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Project leader:	Professor Simon Pearson
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Key staff:	Simon Pearson
Location of project:	
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Date project commenced:	June 2014
Date project completed (or expected completion date):	May 2016

DISCLAIMER

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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Director

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SCIENCE SECTION

SECTION 1. THE FUNDAMENTALS OF LIGHT AND BIOLOGICAL RESPONSES

The aims of this review are to examine the technology used to optically and spectrally modify greenhouse cladding materials. The horticultural impact of these and other potential modifications are considered. This review compliments and brings up to date prior and existing AHDB funded studies on horticultural lighting system and spectral filters (see for example, AHDB Reports CP139, Commercial Review of Lighting Systems; CP085, Principals of Lighting Systems; PC150, Spectral filters for bedding plant production; CP019, Spectral filters for Nursery Stock; CP088 LED's to improve insect trapping; etc). The quantum of work conducted is significant and demonstrates the fundamental importance of light optimization to horticulture. In addition, there is a significant body of international industrial development and academic research which has attempted to exploit and understand plant light responses. This review just focusses on the application of spectral filters and optical coatings used to modify greenhouse cladding materials. The advantage of this approach is that spectral or optical manipulations of the light environment offers an entirely passive means to optimise productivity and/or minimize pest and disease infestation.

Light is a form of electromagnetic radiation; it is typically grouped in series of wavebands, which includes the ultra-violet (290 to 400nm), photosynthetically active radiation (400 to 700nm) and near infra-red (700 to 4000nm). Figure 1.1 shows a typical spectral distribution of light emitted by the sun. This spectrum will change with solar angle, atmosphere turbidity, time of day, cloud cover etc., but c. 42% of the incoming energy is in the PAR range (400 to 700nm). Solar radiation is typically measured in terms of the energy falling on a defined area in a second (Wm^{-2}), the amount of radiation falling over a day is often measured as $MJm^{-2}d^{-1}$. Understanding pure energy incident upon a surface is biologically important as this affects the thermal environment under which a plant is grown, and also the amount of transpiration. Transpiration is an energy driven process and rate of water loss is correlated to energy incident upon a plant.

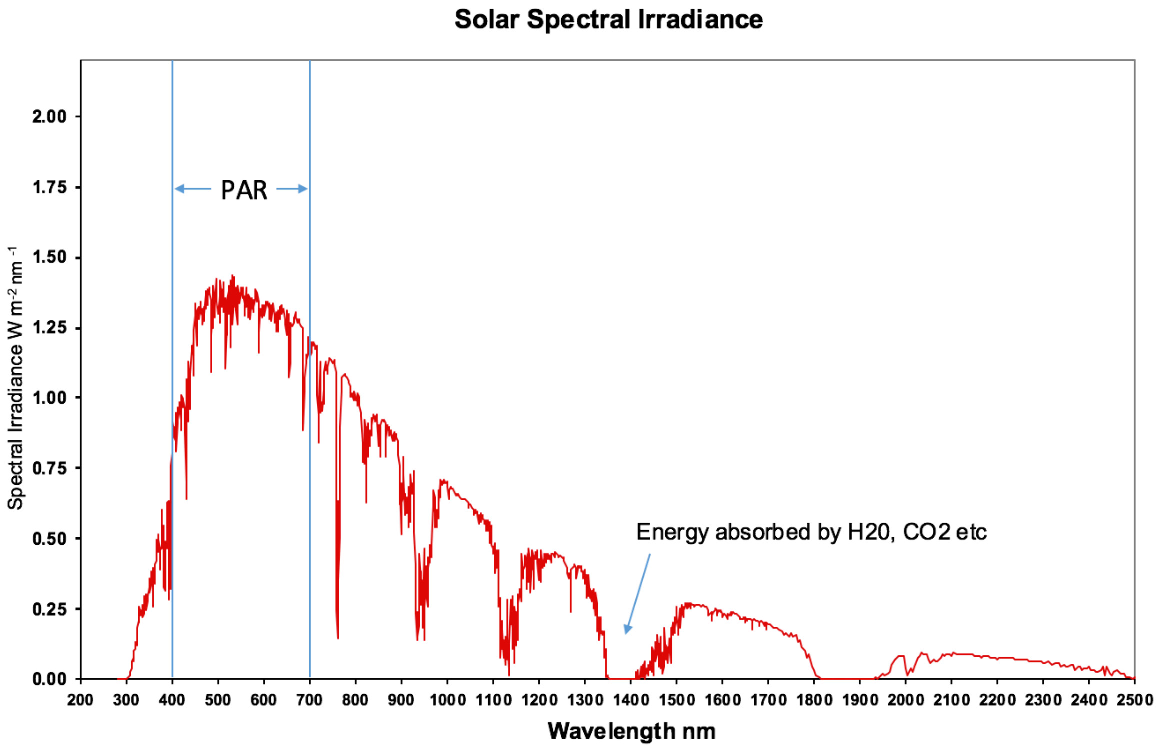


Figure 1.1. A typical solar spectral irradiance (clear day) from the global incident international standard ASTMG173. The marked lines denote the PAR region from 400 to 700nm.

Solar radiation can be considered to arrive in "packets" of energy called photons. The amount of energy in a photon is dependent upon its wavelength; shorter wavebands (such as UV photons) have proportionately more energy per photon than longer wavebands. The number of incident photons drives many biological processes, in particular photosynthesis, rather than the energy contained within those photons. On this basis for horticultural applications, it is now convention to measure photon number within defined wavebands incident upon a surface. The total light received over a day is referred to as the daily light integral (DLI) measured as $mol.m^{-2}d^{-1}$. Photon numbers do not drive all light responses; evapotranspiration rate is typically proportional to total energy receipt (W). Readers of studies on plant responses and lighting systems will repeatedly come across a range of different units used to measure light, ranging from the foot candle to lumen and lux (a lux is equivalent to one lumen falling on a set area of $1m^2$). Within the lighting industry lumen and lux are typical measures, but they are entirely inappropriate for use with horticultural applications. A lumen is measured with a weighted action spectrum in proportion to the sensitivity of the human eye to light; so for example human eyes have greater sensitivity to green rather than red or blue light. The human eye's sensitivity to light is very different to plants; therefore, the lumen light measure is not appropriate for plant related biological systems. There are though widely available conversion factors to enable switching between lux, Wm^{-2} and $\mu mol.m^{-2}s^{-1}$, and these are dependent on the light source (see for example Davis, 2016, Lighting the Principles and in Practice, http://horticulture.ahdb.org.uk/led-principles-and-practice).

The spectral output of a radiant source is defined by the emitting bodies surface temperature. As surface temperature increases it emits light at shorter wavelengths and with a greater intensity. The spectral quality above the surface of the earth is therefore a function of the temperature of the surface of the sun (5778K). It is very constant. As solar radiation passes through the atmosphere specific wavebands are absorbed or scattered by molecules in the atmosphere, such as water, carbon dioxide, etc. The impacts are shown on figure 1.1, demonstrated by the sharp absorptions of specific wavebands of light. Shorter (especially ultra violet and blue, 300 to 450nm) are more likely to be scattered in the atmosphere than longer wavebands. This phenomenon is known as Rayleigh scattering and explains why the sky appears blue on a clear day. Spectral quality can change quite significantly on cloudy days. Clouds increase the amount of light scattered and reflected and also have a higher absorption of specific wavebands of light.

Plant Responses

Plants use photoreceptors in order to absorb and respond to different wavebands of light. There are a whole series of photoreceptors governing fundamental processes including the rate of plant photosynthesis, morphological responses to light quality (e.g. shade avoidance), defense processes against ultra violet radiation, water movement, time keeping, etc. Plant responses to light quality are highly complex, and still poorly understood, in particular the interactions between different photoreceptor responses. For example, the rate of photosynthesis is considered to be highest under red rather than blue light (see Figure 1.2, from McCree), but we also know that blue light has a key impact on plant morphology (high blue tends to reduce stem elongation). Thus driving short-term photosynthesis via the exclusive use of red light may not produce an optimum quality over the duration of a crop cycle. Research evidence also supports the complexity of these responses, for example in the US, Hernandez and Kubota (2015) showed, in growth cabinets, that the highest dry matter content of cucumber was noted when they were grown in 100% blue light, compared to a red rich or environments with different ratios of blue to red. The lowest dry weight was found in the 100% red rich environment. These data are the opposite to the expectations one would have from solely examining the McCree relative quantum use efficiency spectrum. This work is consistent with analogous studies in the Netherlands. Thus overall plant growth is a function of a multitude of complex light driven feedback loops. Due to the complexity of these feedback loops, there is no single optimum “recipe” with which to irradiate plants.

Furthermore, there are significant variations in responses between plant species, seasons and even within the lifecycle of a single crop. This makes light optimization and selection highly problematic. *Therefore, notwithstanding any capital cost implications, final light choice will always be dependent on growers making informed choices, often following their own on-site trials.* However, there are a number of key principles, which can help inform these choices.

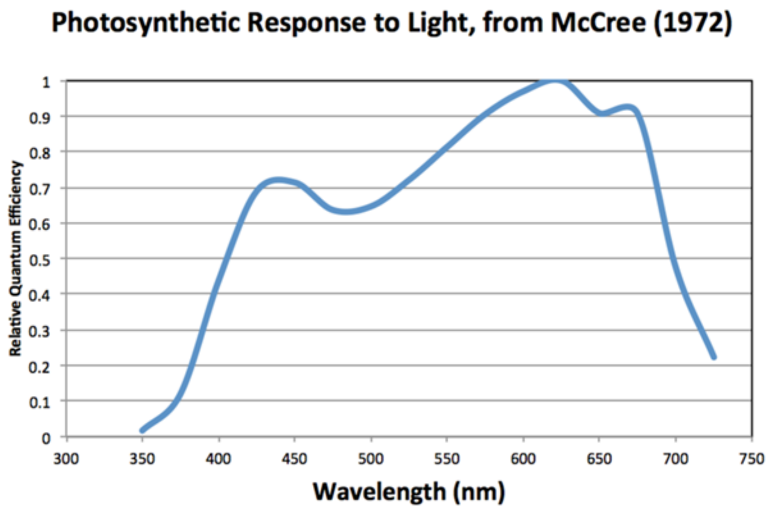


Figure 1.2. The McCree (1972) action spectrum for single leaf photosynthesis at different wavebands of light.

Quantity

The fundamental driver of plant growth is the process of plant photosynthesis and the rate of this process is strongly correlated to biomass production. However, the response to light of a single leaf is not linear and differs between species; the photosynthetic response for some species can be quenched at relatively low light levels. The rate of photosynthesis of a leaf is also highly dependent upon the age of the leaf, whether the leaf developed in low or high light conditions, the nutrient status of the plant etc. In tall canopies, such as tomatoes and cucumbers self-shading of solar radiation between layers of leaves can lead to reduced rates of photosynthesis from leaves deeper in the canopy.

It is though well known in crops such as tomatoes and cucumbers that there is a close correlation between incident light and overall yield. High wire crop yield, for products such as tomato, pepper and cucumber, will increase as light level increases, where broadly a 1% increase in light has been shown to drive up to a 0.7 to 1% yield gain (Cockshull *et al.,* 1992 J. Hort Sci., 67, 11-24: Marcelis *et al*., 2006, Acta Hort 711, 98-104) with slight variations with crop and background solar radiation levels (winter / summer). Strikingly similar responses also occur for flower crops such as Rose, Chrysanthemum, Freesia, Lilies as well as pot plants including Poinsettia and Kalanchoe (see Marcelis *et al.,* 2006). To demonstrate the response further Marcelis *et al.* (2006) quantified the yield response to light for cucumber with data taken from 14 Dutch growers (see Fig 1.3). This shows a curvilinear response with the impact of light reducing as the light integral increases. The shape of the curve is similar to the response of canopy photosynthesis to irradiance.

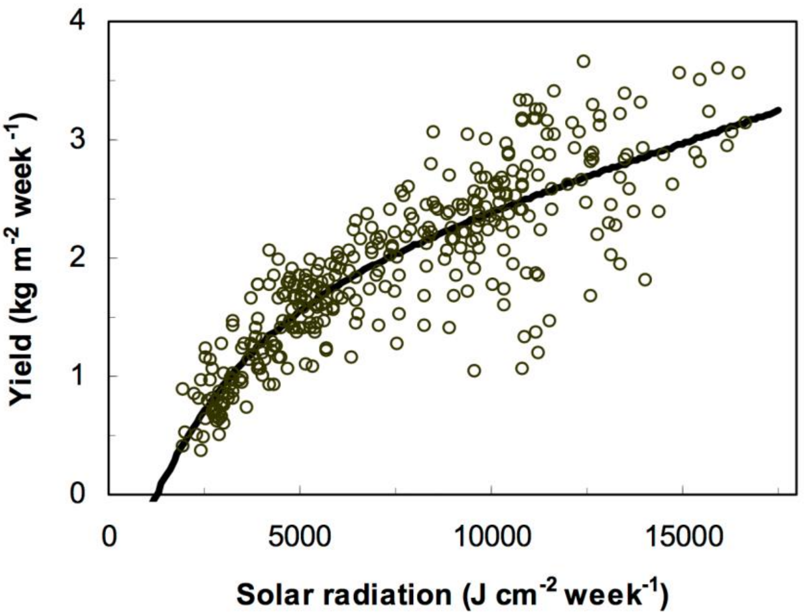


Figure 1.3. The yield of cucumber grown on 14 Dutch holdings in 1996-97 plotted against light integral (Marcelis *et al*., 2006).

To drive this yield reaction, the response of canopy photosynthesis is nonlinear, however, it is typically quenched at a higher light level than for a single leaf in isolation, see Figure 1.4 which shows the effect of light on tomato canopy photosynthesis reported by Acock *et al.,* working at the GCRI, in 1978. Clearly, there are significant opportunities to drive productivity by increasing light incident upon a crop. This response has been a primary driver of greenhouse construction and cladding material design for the last 50 years.

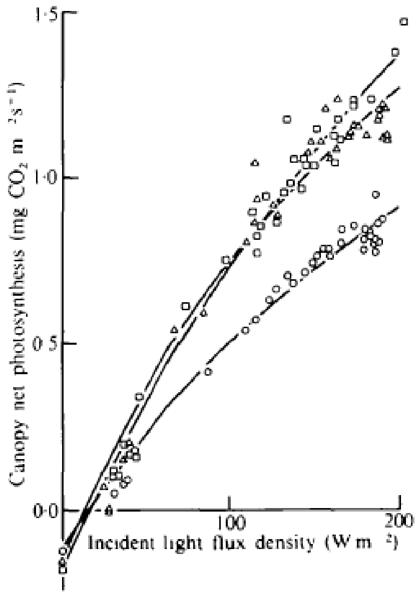


Figure 1.4. The relationship between light level and net canopy photosynthesis in tomato crops (Acock *et al.,* 1978).

Impact of Light Quality on Plant Morphology. Plants have developed complex acclimation systems that respond to light quality. Light quality photoreceptors have evolved to enable plants to gain competitive advantage from other species within the same environment. For example, the red / far-red photoreceptor evolved as a shade avoidance mechanism. Leaves absorb red light but tend to transmit far-red light, therefore deep within a canopy the light is far-red rich; this signals the plants to increase stem elongation in order to seek light. There are a number of photoreceptors, which are well known, and the action spectrum of the responses is shown in Figure1.5.

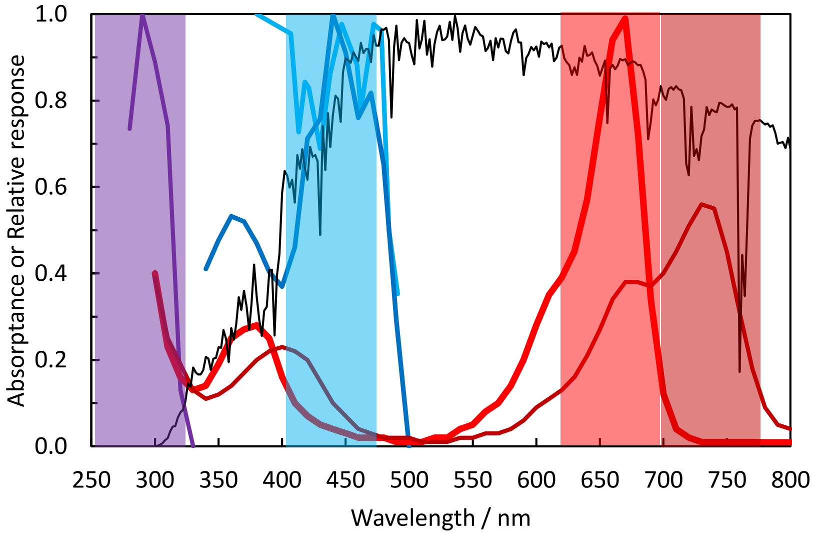


Figure 1.5. The action spectra of different photoreceptors. Purple line – the action spectra of UVR8 (Gardner *et al.,* 2009). Blue lines indicate the action spectra of phototropin and cryptochrome (Briggs and Christie 2002). Bright red light shows the absorption spectra of the inactive form of phytochrome B and the dark red line indicated the absorption spectrum of the inactive form of phytochrome B. The coloured panels indicated the regions of the spectrum that are important for controlling plant morphology.

Other than the red / far-red receptor, which has a diverse range of activities, including end of day timing, flowering rate, de-etiolation of seedlings, leaf shape and thickness, there are also key photoreceptors acting within the blue and ultra violet regions. The blue photoreceptors are typically referred to as phototropin and cryptochrome. Cryptochrome drives the inhibition of the stem elongation response to blue light. Phototropins have a key role in the movement of plants directionally to light sources, they are stimulated by blue light and one of their most important impacts is on stomata opening. Blue light stimulates the opening of stomata and is therefore critical in plant water relations. Blue light therefore has a critical and well-known impact on plant growth, and due to these responses all the known LED systems on the market have blue emitting diodes, to various degrees. The response to blue light, and magnitude of the responses, also varies between species. Blue light can also affect phytochemical and secondary metabolite production. A recent study in Denmark by Ouzounis (2014) showed that with increasing amount of blue light, roses, chrysanthemums, and campanulas increased their phenolic content; *Phalaenopsis* cultivars increased their pigments; lettuce plants increased both their phenolic and pigment content. The effects varied between species, highlighting the fact that plant responses to blue and red light are species and/or cultivar dependent. There are also a number of key UV photoreceptors which not only drive plant responses but also the vision of insects and these are considered in a later section.

Section 2. Light transmission through a material, ar and low iron materials

The transmission of light through greenhouse cladding materials is well defined, light is either transmitted, absorbed or reflected from the surface. Modern glass is designed to reduce both the reflected and absorbed proportions of light. Figure 2.1 shows the various mechanisms in which light interacts with a cladding material.

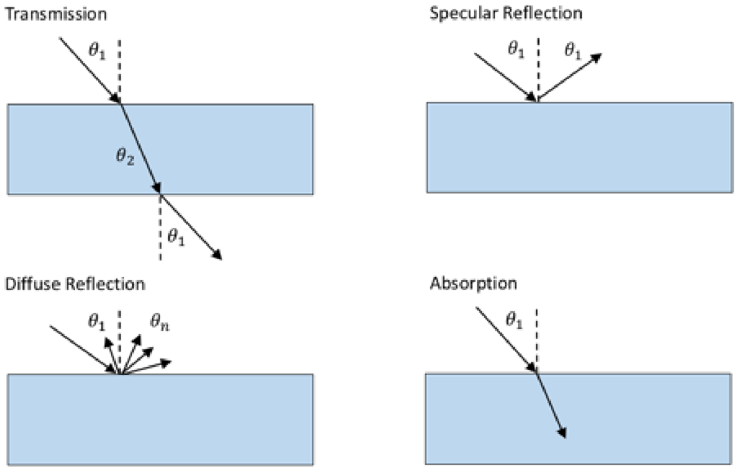


Figure 2.1. The fundamental interactions between light and a greenhouse cladding material such as glass, θ_n is the angle of incidence.

There are three primary mechanisms which need to be considered.

1) Transmission: This is where the beam of light passes through the medium. The amount transmitted depends upon refractive index of the medium and the angle of incidence of light, i.e. the angle between the incoming beam and the perpendicular to a surface (shown as θ_n on the diagram). As the angle of incidence becomes more acute (low solar angle) more light is reflected and less transmitted. As the beam enters the medium it can pass through it unimpeded or it can be scattered as a function of the surface or internal properties of the medium.
2) Reflection: There are two types of reflection, specular and diffuse. Specular reflection is “mirror like” and is light that is reflected off the surface at the same angle of incidence of the incoming beam. Diffuse reflection occurs when the surface is rough and light scatters off at all angles.
3) Absorption: Finally, a small proportion of light can be absorbed by the glass.

The angular dependence of light transmission for a range of different glass based materials is shown in Figure 2.2 (from Hemming *et al.,* 2014 Acta Hort. 1037, 883-895). This shows that transmission decreases as the angle of incidence of the incoming beam to the surface of the material becomes more acute. However, materials do differ in their sensitivity to angle of incidence. The experiments of Hemming tested a series of materials with different levels of haze (20%, 50%, 75% and 85%, shown as D20 to D85 on the figure) as well as variants with anti-reflective coatings which will be discussed in a later section. There were differences in the angular transmission of light between all materials, but transmission for all material dropped rapidly as the angle of incidence increased over 50 degrees.

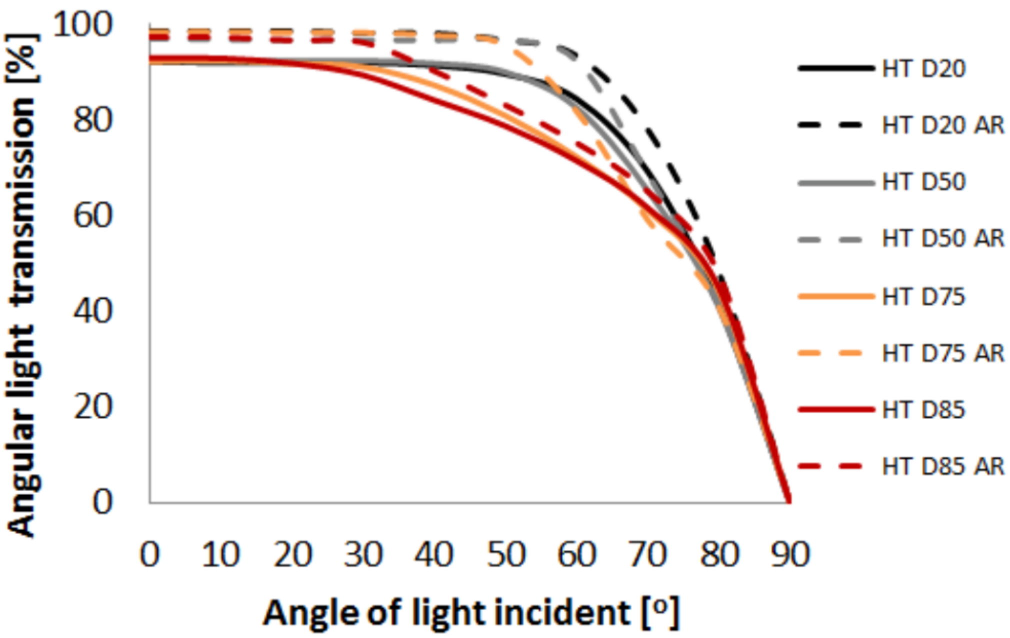


Figure 2.2. The relationship between light transmission and angle on incident for 4 diffuse glass materials (20, 50, 75 and 85%) with or without anti reflective (AR) coatings from Hemming et al., 2014.

The backwards reflection of light from glass has received less attention. However, there are two mechanisms to reflect from a surface; specular or diffuse reflection. Specular reflection is a mirror like reflection. The reflection of light is at the same angle of incidence as the incoming beam. Diffuse reflection occurs when surface irregularities change the direction of reflected light from a surface. Modern glass is now available with anti-reflective (AR) coatings. AR coats can be applied to one or both sides of the glass. They are effectively Nano thick coatings (e.g. MgF_2) which are typically sputtered onto the glass surface. AR coatings reduce the reflection of light from a surface by creating an interference effect which prevents the reflection of light at specific wavebands. They are typically found as coating on reading glasses but are now available for greenhouse glass installations. Hemming *et al.* (see Fig 2.2) showed that they are highly effective and can increase overall glass transmission by c. 5+%. This is a very significant increase in overall light transmission, as yield is known to increase by 0.7 to 1% per 1% increase in light. The effect is very dependent upon the manufacturer and tests must be made before selecting glass, however, as an example Hemming showed that for a 20% diffuse glass the transmission without an AR coat was 83.1, compared to 86.9 with one coat and 89.3 for an AR coat on both surfaces.

AR coatings can also affect the spectral transmission of the glass and this should be considered when evaluating a material. Figure 2.3 shows the spectral transmission of 3 AR coated glass products from different manufacturers reported by Hemming *et al.* (2011, Acta Hort. 893: 217-26). This shows that one manufacturer (GG) produced a product with significantly reduced UV (300 to 400nm) compared to the other materials, and a small cut off of transmission in the blue (400 to 415nm) region.

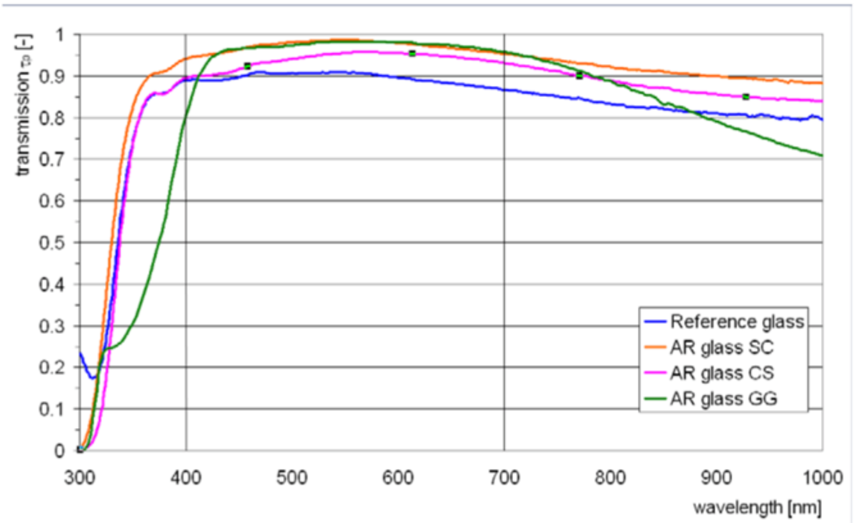


Figure 2.3. The spectral transmission of 3 different AR coated sheets of glass compared to a reference from Hemming *et al.* (2011).

It should be noted though that whilst AR coats are shown to be durable in an external environment, they cannot be cleaned with acid or chemical based materials. They can only be cleaned using hot water. Mardenko, who manufacture paints are also now reporting a new spray on product (Anti Reflect) which may have similar properties to an AR coating. They claim a c. 2% increase in light transmission and this is quite substantial, although as the product is new there is no independent data available on its performance.

Light can also be absorbed by a cladding material, the amount of light absorbed depends upon the medium, its content and thickness. Within glass the amount of light absorbed has typically been a function of the materials iron content, but new low iron glass formulations are now available. Hemming *et al* (2011, Acta Hort. 893: 217-26) measured the transmission of a number of standard and low iron glass materials, with and without AR coatings. For all treatments and materials, the low iron glass had a c. 2% higher transmission than conventional glass. The impact of low iron materials is smaller than AR coatings but still significant.

One of the key impacts on greenhouse light transmission is whether and how condensation occurs on the surface of the cladding. Pearson *et al* (1995, J. Ag. Eng. Res., 62, 61-70) showed that droplet condensation on polyethylene reduced the light transmission by 13%, but this was reduced to 5% when the condensate formed as a film. Pollet and Peiters (2000, J. Ag. Eng. Res, 77, 419-428) conducted more detail studies on a wider range of materials and using bespoke optical equipment. Figure 2.4 shows the nature of condensation formed on a range of greenhouse cladding materials, some formed spherical droplets, others such as glass more irregular shapes and the anti-drop PE material formed a film.

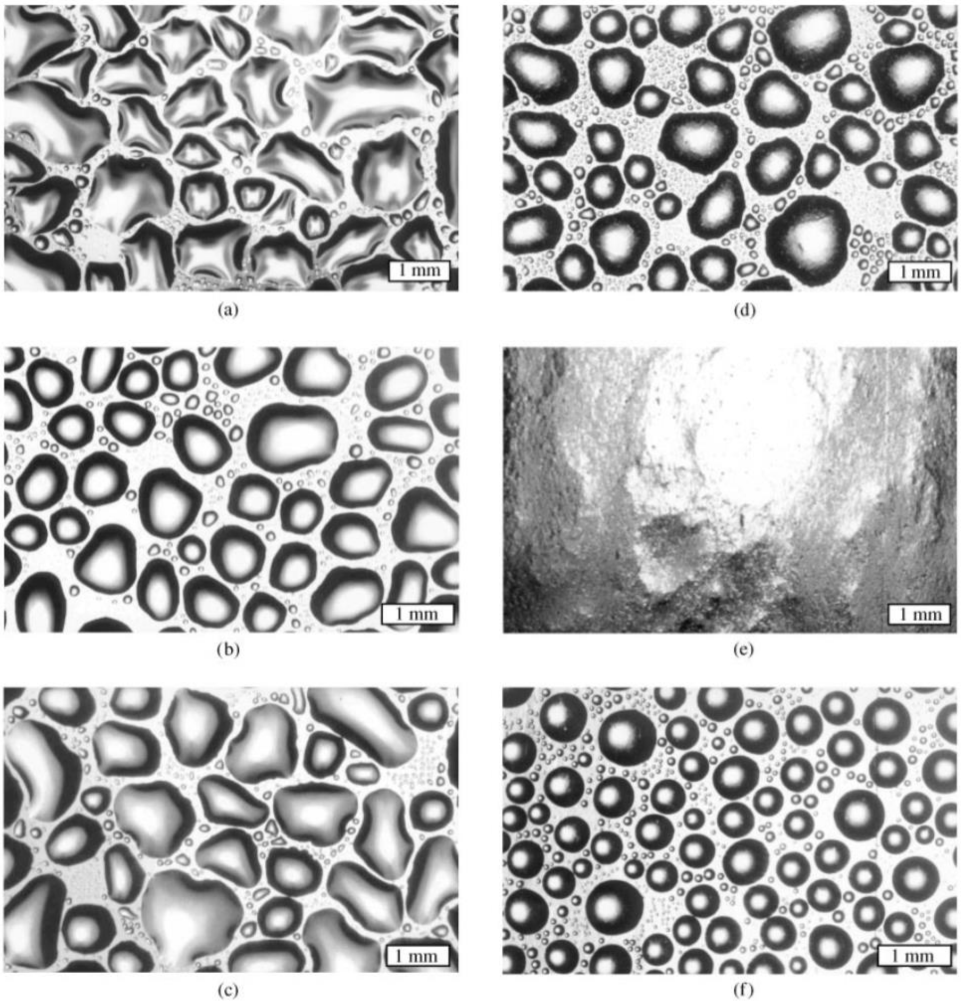


Figure 2.4. The types of condensation found on (a) glass, (b) low emissivity glass, (c) double glass, (d) LDPE, (e) anti drop LDPE and (f) anti-dust LDPE from Pollet and Pieters (2000).

Pollet and Pieters showed that the impact of condensation was dependent upon the angle of incidence of inbound light (see Figure 2.5). Thus on single glass the impact of condensation was greatest at incidence angles beyond 30 degrees.

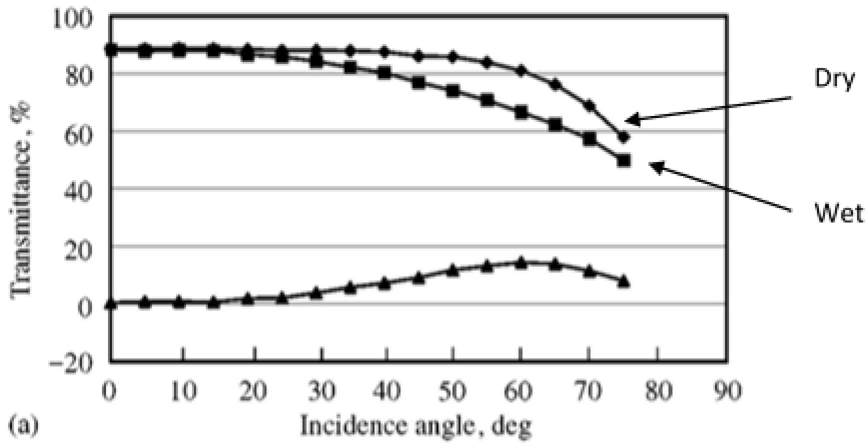


Figure 2.5. The impact of condensation on glass (block square) compared to a dry surface (diamond). The triangles show the difference between dry and wet.

Overall Pollet and Pieters (2000) showed that condensation reduced the transmission of glass by 8% (single and double pane), 11% for LDPE and 13% for anti-dust LDPE. Manufacturers are now marketing anti condensation paints for glass, such as the Mardenko AntiCondens or Royal Brinkman D Condens coatings which are reported by the manufacturers to increase light transmission by between 2 to 14% (see Mardenko website). In terms of polyethylene there are a number of anti-fog formulations which prevent droplet condensation forming. These have a surfactant embedded into the polymers which reduces droplet water surface tension. These are highly effective, droplet formation on polyethylene can reduce light transmission by 13%.

Section 3: diffuse optical coatings for glass

Light is the most fundamental driver of crop growth, development and yield. Greenhouse growers have a unique ability to manipulate the light environment to optimise yield and crop growth. For most high wire greenhouse crops, such as tomatoes, cucumbers and peppers there is a now generally accepted principle that a 1% increase in light broadly equates to a 1% yield gain. This principle has stimulated multiple innovations in glasshouse design, orientation, shape, structural support and glass technology to maximise greenhouse light transmission. These innovations still continue and glasshouse designs with fewer glazing bars and new high transmission glass (e.g. low iron) are still entering the market. However, it has been recognised for a number of years that glass, or other greenhouse claddings, can be manipulated to further drive crop growth. These approaches include the diffusion of inbound direct solar radiation. Here we review the technical approach and potential impact of these innovations.

Diffuse Light

Light inbound from the sun arrives at the surface of the earth as either a direct beam of radiation or scattered by aerosols or clouds (diffused). The ratio of direct beam to diffuse radiation changes in proportion to the time of year, solar angle and of course the cloud cover. Fig 3.1 shows the total and diffuse radiation recorded over a year in Cambridge UK., the difference between the total and diffuse elements is the direct beam radiation. Over a year just under half of the inbound radiation is direct beam, but this is greatest during the summer months.

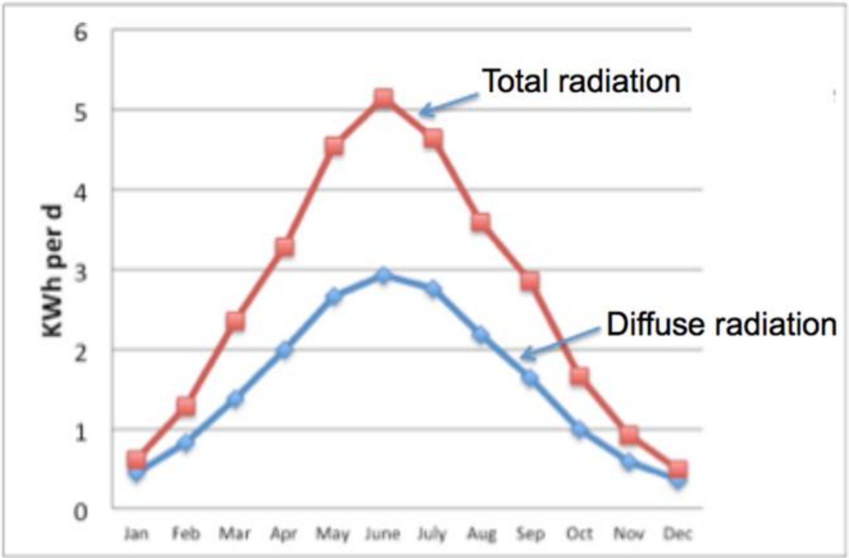


Figure 3.1. The global and diffuse radiation received in Cambridge UK. The difference between the global and diffuse radiation is the direct beam element.

A high load of direct beam radiation is needed to drive crop growth, but it now well established that this is not the most effective way to irradiate a crop. This is for two primary reasons, firstly the photosynthetic response is quenched at relatively low light levels, so a highly focussed beam of light on a relatively small leaf area (the top of a canopy) is inefficient. The photosynthetic process simply cannot convert high loads of lights into carbohydrate. These impacts are highlighted on the shadow diagram shown in Fig 3.2. This illustrates that on 1st April at 3pm up to the first 2.5m of a 4m tomato canopy are completely shaded from direct beam radiation intercepted by adjacent rows. The shaded leaves will have a lower photosynthetic rate than the upper canopy layers. Secondly, light is also a source of thermal energy, so high localised loads of solar radiation on the top of a canopy from direct beam radiation simply heats the leaves. This localised heating can have dramatic effects on the growth of the crop including imbalances in crop development, transpiration and in extreme cases leaf scorch.

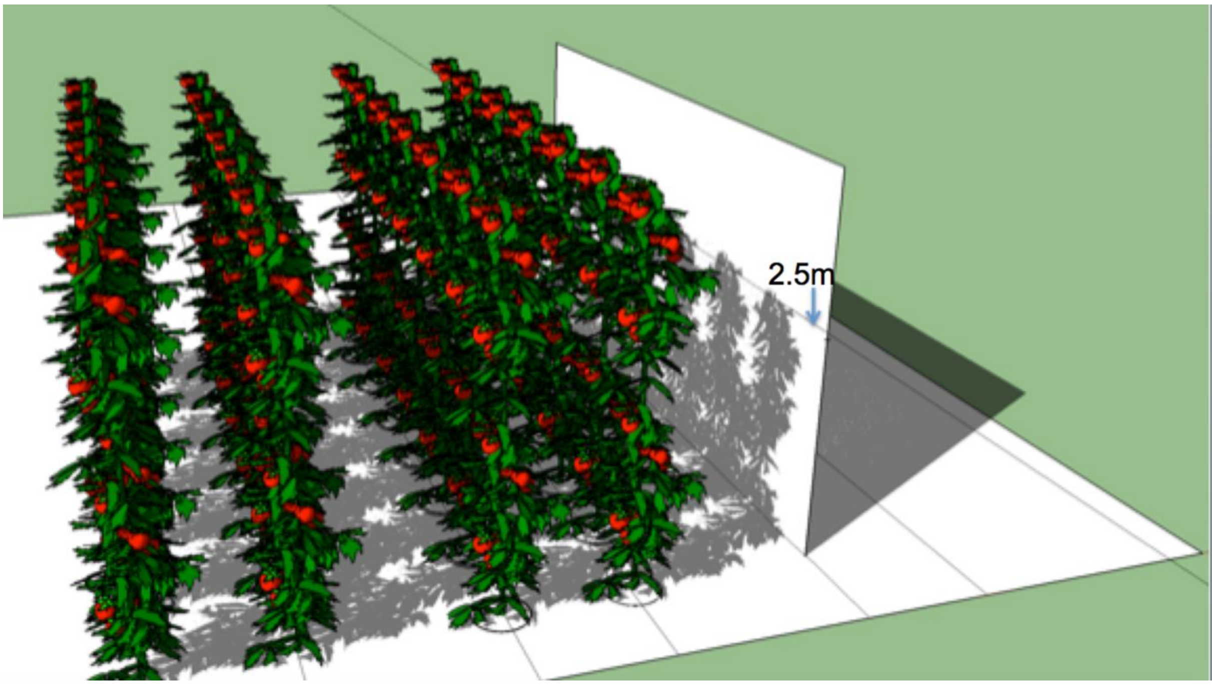


Figure 3.2. Shadow diagram of a 4m tomato crop.

The obvious approach to reduce this self-shading impact is to diffuse or scatter all in bound direct beam radiation by changing the physical properties of the glass or greenhouse cladding material. This enables scattered light to enter deeper or vertically into the canopy. This has the combined impact of reducing the radiation load on the upper parts of the canopy and increasing light interception in the lower parts of the canopy. Diffusion has the additional benefit in that it creates a more uniform light environment in the horizontal as well as vertical planes within the canopy. In a horizontal plane solar radiation from the sun is highly variable in intensity, this reflects rapid changes in cloud cover and solar angle. Within a greenhouse the changes in solar angle affect the shade patterns from the greenhouse roof glazing bars and gutters. This creates areas of sunspots and shade within a horizontal plane across a canopy. These sun and shade spots are accentuated by leaf self-shading as the light moves deeper into the canopy. Tau Li at Wagenginen UR has recently measured the horizontal uniformity of light 50cm below the top of a tomato canopy and showed dramatic differences in the uniformity of the light environment (see Figure 3.3).

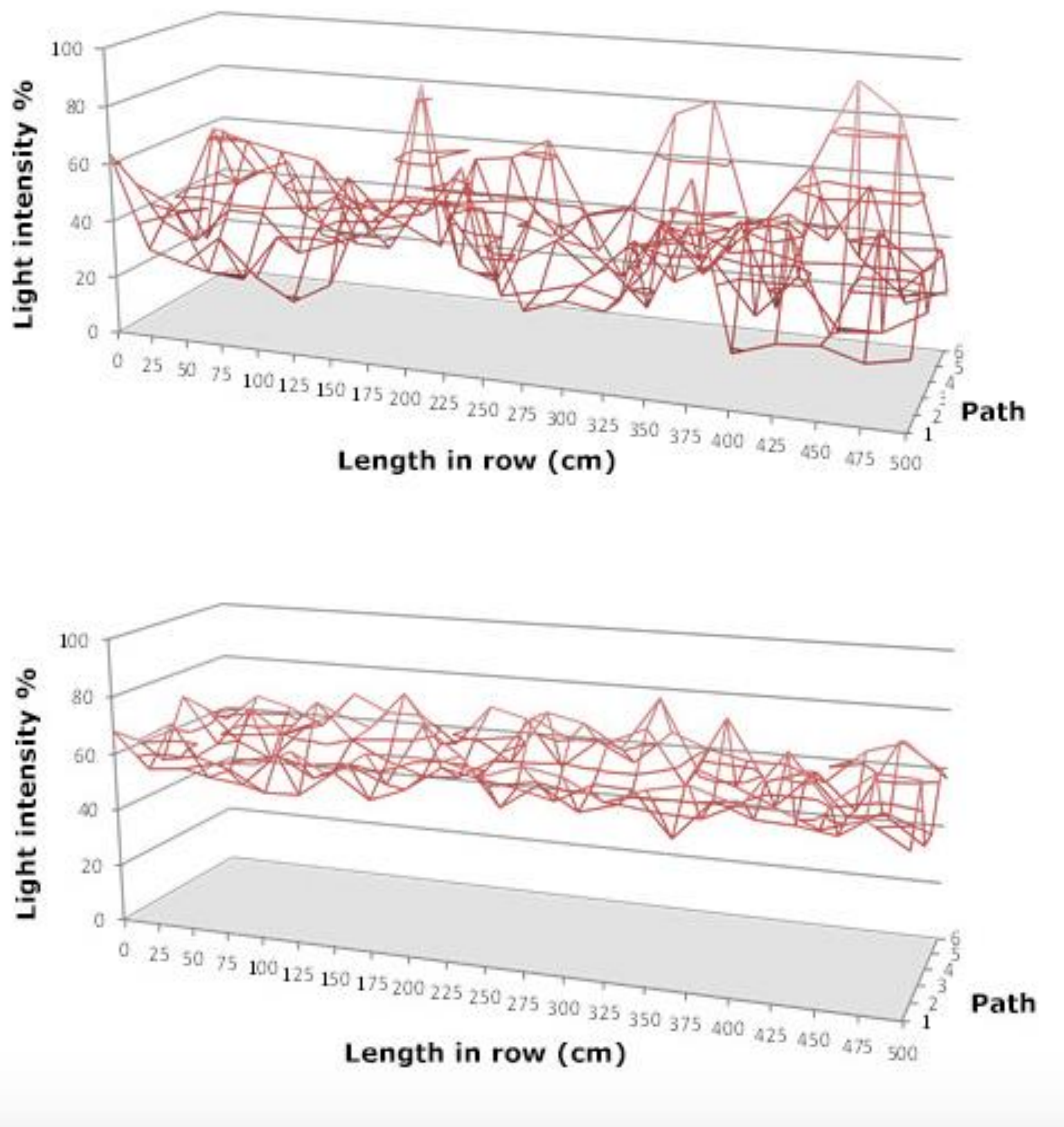


Figure 3.3. The spatial variability of light in a horizontal plane measured 50cm below the top of a tomato canopy with both clear (top) and diffuse (lower) glass. source Wageningen UR.

Thus diffuse glass produces a more even light distribution both within a vertical plane (drives light deeper into a canopy) and across a canopy within a horizontal plane. The impact of a uniform horizontal light plane could be significant as leaf photosynthesis has a non-linear relationship with irradiance. At high irradiances, i.e. within sunspots in a horizontal plane, photosynthetic capacity can be quenched, reducing the overall radiation use efficiency of the crop.

In terms of practical implementation, the principle of light diffusion has been considered for many years and first emerged as an experimental approach in the late 1960's with work at the Glasshouse Crops Research Institute (Edwards, Lake and Sheard, 1969 onwards). The team at the GCRI were tasked to design new experimental glasshouses with highly uniform light environments and examined the use of diffuse glazing materials. The materials examined were textured or decorative glass systems (see Figure 3.4). These materials are expensive and have a low light transmission relative to modern systems. However, they were installed on a number of glasshouses and can still be found in older structures in France (Fig 3.5), where the high solar loads have a greater impact than in the UK.

Figure 3.4. Decorative or textured glass, manufactured by Pilkington's.

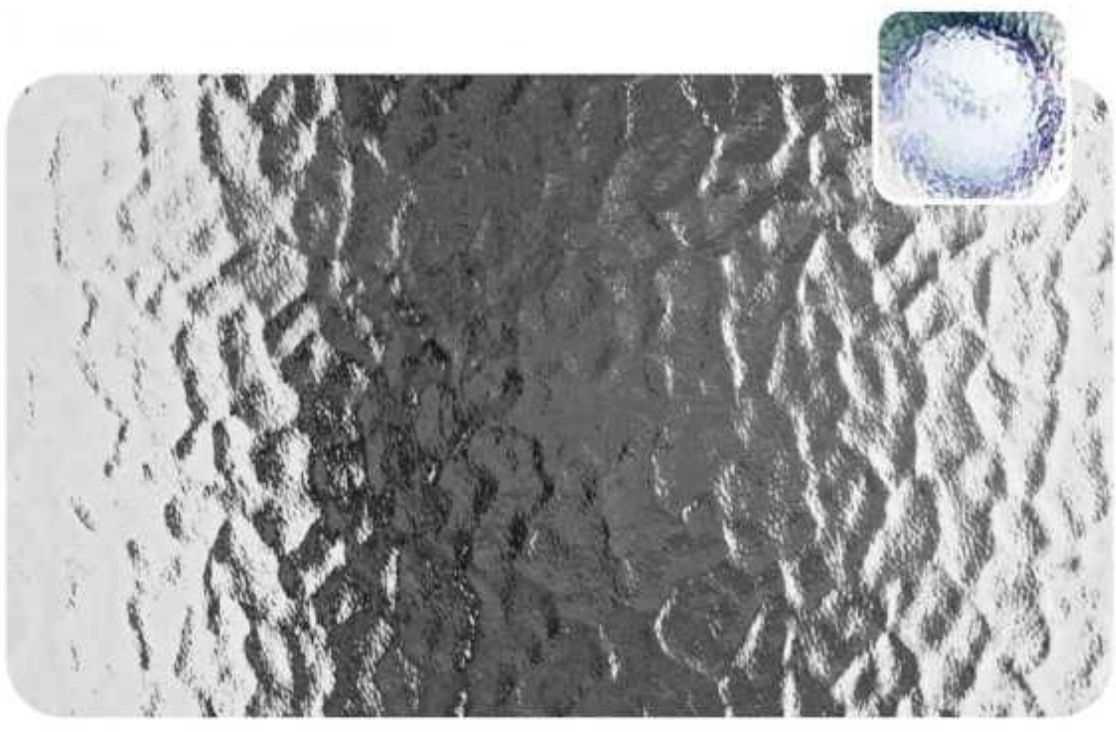


Figure 3.5. A greenhouse in France glazed with textured glass to achieve diffusion.

Modern systems to diffuse light are now very different to the early textured glass systems that did not take off due to issues with cost and overall light transmission. Modern diffusion systems use a range of techniques to optimise the proportion of light diffused as well as the overall scattering pattern. However, there is a great diversity in the performance of these modern materials and this reflects both the proportion of direct beam radiation which they diffuse (haze) and also its scattering pattern. Figure 3.6 shows how the scattering patterns can broadly change with material.

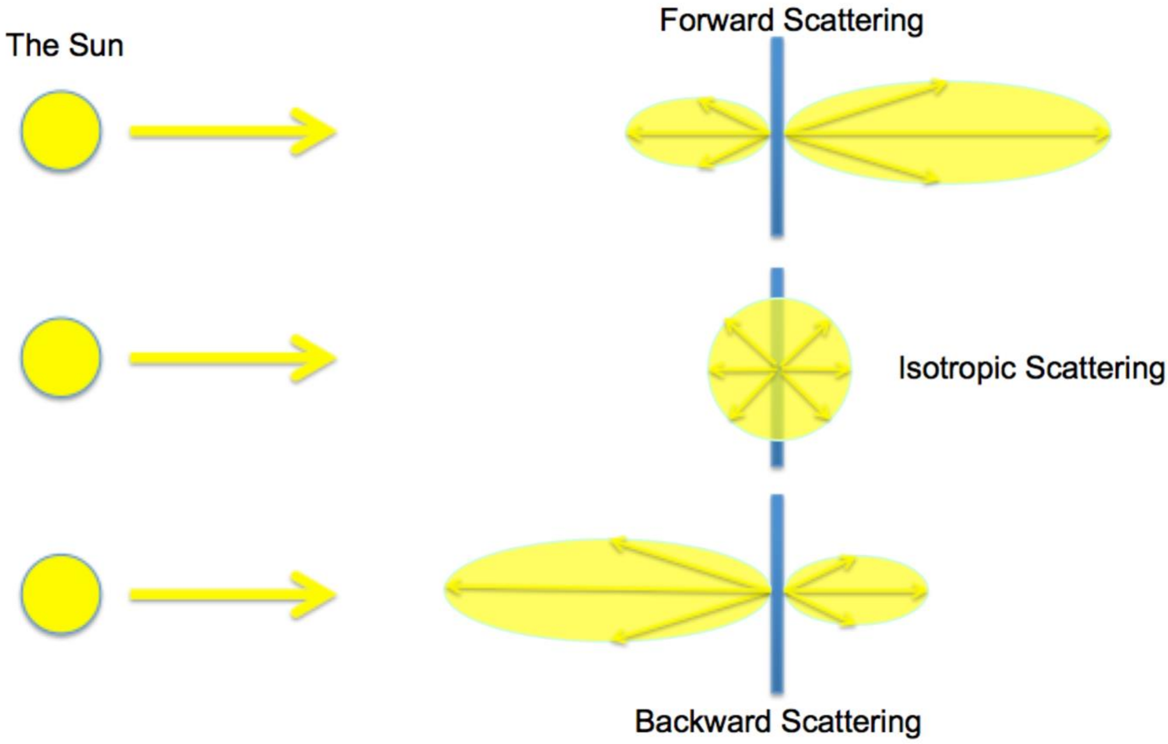


Figure 3.6. Materials diffuse light with a range of different scattering cones and directions, and these depend on the material internal and surface properties.

Figure 3.6 emphasises that not all materials scatter light in a uniform direction (isotropic), in fact nearly all materials have non-uniform, anisotropic, or directional scattering. Most highly transparent materials have a high degree of forward scattering, reflective materials tend to show anisotropic backward scattering. It has not yet been shown which is the optimal scattering pattern for a greenhouse glazing material. However, directing as much light as possible into a canopy will likely require a highly isotropic scattering pattern, i.e. the light is thrown evenly in all directions from a material.

The amount of scattering and its scattering pattern is a function of the surface and internal properties of a material. There are multiple ways to adjust the internal properties of a material to influence the way it scatters light, one good example is the polyethylene material Luminance, marketed by BPI Visqueen but designed in an EPSRC LINK project in conjunction with the University of Reading in the early 90’s. Luminance contains a simple inert but shaped additive that scatters light (see Figure 3.7).

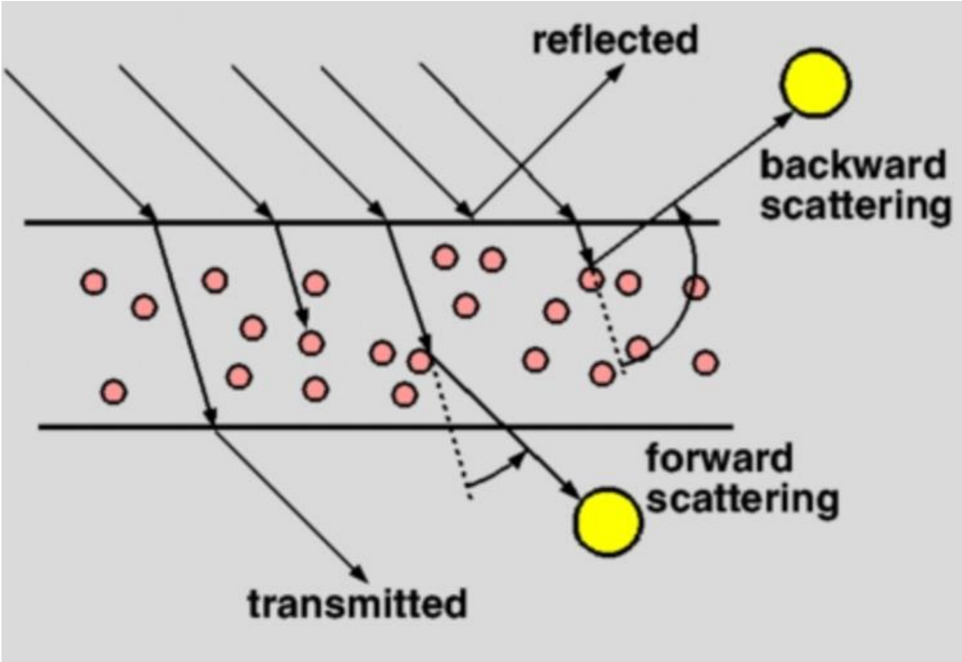
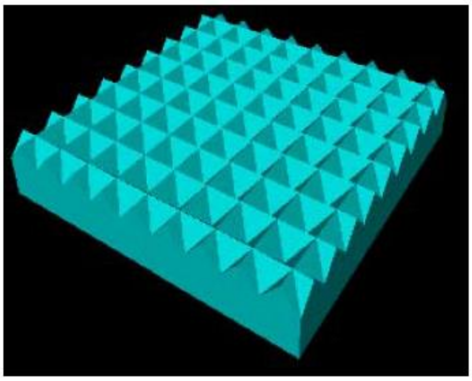


Figure 3.7. The light scattering mechanism of cladding materials with diffusing particulates.

With particulate scattering materials as light passes into the medium it hits a shaped particle and its path is then diverted, some of the light will be back scattered, some of it forward scattered and some will pass through unaffected. The actual scattering pattern is then a function of the shape and size of the particulate, its refractive index, and concentration in the material. This has proved a highly effective approach and Luminance THB plus other similar variants are now widely used globally as cladding materials for polyethylene tunnels (see Figure 3.8).

Figure 3.8. shows Luminance UHB clad on a multi span tunnels of table top strawberries.

This approach could be used on glass, but more conventionally glass is made diffuse either by coating the material with a polymer based diffusing layer or by changing the surface properties of the material. There are a number of approaches that can be used to modify glass surface properties; these include the generation of specific geometric structures upon the surface of the glass or by simply roughing it. Two examples of products with geometric surfaces are the San Gobain Albarino P and G ranges (see diagram 3.9 below)



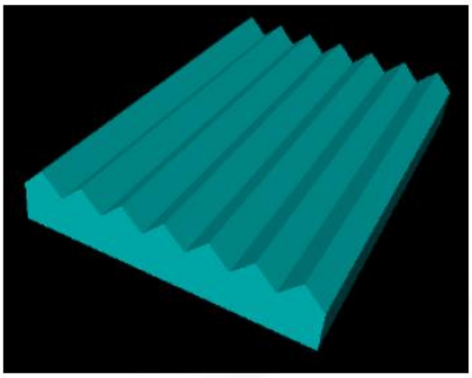


Figure 3.9. The surface of Albarino P (left, inverted pyramids) and G glass (right, grooved) from San Gobain.

San Gobain produced these materials as high transmission glass solutions for the solar PV industry. They are designed as light traps and can achieve transmissions in the order of 3% higher than flat surface glass. This is because the shapes act as light traps, any reflected light can hit the steep surfaces of the geometric surface and then bounce back through the original pane. The materials are also highly diffuse and can scatter light. There are concerns though as to whether the inverted pyramids may gather dirt, and hence Albarino G was produced. This is grooved and therefore is likely to reduce the accumulation of surface dirt. Figure 3.10 shows from the San Gobain product information sheet images of the actual appearance of the marketed products.

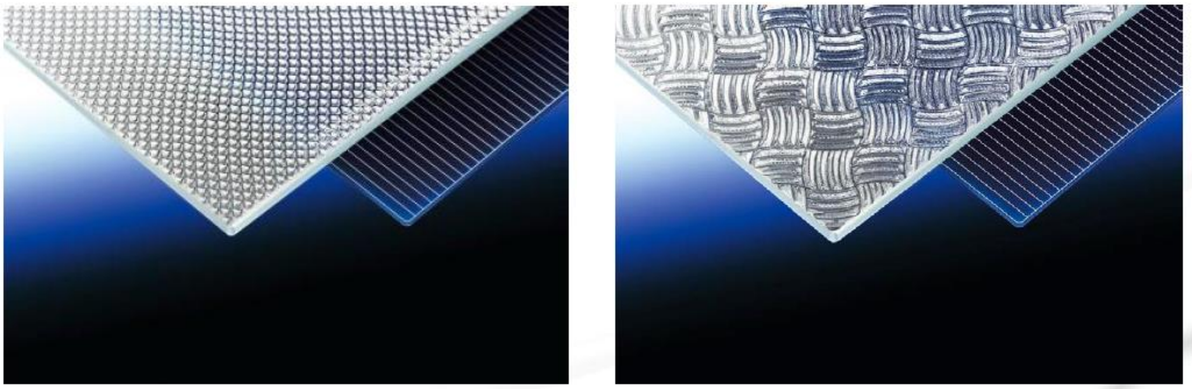


Figure 3.10. San Gobain P (left) and G (right) glass products with geometric surface properties.

Wide ranges of diffuse glass materials have now been tested for horticultural application. The surface properties of a range of materials tested by Hemming *et al.,* 2012 at Wageningen UR are shown in Figure 3.11.

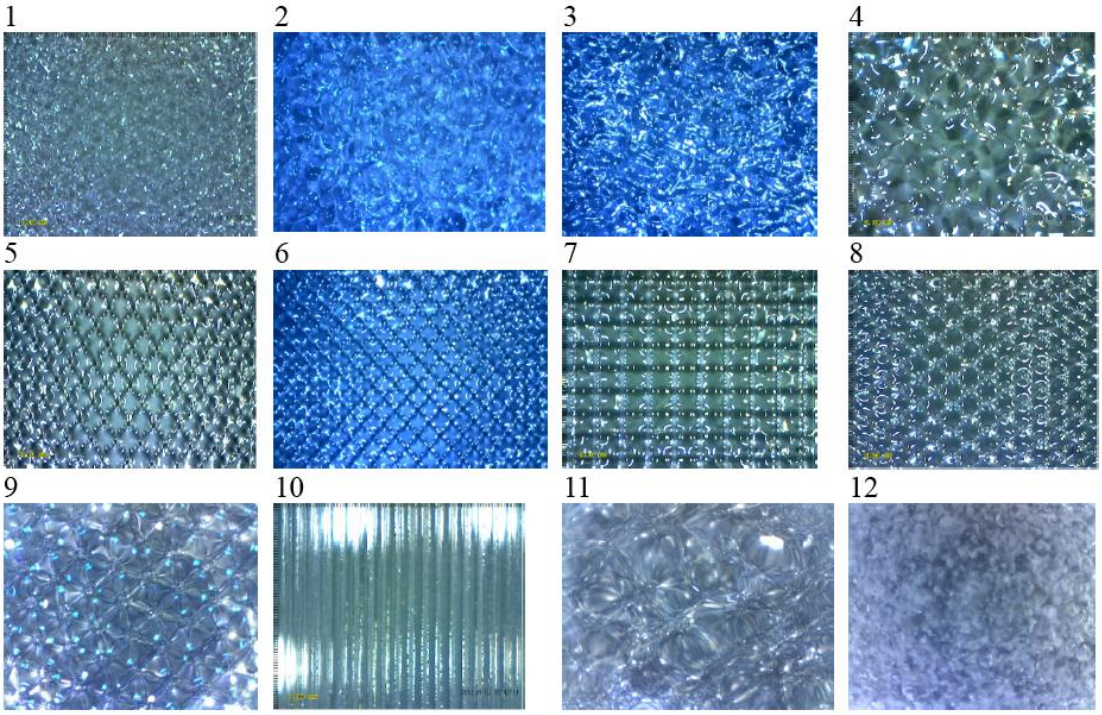


Figure 3.11. Images of the surfaces of 12 diffuse glass materials examined by Hemming *et al.,* 2012 at Wageningen UR.

This shows that a very diverse range of materials are now on the market, these include the grooved and prismatic (inverted or not) materials shown in Figure 9 as well as a range of matt or etched surfaces. Hemming's *et al.,* also showed very significant differences between the optical performances of the materials (see Table 3.1).

Material code	Basic glass	Surface structure	η [%] (TNO/WUR)	τ_h [%] (TNO/WUR)	τ_p [%] (NEN 2675)
FLOAT	Normal	Float	0	82.7	89.8
FLOAT ARAR	Low-iron	Float	0	91.9	96.0
HT 20	Low-iron	Matt/matt	25	84.3	92.1
HT 20 AR	Low-iron	Matt/matt	20	91.5	98.6
HT 50	Low-iron	Matt/matt	52	83.5	92.3
HT 50 AR	Low-iron	Matt/matt	51	89.2	97.0
HT 75	Low-iron	Large matt/matt	76	79.4	92.1
HT 75 AR	Low-iron	Large matt/matt	77	86.9	98.3
HT 85	Low-iron	Prismatic	84	78.2	92.9
HT 85 AR	Low-iron	Prismatic	85	83.0	97.3

Table 3.1. The optical transmission of a range of different glass materials tested at Wageningen UR by Hemming et al., 2012. η is the haze (proportion of light scattered or diffused by more than 5 degrees from the norm), τ_h is the hemispherical transmission (i.e. the transmission calculated for incident light incoming at all directions), and τ_p is the perpendicular transmission when light hits the glass perpendicular to the surface. AR refers to anti reflective coatings,

Table 3.1 shows dramatic differences in the performance of different materials. The greatest haze (84 to 85%) was created by the prismatic materials. A large matt/matt surface also created a high degree of haze (76 to 77%) whilst some materials only created 25% of haze. The issue with visual inspection of glass is that is difficult for the human eye to determine how haze percentage varies between materials; physical measurements are therefore critical to assess differences. The second issue with material assessment is that it is difficult for the human eye to determine the scattering pattern of any material. A material can have a relatively high haze value but all the light might still be focussed within a very narrow scattering cone.

To assist with material assessment, Wageningen UR developed a measurement system called the F-scatter. This uses analytical equipment to calculate how far light is dispersed by a material and compares it relative to an isotropic scattering pattern. The F-scatter is thus a relative measurement (varies from 0 to 1) to an isotropic scattering pattern, if all the light was scattered evenly in all directions (isotropic) then the F value would be 1.0 if the light is not well scattered and stays within a tight cone then the F value is very low and could approach zero.

Figure 3.12 shows the scattering pattern of four glass materials measured by Wageningen UR. This shows a very high degree of variation between materials, some had wide scattering cones and others very narrow.

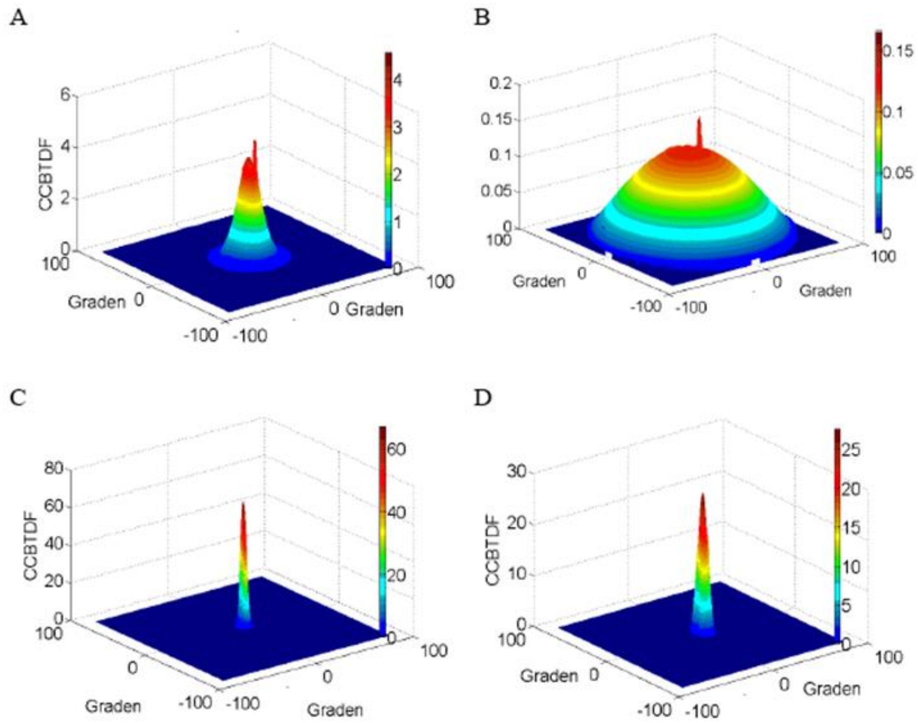


Figure 3.12. The scattering pattern of 4 glass materials measured at Wageningen UR by Hemming *et al.,* 2014 Acta Hort 1037, pp883, material A had a reported haze of 92% and F scatter of 0.67, material B haze of 94.7% and F scatter of 1.0, C an etched material with haze of 41% and F Scatter of 0.153 and D a prismatic material with haze 73% but F scatter 0.351.

The differences in the optical properties of materials are very significant and difficult for a human to perceive. It is therefore important for a grower who might be selecting diffuse glass to ensure that they have a full technical data set that describes the total transmission of light as well as the scattering patterns.

The final way to diffuse light within greenhouses is by the application of diffusing paints to the glass surface. A number of manufacturers such as Mardenko and Royal Brinkman produce paints that can be applied to glass to diffuse light. The Mardenko diffusing paint is sold as Redufuse (http://www.redusystems.com/en/redusystems/diffusion/redufuse-en/) and the Brinkman version is DFuse (see http://www.brinkman.com/catalogue/teelt/teelt-papri/d-fuse-vegetables-495-15-l-detail), other manufacturers may sell similar products. There is more limited standardised information on the performance of these materials. The Brinkman product is also branded as Hermadix. Hemming et al tested Hermadix coatings at different concentrations and showed that light transmissions were very variable according to whether the coating surface was wet or dry; wet coats had a higher total transmission than dry (up to 79% wet compared to 60% dry), but a greater amount of haze was caused by dry rather than wet surfaces. There is limited experimental evidence of the impact of paint coatings on yield, however, of note Dueck *et al,* (2012, Wageningen report GTB-1158) showed that if Redufuse was applied in May tomato yield was 5% greater than a control. This is a significant impact for a short duration of application. However, more independent information is required to assess the durability of these materials, and AHDB trials (PO 019) are on-going through the summer 2016 at the AHDB Bedding Plant Centre in Baginton.

Biological Responses to Diffuse Light

The responses of crops to diffuse light are only just being unravelled. The key interest is whether diffuse cladding impacts yield or crop quality. For many crops there is a tangible lack of clear and simple studies comparing crop yield in diffuse compared to clear radiation environments. However, in the soft fruit industry diffusing polyethylene materials, such as Luminance THB are almost ubiquitous in commercial production within the UK and in many countries worldwide. Leading greenhouse producers such as Haygrove cite very significant commercial yield increases from diffusing materials.

The most detailed scientific studies are arguably those conducted at Wageningen on a range of glasshouse high wire (tomato, cucumber and pepper) and some ornamental crops. For cucumber, Hemming *et al.,* (2007, Wageningen note 448) showed that cucumber yield was 4.8% higher in a diffuse greenhouse compared to a control, despite the measured light transmission through these early materials being 4% lower than the control. On tomatoes, Dueck *et al.,* (2012) showed an 8 to 11 % yield increase when the crop was grown in glass with a haze level between 45 to 71%. The majority of the impact was via an increase in fruit size rather than number. Dueck *et al* also suggested that plants may be more tolerant of botrytis when grown under diffuse compared to standard glass. A more recent review of the literature by the key Wageningen research group responsible for most of the authorative studies suggested diffuse light generally gives a 5 to 10% yield increase in key crops such as tomato, pepper, cucumber, roses and potted plants (see Marcelis *et al*. 2014, Acta Hort 1037, 39-46).

For ornamentals, some of the impacts can be very dramatic. In Anthurium for example van Noort (see Figure 3.13) showed very significant differences in leaf morphology and overall quality with diffuse light.

Figure 3.13. The effects of diffuse light on Anthurim leaf size and shape, the plant on the left was a control compared to 41 (middle) and 74% (right) treatments.

However, in Anthurium the effects of diffuse light were highly cultivar sensitive (see Li *et al.,* (2016, Front. Plant. Sci, 7:56). For a further crop, roses, Garcia Victoria *et al.* (2011, Acta Hort, 952, pp 241-248) showed a 5.1% increase in stem yield with 72% haze against a standard glass control.

The key biological question is how diffuse light drives these yield increases. Li *et al.,* (2014, Ann Bot, 114, 145-56) recently examined in considerable detail the key drivers for crop photosynthetic activity within a diffuse compared to a direct and diffuse irradiated crop. They showed that 33% of the response was directly related to a more uniform light environment within the horizontal plane (as also shown in Fig 3.1). This reflected a reduction in sun / shades spot on the leaf surface creating a more efficient leaf photosynthetic response. An improved vertical distribution of light (i.e. diffuse light penetrating deeper into the canopy) was responsible for a further 21% of the response. This response was shown clearly by measuring light penetration within the canopy via an array of tube solarimeters (Figure 3.14). This shows that a higher proportion of the light was reaching the middle layers of the canopy in 71% haze compared to control treatments.

A further key finding by Li *et al* was that the middle layer leaves showed a clear anatomical adaptation to the higher light levels within the middle of a canopy illuminated with diffuse radiation. This included a significant increase in the thickness of the mesophyll, spongy and palisade leaf tissues. These anatomical responses are well known in nature where sun leaves tend to be thicker than shade leaves. The consequences of these adaptations were that leaves within the middle of a diffuse canopy have higher photosynthetic responses than those in a clear glass illuminated canopy (see Figure 3.15). This adaptation was responsible for 23% of the overall response of canopy photosynthesis to diffuse light.

The final impact of diffuse light was on leaf area index that was slightly higher in the diffuse compared to control treatment. The leafier canopy within the diffuse light treatments was responsible for 13% of the overall canopy photosynthesis response. The study of Li *et al* (2014) eloquently described the responses of the crop to diffuse light in tomato. Although less data is available, we would expect similar mechanisms to be involved in the responses of other high wire crops.

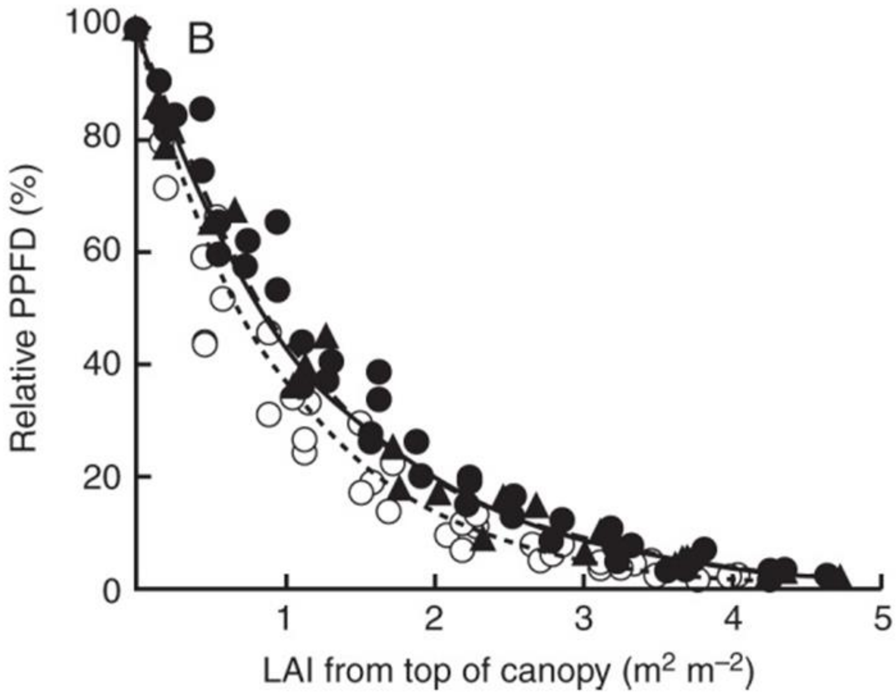


Figure 3.14. Light penetration into a canopy for a greenhouse clad with clear glass (open circle), 45% haze (black triangle) and 71% haze (closed circle), from Li *et al.,* (2014).

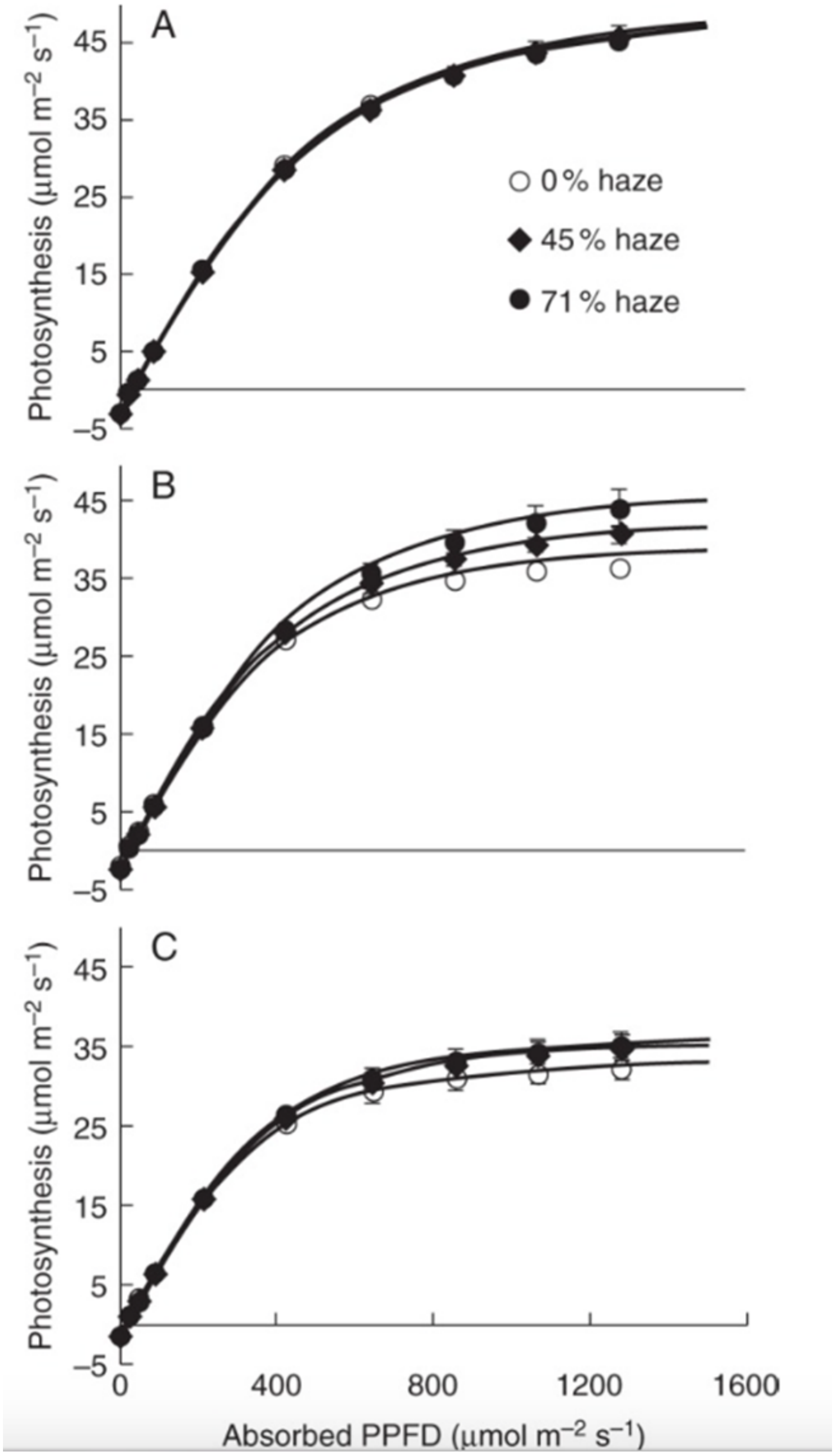


Figure 3.15. The leaf photosynthesis light response curves at the top (A), middle (B) and bottom (C) of a canopy from Li *et al* (2014).

Commercial considerations

In terms of investment decisions for glass glazing systems, growers are clearly faced with a multitude of opportunities. Any investment decision must be made solely by the grower, using costs provided by suppliers. However, as a guide Montero *et al.,* (2012) provided some indicative costs (provided to them by Hogla, NL) of different diffuse and AR coated glass solutions, shown below;

Glass type	Investment (euro/m^2)
Horticultural glass, not tempered	3.5
Horticultural glass, tempered	6.5 to 7
Diffuse and tempered glass	11 to 12
Diffuse, tempered and AR coated glass	16 to 18

They concluded the payback of diffuse / AR glass on a cut rose crop with a yield gain of 10% would be 4 years compared to standard horticultural tempered glass. We are aware of no other published pay back analyses on other crops, but these are indicative of decent returns, assuming the materials keep performing and can be kept clean over extended periods.

Summary

It is clear therefore that in a range of crops from high wire vegetables to ornamentals and soft fruit that diffuse light has a significant positive impact on crop yield. Although diffusion technology, whether applied with polyethylene or glass is well known, it has still yet to be fully optimised. Key opportunities to improve the technology still remain, this includes the development of materials with even higher haze percentages and in particular a better understanding between the scattering pattern of a material and the crop response. For example, what is the impact of the scattering cone on the response, can materials be developed which specifically target scattering to certain parts of the crop. Furthermore, the long term sustainability of the material's efficacy needs to be established, for example, do diffuse materials collect dirt at a higher rate than clear materials, how should these materials be cleaned?

Section 4: ultra violet radiation

Ultra violet radiation can be subdivided into UVC (200 to 280nm), UVB (280 to 320nm) and UVA wavebands (320 to 400nm). For health and safety reasons applications with high doses of UVC and UVB should be treated with extreme caution. However, UVA and UVB in small irradiances can have significant biological impacts; this is because plants have evolved mechanisms to screen the potentially damaging impacts of very short wave radiation. This includes adaptations to morphology in response to UV as well as the synthesis of protective phytochemicals. The ultra violet photoreceptors also affect stem elongation but can have dramatic effects on plant phytochemical synthesis, in particular essential oils, flavonoids and anthocyanins; compounds which impact plant flavour and colour. This was shown in detail by Tsormpatsidis *et al* (2008, Env and Exp Bot, 63, 232-9) who grew Lollo Rosso lettuce under polyethylene materials which cut off UV light up to very defined wavebands within the UVB and UVA regions (see Figure 4.1).

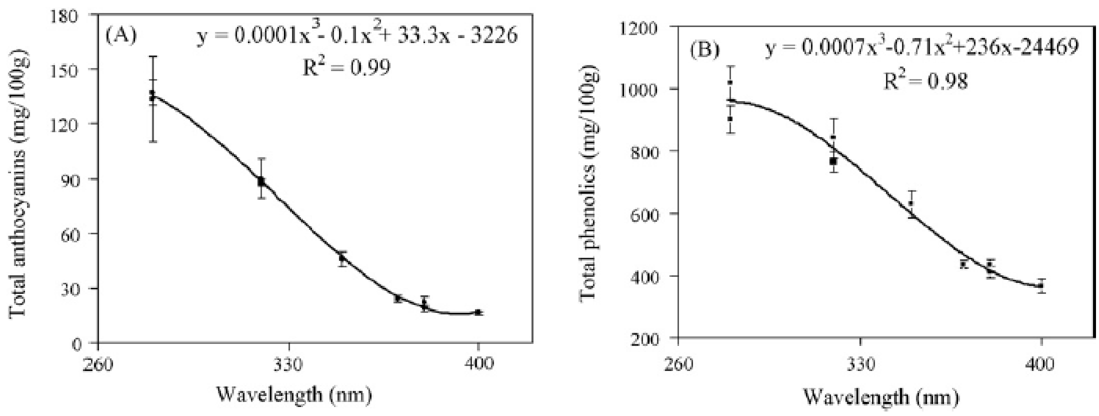


Figure 4.1. The impact of filtering UV up to specific waveband on the anthocyanin and phenolic content of lettuce Lollo Rosso, from Tsormopatsidis *et al.,* 2008.

They showed that the highest level of anthocyanins and phenolics were found when the lettuce was grown with all the wavebands of UV light. As wavebands were cut off towards 400nm the amount of these compounds decreased. This is clearly demonstrated in plate 4.1, which shows the Lollo Rosso grown with full UV (left) and with UV blocked (right).

Plate 4.1. Lollo Rosso lettuce grown with full UV (left) and without UV (right), plate courtesy of Dr Fred Davis, University of Reading.

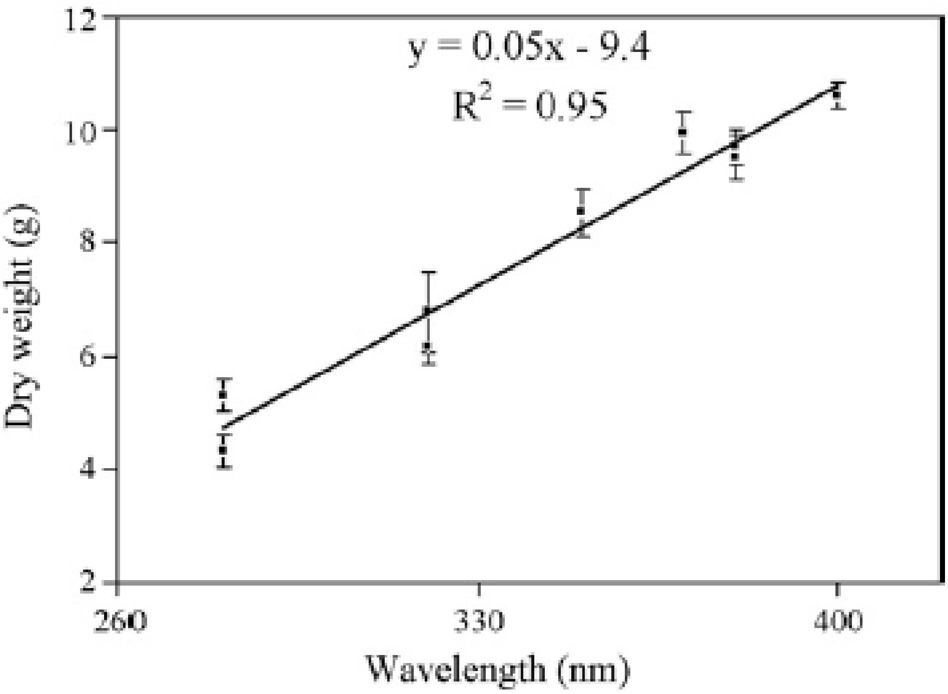


Figure 4.2. The effect of cutting off different wavebands of UV up to 400nm of Lollo Rosso dry mass (Tsormopatsidis *et al.,* 2008), i.e. for the 400nm treatment all UV was completely blocked, for the 280nm treatment all UV was transmitted by the material.

It is apparent from the photograph that in lettuce UV has an impact on total biomass production. Tsormopatsidis *et al*., (2008) showed that biomass production increased as the UV wavebands were increasingly cut off up to 400nm (see Figure 4.2).

Tsormopatsidis *et* al attributed these changes in biomass to the changes in leaf photosynthetic capacity and considered that phenolic and anthocyanins may provide a natural screen to reduce UV damage to the leaves. They also considered that manufacturing phenolics may have a high carbohydrate cost to the plant (thereby reducing biomass, see Tsormopatsidis *et al.* 2010, Ann App Biol, 156, 357-66.).

UV is also well known to impact essential oil production of a wide range of crops. For example, in basil, Johnson *et al.* (1999, Phytochem., 51, 507-10) showed considerable differences in essential oil composition when plants were grown either with or without solar UVB. In the oldest plants there was a 4-fold increase in essential oil concentration when plants were grown with UVB. This has a considerable impact on overall product flavour. Tsomopatsidis *et al* (2011, Env. And Exp. Bot., 74, 178-185) also showed a significant increase in strawberry hexanoic acid content when plants were grown with rather than without UV.

As well as impacting growth and flavour, UV also has a significant impact on insect and fungal disease incidence. The integrated impact of the effects of UVB on lettuce crops and their related pest and disease pathogens were studied by Paul *et al.,* (2012, Physiol. Plant. 145, 565-81). They confirmed that lettuce weight and foliar pigment concentrations were reduced when grown under a UVB transparent film. UVB transmitting films reduced the number of offspring of *Myzus persicae* aphids from over 5 per aphid (UV transmitting material) to less than 2 (UV opaque material). In this study, the impacts of UVB on fungal pathogens were not as clear. In contrast. Paul *et al.,* (2005, Photochem and Photobiol, 81, 1052-1060) showed a reduced spore germination of *Botrytis cinerea* as the weighted UV dose increased. The weighting increased the impact of shorter wavebands of UV compared to longer UV wavebands. The weighting reflected more fundamental studies which showed the damaging action spectrum of UV on DNA in alfalfa (see Quaite *et al.,* 1992, Nature, 358, 576-78). This infers UVC has a greater relative impact (per photon) on suppressing *Botrytis* germination compared to UVB. UVC and UVB have been shown to affect the ability of other pathogens to infect plants. For example, for powdery mildew, Suthaparen *et al.* (2016, J. Photochem. Photobiol. B: Biology, 156, 41-49) showed that powdery mildew spores were not infective when irradiated with UV at wavebands shorter than 310nm (UVC prevented infection). These impacts of UVB and UVC on powdery mildew growth are now well known and in Norway and Japan research is ongoing to use UV lights to control the disease. In contrast to the impacts of UV on *Botrytis* spore germination, the sporulation mechanism is stimulated by UV (see West *et al.,* 2000, Ann. App. Biol., 136, 115-120). This is also significant. In a whole crop study of the effects of UV blocking films *Botrytis* incidence was reduced in crops of Primula and Strawberry by 50 and 26% respectively when grown in tunnels which blocked nUV up to 405nm. Similar responses, where *Botrytis* was reduced by UV blocking, were found on a wider range of crops (cucumber, tomato, basil, rose) and with other plant pathogens (*Alternaria*), as cited in a review by Raviv and Antignus (2004, Photochem. PhotBiol. 79, 219-

26). It is clear therefore that the responses of fungal pathogens to UV is complex and worthy of further whole crop experimentation to establish the commercial impacts of different approaches. As a final note of caution, UV incidence can affect the rate at which pesticides break down. For example, van Emden and Hadley (2011, J. Hort. Sci. 86, 196-200) showed that UV opaque tunnels can prolong the life of the insecticide cypermethrin by up to 6 months. Thus care must be exercised when applying UV blocking films as they may have inadvertent impacts on pesticide residue levels.

As already reported, Paul *et al.* showed significant impacts of UV on aphid population, where numbers were reduced under a UVB transmitting material. The impacts of UV are now well established on a wide range of crop pests, vectored virus diseases and predators (see Raviv and Antignus, 2004). For example, Antignus *et al* (2001, Ent. Soc. Amer. 30, 394-9) showed a three to four-fold reduction in white fly population on tomato in crops grown with UV blocked covers. Other studies by the same group (see Antignus *et al.,* 1996. Env. Ent., 25, 919-24) showed dramatic reductions in thrips, aphid and whitefly populations in crops grown with UV absorbing covers, this also led to an up to 50% reduction in TYLCV incidence. The impacts of UV on insects are attributed to impacts of UV on vision (insect vision is tuned to UV, and frequently polarized UV). This prevents insects identifying plants inhibited them from flying into UV deficient spaces, including greenhouses.

Whilst UV blocking can reduce the impact of insect pests it can also negatively impact the sighting of bees. In UV blocking materials which completely block up to 400nm the bees can be completely unsighted and are not able to effectively pollinate crops. Figure 4.3 shows the effects of UV blocking on the pollination activity of *Bombus impatiens* extracted from Morandin *et al.,* (2001, 133, 883-93). In this study, bees doubled the number of flower visits when they were kept in a greenhouse which transmitted UVA and UVB compared to a blocking materials.

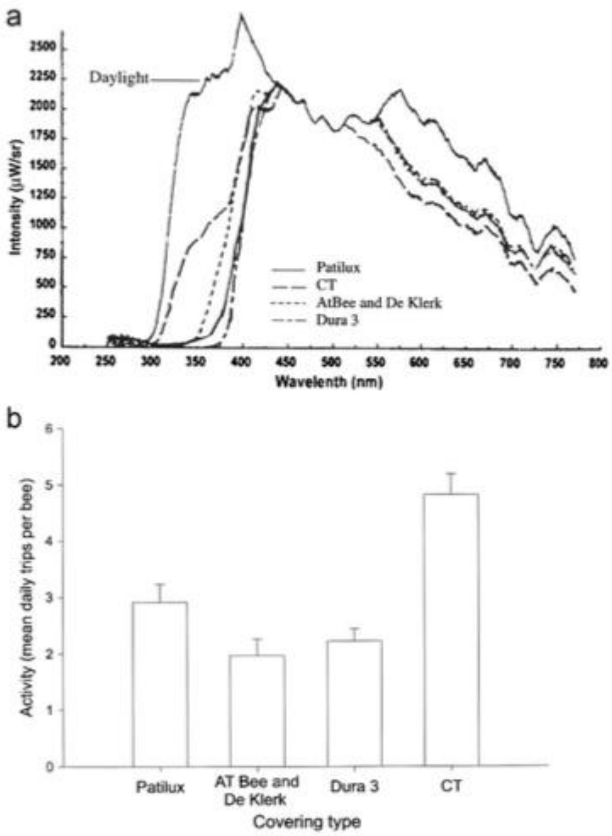


Figure 4.3. The impact of different cladding materials of bee activity, from Morandim *et al.,* (2001).

It is clear from this review that the effects of UV on crop, insect and pathogen growth and quality are highly sensitive and complex. Small changes in UV transmission can have significant biological impacts. The selection of an appropriate cladding material for different crops and circumstances will need to be carefully considered and properly tested prior to large scale capital investments by growers.

Section 5: near infra-red radiation.

Near infra-red radiation is beyond 700nm, it has no impact on plant photosynthesis but comprises c. 50% of the incoming solar radiation load. It therefore has a critical impact on leaf and greenhouse temperature. Absorbed NIR is converted to thermal energy which increases the temperature of the leaf, and surrounding environment. A large proportion of the radiation is used to drive evapotranspiration, and therefore crop water uptake and use. It is frequently thought that reducing the NIR load on a greenhouse could have multiple positive impacts, this could include;

- a reduced need to ventilate the greenhouse, thereby enabling the maintenance of a higher carbon dioxide concentration to drive crop yield
- a reduced greenhouse temperature, thereby enabling greater control of crop growth and potentially higher yield
- a reduced use of water as the irradiation load is reduced on the crop.

The most sensible way to reduce NIR load on a greenhouse is to use the cladding material to reflect the radiation back to space. If the radiation is absorbed by the cladding it will just heat the greenhouse structure, some of this energy will then be re-radiated back into the greenhouse or heat the cladding surface potentially impacting its long term durability.

The impact of a NIR reflecting material is though reduced by the fact that the crop is already an effective reflector of NIR. Leaves can reflect up to 40% of the NIR, whilst they only reflect c. 5% of the PAR. The reflection of tomato leaves to NIR is shown in Figure 5.1 (from Xu *et al.,* 2007, Biosys. Eng. 96, 447-54). This indicates that on some leaves up to 60% of the inbound NIR can be reflected by a leaf.

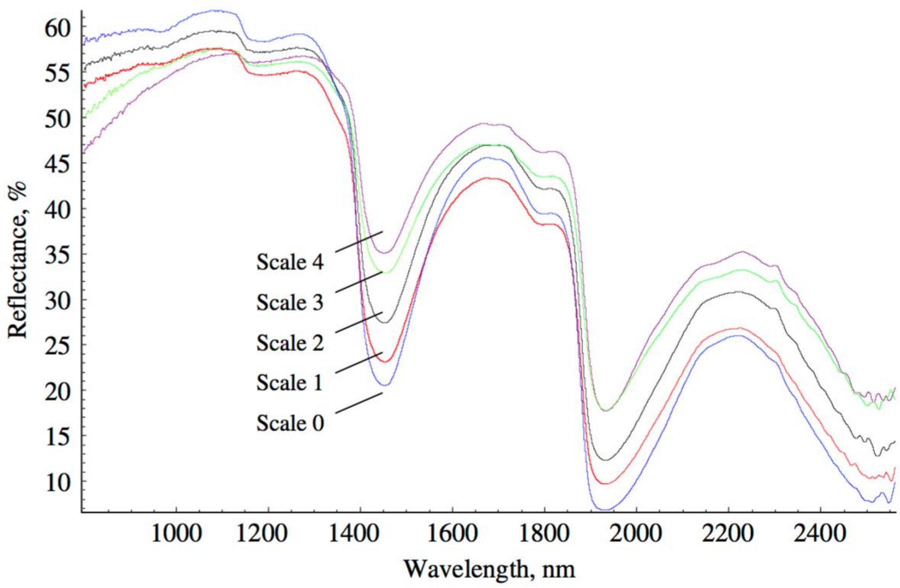


Figure 5.1. The reflectance of a tomato leaf at various scales of infection by leaf minor from Xu *et al*, 2007.

This high level of reflection reduces the impact of a NIR reflective filter on the overall energy balance, since the leaf has its own mechanism to reflect NIR. However, NIR reflective screens could still have a significant impact. In terms of overall energy balance a NIR reflective cladding material which reflects 25% of the inbound solar radiation would reduce the energy balance or loading of a canopy by 9% but this increases to 19 and 29% when 50 and 75% of NIR are reflected by a cladding material. This reduction in energy loading on a crop can be manifested in many ways, for example it could lead to a reduction in leaf temperature or a reduced rate of crop transpiration. For example, Stanghellini *et al.,* (2011, Biosys. Eng, 110, 261-71) showed that greenhouse clad by a NIR material manufactured by 3M (Prestige range) that reflected 25% of the NIR reduced the transpiration rate (and therefore water uptake) of a rose crop by 8%. This also led to a reduction in ventilation rate and a slight increase in greenhouse CO_2 concentration (by 32ppm) over a normal structure. Stanghellini *et al* found no detrimental impacts of NIR reflection on the rose crop so the challenge is to find a material with a very high level of NIR reflection.

The challenge for NIR reflective films is the lack of the commercial availability of very high performance materials at a reasonable cost. Stanghellini *et al.* tested a material manufactured by 3M which is a high performance interference filter coated to a conventional layer of glass. The material was developed for building heat control and is now being deployed worldwide and within the automotive sector. Its optical properties are shown in Fig 5.2 (from Stangehellini *et al*). This shows that the material was an excellent reflector of NIR between 900 to 1100nm, about 25% of the incoming solar load. However, Stanghellini's research showed that to be effective NIR reflective materials need to show a higher degree of efficacy. Hemming *et al.,* (2006b, Acta Hort.719, 97-106) reviewed a wider range of NIR reflective materials including “hot mirrors” from optics companies, additives used in polyethylene and solar reflective paints (ReduSol and ReduHeat, see Figure 5.3). “Hot Mirrors” are specialist NIR mirrors made for high performance optics applications but are typically made by spluttering multiple layers of metallic compounds or dielectric materials (Si) to create interference effects.

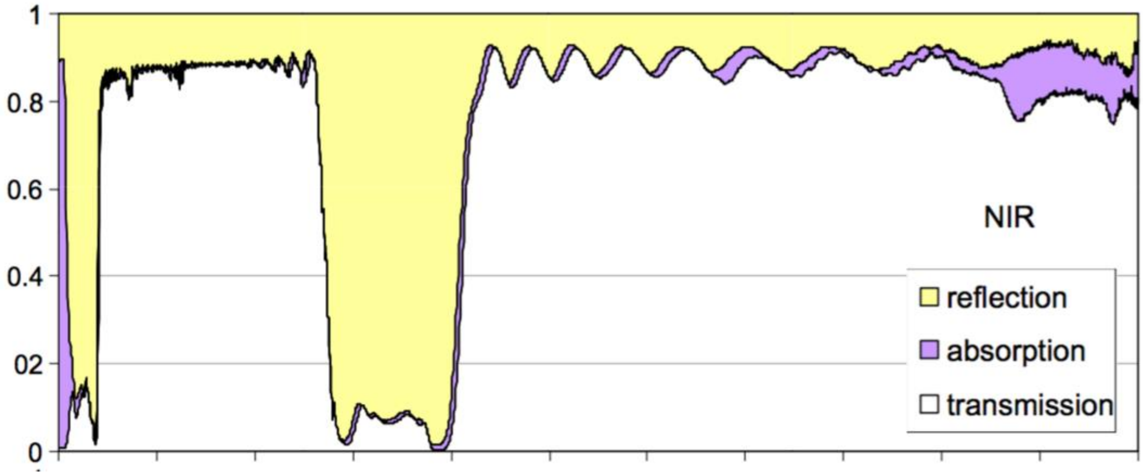


Figure 5.2. The optical properties of the 3M material tested by Stanghellini *et al.,* (2011). The material shows strong reflection 900 to 1100nm.

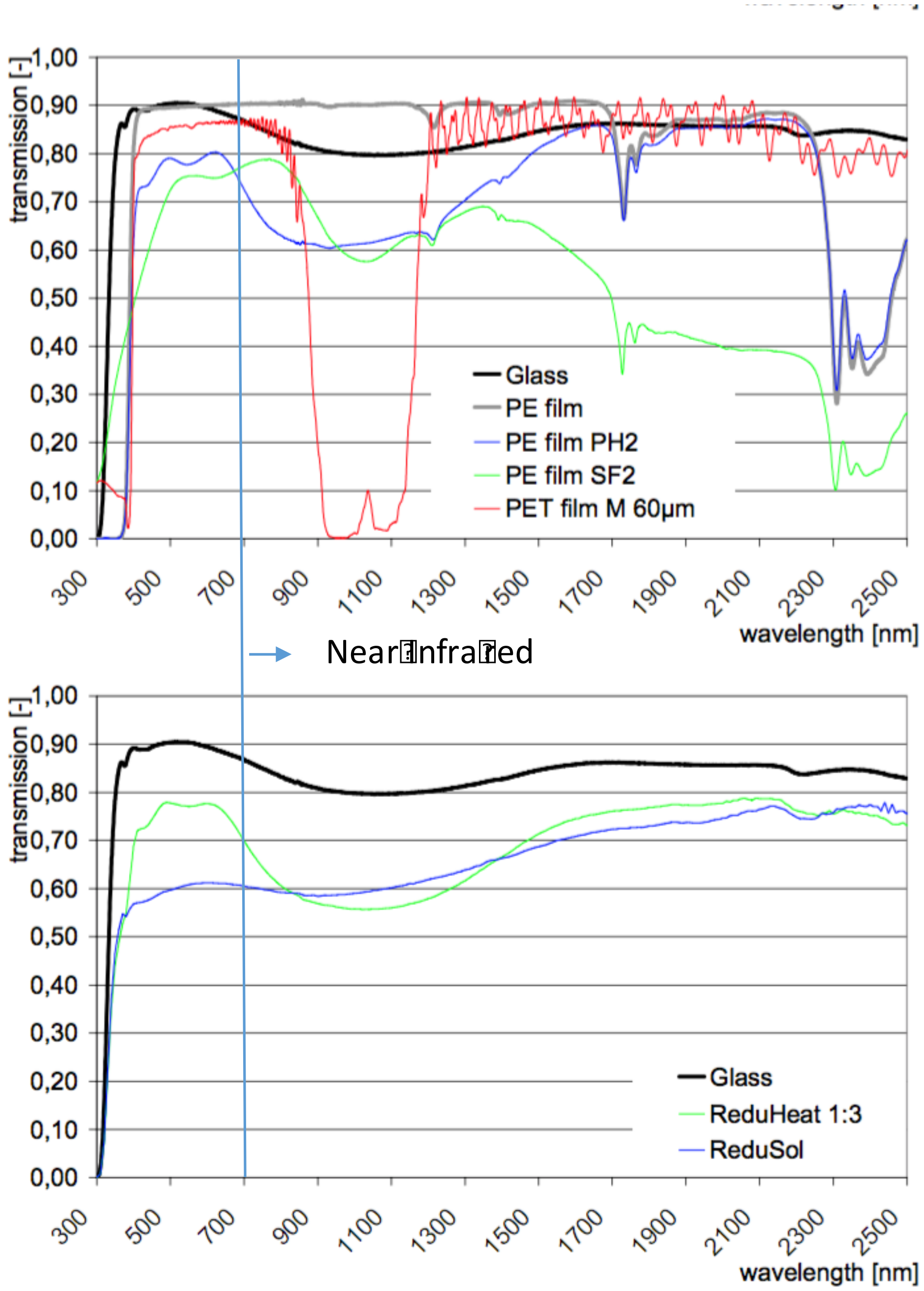


Figure 5.3. A review of current NIR materials measured by Hemming *et al* 2006b. They include polyethylene (PE) doped with NIR absorbing of reflecting pigments, the 3M interference filter (PET film M) and two glass applied paints ReduSol and ReduHeat.

The data from Hemming *et al.,* (2006b) again showed the high performance of the 3M material with reflection between 900 to 1100nm. The PE materials with dyes and the paints (ReduSol and Reduheat) all showed a reduced transmission to NIR but in all cases there was a loss of transmission for the PAR radiation. This may limit their application to non-light sensitive crops, although new materials and additives are continually coming onto the market. To show the potential of the materials Figure 5.4 shows the performance of a new “Hot Mirror” produced by Thorlabs in Germany. This shows an extremely effective performance with an almost 100% reflection of NIR between 700 to 1200nm.

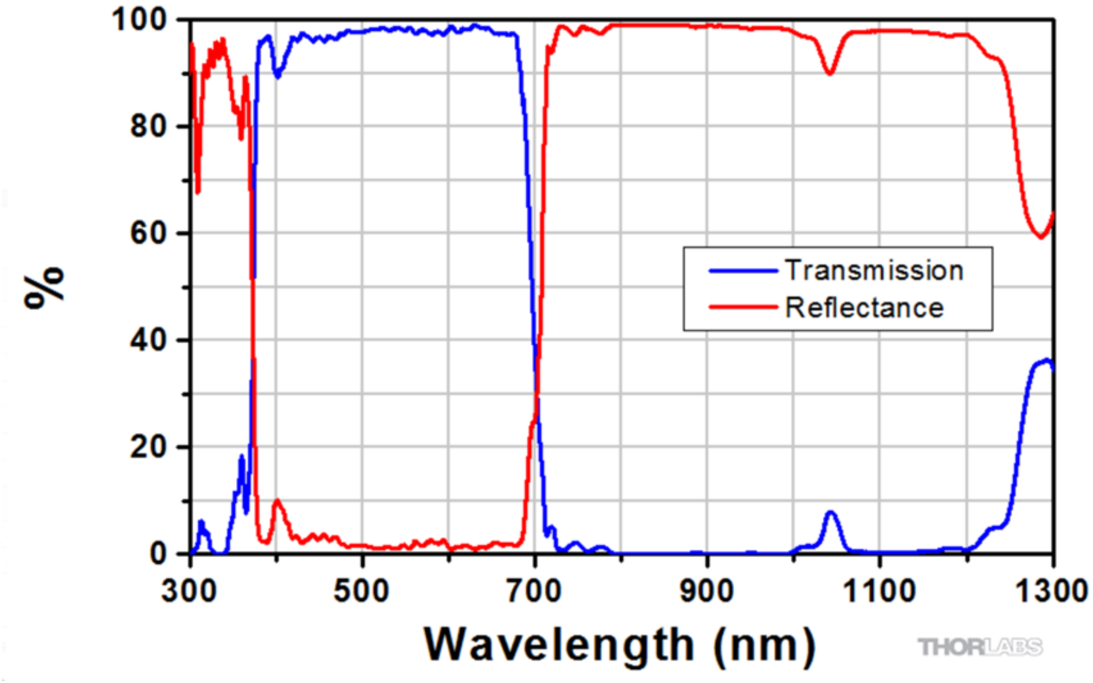


Figure 5.4. The transmission and reflectance of a hot mirror manufactured by Thorlabs.de (M254H45)

This mirror is highly specialist but photonics innovations in the future may enable similar performance materials become available for the greenhouse industry. These innovations are worth pursuing, Hemming *et al* (2006c, Acta Hort, 711, 411-416) used models to calculate that summer tomato yield would be increased by between 8 to 12% if the NIR can be removed. This reflected an ability to increase summer carbon dioxide level, and the models predicted a cooler summer greenhouse temperature and reduced transpiration rates.

Suppliers

Suppliers of materials identified during research for this review are included below as an indicator although is neither an exhaustive list nor a recommendation.

Glass. Most glasshouse installation companies will provide a range of options in terms of glass suppliers.

Suppliers include;

Saint Gobain Alabarino see http://merint.com/site/ourbusiness/SGG%20ALBARINO.pdf

Van Looveren Terrasol see http://www.vanlooveren.be/en-US/diffuse-glass/

GlasImport Vetrasol see http://www.glasimport.nl/greenhouses.html

DA Glass (Poland) see http://en.daglass.pl/produkty/szklo-dyfuzyjne-21/

Polyethylene

Suppliers include;

BPI Visqueen e.g. Luminance and LumiSol see http://www.bpivisqueenhort.com

XL Horticulture e.g. see http://**www.xlhorticulture.co.uk**

Ginegar Plastic Products e.g. see www.ginegar.com

Plastika Krittis e.g. see http://www.plastikakritis.com/en

Chemical Coatings

Suppliers include;

Royal Brinkman see e.g Dfuse www.**brinkman**.com/Folders/D-Fuse1%20engels%20def.pdf

Mardenko see e.g. ReduFuse
http://www.redusystems.com/en/redusystems/diffusion/redufuse-en/

Conclusions

Optical coatings or spectral filters for both glass and polyethylene greenhouses have been seen for many years as a key technology which may bring about increased yield, changes to pest and disease behaviour and improvements to crop quality. The technology is environmentally passive and may have significant potential to drive improved economic returns. The uptake of the technology has though been slower than many anticipated and this review examines the state of the art, where applications are becoming mainstream and some of the key challenges to further develop these technologies. The applications which are now becoming main stream include the use of diffuse glass, anti-reflective coatings to glass and low iron glass. Investment decisions can be made as estimates of the crop yield responses of key crops such as tomatoes and cucumbers (e.g. 0.7 to 1% per 1% increase in light transmission) are available. Diffuse glass has also been shown to increase yield by 5 to 7% depending on the glass used and crop. More work is though required to establish how diffuse glass can be cleaned to ensure the response is resilient over multiple years after installation. Ultra violet modified transmission materials also have great potential as the biological responses to UV are very strong. However some of the impacts can be opposing, for example bees need UV to pollinate, but removing UV also blinds many insects. Further whole crop responses work is needed to fully understand the economic benefits of materials which either absorb or transmit UV. It is likely that some situations may need fully opaque or transmitting materials and in others a balance where materials both transmit and absorb elements of the UV may be required. Near infra-red reflective materials have great potential to passively reduce solar gain, achieve higher summer carbon dioxide levels through lower ventilation, reduce crop water use and drive yield. The material technology is in its infancy and further material innovations are required to enable large scale horticultural adoptions. However, the rate of material development is very high and innovations within this space need to be monitored closely.

Knowledge and technology transfer

To date there have been three KT events for this project including presentations to the Cucumber and Peppers Growers Association, the AHDB lighting conference and the Tomato Growers Association working party.

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