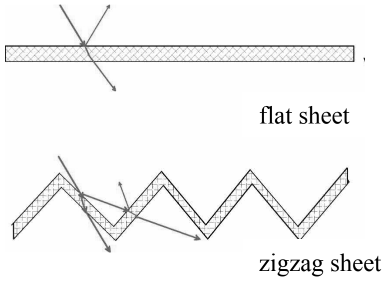

Fig. 1. The principle of the transmittance and reflection of light beams hitting a flat sheet (above) and a zigzag-sheet (below).

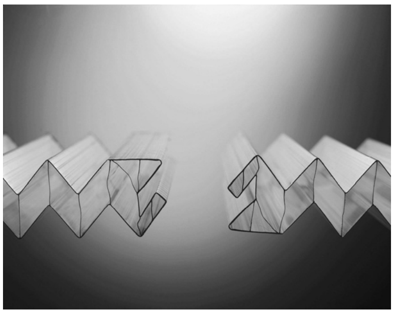

Fig. 2. Cross-section of the polycarbonate zigzag-sheet with the side click-connection (no glazing bars!).

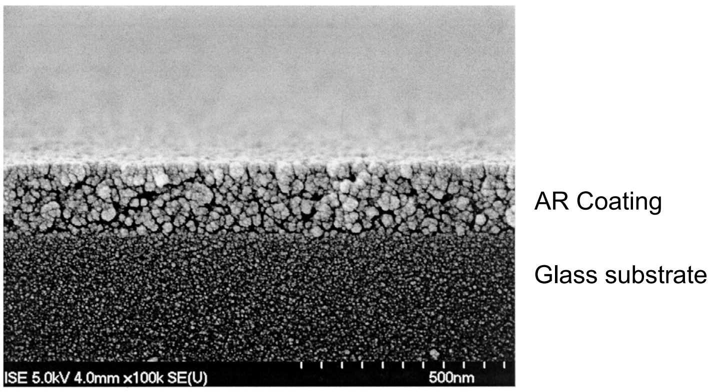

Fig. 3. Microscope picture of the coating structure.