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UV Transmission in Laminated glass: Effects on Plant Growth and Development

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Abstract

When glass is laminated for safety reasons, it usually blocks UV radiation partially or even completely when UV blocking materials are used. In the last decade, there has been an increasing interest in interlayers with high UV transmission, especially in relation to greenhouse applications. In this paper, we present an overview of the effects of UV transmittance on plant growth and development, in order to advice on the use of the high transmission interlayers versus the standard interlayers. Using UV transmitting films instead of UV blocking films has opportunities to alter plant growth and morphology. In general, plants grow more compact with increased UV transmittance, growth and biomass are reduced, flowering is stimulated (although the effects are species dependent), concentrations of secondary metabolites which are positive from nutritional perspective are stimulated and flower appearance (color) can be positively influenced. Pollination by bees is improved when UV is present and plant resilience to pests and diseases is improved. These results show that UV transmitting materials can have potential to be used in for example botanical gardens, office centers and garden markets, where producing biomass might even be unfavorable. On the contrary, the increased ornamental value by improved shape and flower color will be appreciated. Therefore, these aspects of transmitting UV to plants can have potential for markets where plant production is not the main goal.

Keywords

Glass, UV, UV Transmittance, UV Blocking, Plant Growth, Plant Development, Trosifol® NUV, SentryGlas® NUV

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1. Introduction

Laminated safety glass is used in architectural, automotive and photovoltaic industries. Innovative glass-laminating solutions include structural and functional interlayers for safety and security applications, insulation and UV protection. In recent years, there has been an increasing interest in interlayers with high UV transmission, especially in relation to greenhouse applications such as botanical gardens, zoos, rooftop greenhouses and commercial greenhouses.

Using laminated glass can be interesting to protect the crops from e.g. hail incidents. The question is what the relationship is between UV transmission and effects on plants to explore the use of the interlayers with high UV transmission versus standard interlayers. In this paper, we present an overview of the effects of UV transmittance on plant growth and development, in order to advice on the use of the high transmission interlayers versus the standard interlayers.

2. Light

2.1. Spectral composition of light

Sunlight is the electromagnetic radiation given off by the sun. This radiation is filtered by the atmosphere before it reaches the earth as global radiation. Global radiation includes radiation with wavelengths between 300 and 3000 nm, which are grouped as ultraviolet radiation (UV), visible and infrared radiation (Table 1). Radiation in the region 3000-100000 nm (3-100 µm) is referred to as heat radiation. Global radiation can be partly seen by the human eye: 380–780 nm and includes the colours blue, green, yellow, orange and red. The range of 400-700 nm is also referred to as 'Photosynthetic Active Radiation' (PAR), which is the range of the global radiation that plants use for photosynthesis.

Table 1: Grouping of optical radiation.

Name	Abbreviation		Wavelength (nm)	Remark
Ultraviolet	UV	UV-C	100-280	Does not reach earth
		UV-B	280-315	<300 does not reach earth
		UV-A	315-400	
Photosynthetic Active Radiation	PAR	Blue	400-500	
		Green	500-600	
		Red	600-700	
	NIR	Farred	700-800	
		NIR	800-3000	
Far Infra-Red	FIR		3000-100000	

Global radiation can be expressed in $J/m^2/s$ or in W/m^2, which refers to the energy content of the radiation. Photosynthesis of plants is related to the number of photons that are absorbed by chlorophyll in the chloroplasts in the range between 400 and 700 nm and is expressed in $\mu mol/m^2/s$.

2.2. UV light

Ultraviolet radiation (100-400 nm) is the part of the solar radiation with the highest amount of energy. The part of ultraviolet radiation that reaches the earth is in the range 300-400 nm (UV-A and part of the UV-B), since shorter wavelengths are filtered out by the atmosphere. Ozone, SO_2 and NO_2 are the main UV absorbing components.

UV radiation cannot be observed by the human eye. It causes the human body to produce vitamin D, especially UV-B, which is essential for life. Excessive exposure to UV is harmful and causes skin damage. UV also can affect, degrade and discolour materials. UV stabilizers are used to protect plastics and increase lifetime. Exposure of plants to UV-rich radiation leads to generation of free radicals that damage DNA, proteins, lipids, chloroplasts and photosynthetic pigments (Hideg et al. 2013). Plants protect themselves by the formation of pigments and secondary metabolites to shield against UV radiation. In a natural environment, plants are exposed to 10-100 times more UV-A photons than UV-B photons. UV penetration through leaf tissues increases as wavelength increases: UV-A can reach much deeper target sites in the leaves than UV-B can (Verdaguer et al. 2017).

The amount of UV in sunlight varies between 8 and 11% of the PAR (expressed in $\mu mol/m^2/s$) that the plants receive. The absolute amount of UV that reaches the earth is influenced by the amount of total global radiation, the latitude, the altitude, the season, time of the day and cloudiness (Hemming et al. 2004). The seasonal variation in UV-A levels is significantly smaller than those of UV-B. The daily solar UV-B flux is restricted to the hours around solar noon; the daily UV-A flux is present during a larger part of the day (Verdaguer et al. 2017).

To get an idea of the amount of UV reaching the earth: in summer (angle of the sun 48.5°) on a sunny day and clear sky and a global radiation of 600 W/m^2, the amount of UV is 40 W/m^2 which corresponds to 120 $\mu mol/m^2/s$. In winter (angle of the sun 10°), with global lower radiation, the amount of UV is much lower and around 7 W/m^2 which corresponds to 20 $\mu mol/m^2/s$ (Hemming et al. 2004).

2.3. Light and plants

Light is one of the most important factors that regulates plant growth and development. The sun provides light with a specific intensity, cycle (day/night) and spectral quality, which all alter during the day and season. Growth and development of plants are regulated by photosynthesis and photomorphogenesis. Photosynthesis is the primary process in plant growth, where CO_2 is taken up from the air, and converted into sugars to provide energy for plant growth. Photosynthesis requires light energy, and in the process oxygen is released. Photomorphogenesis is the light spectrum-mediated development, leading to differences in morphology, color and flowering of the plant.

Light is not only essential as energy source for photosynthesis. The intensity, orientation and spectral quality provides the plant information about time of the day, season, and it affects plant morphology and flowering. Radiation is perceived by plants through a range of photoreceptors: UVR8, phototropins, cryptochromes, ZTL/FKF1/LKP2 and phytochrome. UV, blue, red and far red radiations are involved in several photo morphogenetic responses like seedling development, vegetative growth, flowering and branching (Huché-Thélier et al. 2016).

Photoreceptors perceive specific light and convert it to a biochemical signaling process. The different photoreceptors influence different processes listed in Table 2.

Table 2: Photoreceptors and characteristics (Kong & Okajima 2016).

Name	Range	Process
UVR8	UV-B	Elongation hypocotyl UV-B tolerance Phototropism Opening stomates
ZTL/FKF1/LKP2	UV-A, blue	Photoperiodic flowering Circadian rhythm
Phototropin	UV-A, blue	Movement chloroplast Opening stomates Leaf orientation
Cryptochrome	UV-A, blue, green	Elongation hypocotyl Flowering Shade avoidance
Phytochrome	Red, farred, green, Also from >300 (UV, blue)*	Shade avoidance Development stomates Chlorophyll content Seed germination

*affecting seed germination

UVR8 is an abbreviation of UV RESISTANCE LOCUS 8, which absorbs between 280-320 nm and is specific for only UV. The absorption range for the other receptors is broader. ZTL/FKF1/LKP2 is a family of UV-A and blue light photo receptors: Zeitlupe (ZLK), Flavin-binding Kelch (FKF1) and LOV Kelch Proteins (LKP2/FKL1).

3. Effects of UV light on plants

3.1. Vegetative growth

Plant growth is the result of key processes such as cell division and elongation, directional growth and branching. UV light can influence plants in different ways. UV light is perceived by receptors, affecting physiological processes developmental phases resulting in crop characteristics morphology, nutritional value, flowering time and biomass. The shape of plants can be influenced by UV light, due to leaf and internode growth and bud outgrowth, resulting in more or less branching and compactness of the plants, and is regulated by cryptochromes and phototropins. Plants direct their growth towards incoming light to best position their leaves in order to optimize photosynthesis. Phototropins are the main photoreceptors involved in the perception of directional light. The signal leads to asymmetrical cell growth by increased cell growth on the shaded side. Also blue light plays a role in this process.

The morphology of the plant can influence the light intercepted by the crop. More branching or bigger leaves will increase the amount of intercepted light by the crop which will lead to a higher crop photosynthesis and thereby plant biomass.

Biomass can also be affected by UV light (perceived by cryptochromes) by effects on photosynthesis due to decrease of chlorophyll content (Nedunchezhian and Kulandaivelu 1997; Kataria et al. 2013) and by affecting the ratio chlorophyll a/b (Lidon and Ramalho 2011). UV-B radiation can stimulate stomatal opening or stomatal closing dependent of the metabolic state of the guard cells (Jansen and van den Noort 2000), which makes the effect hard to predict compared to the promoting effect of blue light on stomatal opening. Effects on stomates can influence photosynthesis which will affect biomass production.

General effects of UV radiation on vegetative growth summarized by Huché-Thélier et al. (2016) are contradictory and species-dependent (Kakani et al. 2003). In numerous species, UV-B exposure decreases shoot length, shoot dry mass and foliar area (Kuhlmann and Müller 2009a, b; Liu et al. 2013; Singh et al. 2011; Torre et al. 2012; Wargent et al. 2006; Zhang et al. 2014). In basil, exposure to supplementary UV-B light (2 to 4 kJ/m^2/s for 7 days) significantly increased leaf area as well as fresh and dry biomass (Sakalauskaite et al. 2013). The effects of UV-A on plant morphology have been less studied, but Krizek et al. (1997) noted that exposure to UV-A without UV-B radiation decreased plant height and leaf area. Even if the effects of UV-B on branching vary in range according to species, UV-B exposure tends to increase the number of stems/tillers (Barnes et al. 1990; Torre et al. 2012).

In the overview of Huché-Thélier et al. (2016), research data were used based on exclusion of UV from solar radiation and of addition of supplementary UV (UV-B, UV-A or a combination) with different doses (intensity x duration) in growth cabinets and greenhouses. The effects of UV on plants are not always consistent. An important factor for this inconsistency is the way the research was done. In nature, UV is a part of the total amount of radiation that the plants receive and is depended of the light intensity, season, cloudiness and varies between 8 and 11% of the PAR (expressed in µmol/m^2/s, Hemming et al. 2004). In research carried out in growth cabinets without sunlight, plants can be exposed to UV of a certain spectral quality, duration and intensity. Effects of UV by exposure of plants to additional UV can be different and even opposite to the effects of UV by excluding UV from sunlight. Also adding supplementary UV radiation in greenhouses alters the ratio between UV and PAR and can affect the conclusions of the effects of UV-B on crops (Rozema et al. 1997).

In this paper, we focus on information where UV radiation is excluded compared with natural light. Research on the effects of UV radiation on different crops by exclusion of UV radiation was carried out in chambers or tunnels in the field covered with foils that transmit or (partially) block UV (Krizek et al. 1997, 1998; Kataria et al. 2013; Terfa et al. 2014, Tsormpatsidis 2008, 2010; Kittas et al. 2006; Kolb et al. 2001). In general, films are thinner than laminated glass interlayers but the effects of (partially) blocking UV on plant growth will be comparable. Overall findings were that blocking ambient UV during cultivation affects morphology, development and biomass in several crops like cucumber, soybean, pot roses, lettuce, eggplant, cotton, wheat, amaranthus and sorghum. When UV was blocked, plants were taller, leaves were bigger and more biomass was produced. Effects on morphology and biomass were larger when both UV-A and UV-B were excluded compared to only exclusion of UV-B.

To illustrate these results, some examples are given. Eggplants were cultivated under foils that transmitted 0, 3 or 5% of the UV. Without UV, plant height was increased with 21%, leaves were bigger (17%) and production was tended to be increased in quantity (bigger fruits) and in quality (Kittas et al. 2006), although not significantly.

Tsormpatsidis et al. 2008 cultivated a red cultivar of lettuce (Lolla Rossa) in polyethylene tunnels with different transparencies for UV, from no bocking, partial blocking to total blocking. UV was cut off above 320, 350, 370 and 380 nm. The PAR transmission was in the same range of 79-86% and UV transmission varied: 81-39-22-10-3.5-0 %. Plants under a complete UV blocking film (UV400) produced up to 2.2 times more total above ground dry weight than plants under the UV transparent film.

Photosynthetic rate was not influenced by blocking UV in lettuce (Tsormpatsidis et al. 2010) and no stress was measured in plants exposed to ambient UV compared to plants cultivated without UV. Stress was measured by using a fluorescence technique which determines the amount of light used for photosynthesis and fluorescence (by measuring Fv/Fm). The reduced biomass was probably caused by the high metabolic costs of photoprotection such that the plants divert energy produced by photosynthesis to synthesize phenolic compounds.

A different method was used by Zhang et al. (2014) who cultivated soybean in a glasshouse which transmitted much UV-A (increasing from 0% to about 80% from 320 to 360 nm, and about 80% across the 360–400 nm range) and excluded UV-B. The other greenhouse was a polycarbonate greenhouse which excluded UV-A and UV-B. To compare the effects with full sunlight, part of the plants from the glasshouse where transferred to outside from 9:00-17:00 h. In this way not only the amount of UV was different, also other climate factors changed by transferring plants to the outside. Plants elongated without UV (A and B). The total biomass and pod yield were higher without UV.

Biomass of tomato was positively affected by UV-A due to higher chlorophyll content and rate of photosynthesis of plants exposed to UV-A compared to blocking of UV. Plants were grown in cabinets with sunlight and foils which transmitted radiation above 290 nm (UV-A and UV-B), above 320 nm (UV-A) and above 400 nm (blocking UV). Plant height was not influenced after 46 days of cultivation. Senescence of tomato leaf was delayed in presence of UV-A (Tezuka et al. 1993). They state that enhancement in the growth and physiological activities of plants by UV-A radiation seems to result of appropriate regulation of the activities of enzymes and the levels of components participating in various metabolic pathways by UV-A radiation.

It is not clear why in the research of Tezuka et al. (1993, 1994) the effect of UV-A was positive on biomass production, while other research mentioned before in this paragraph did not report positive effects of UV-A on biomass (Krizek et al. 1997, 1998; Kataria et al. 2013; Terfa et al. 2014; Tsormpatsidis 2008, 2010; Kittas et al. 2006; Kolb et al. 2001; Zhang et al. 2014). The variable UV-A response may be caused by small changes in the balance between multiple, simultaneous UV-A effects, including stress, changes in morphology, changes in photosynthesis and accumulation of phenolic compounds (Verdaguar et al. 2017). In general, it can be concluded that using UV transmitting films can be interesting to keep the plants compact and to reduce growth and biomass.

3.2. Flowering

In plants, flowering is species-dependent and is under control of internal signals (autonomous, aging, hormones) and external signals (e.g. temperature, vernalization and daylength). Al these signals converge towards floral genes (Huché-Thélier et al. 2016). UV-B is perceived by UVR-8 and acts as an input signal of the circadian clock involved in the photoperiod pathway (Feher et al. 2011). The effect of blocking UV will not disturb this process fully because also other wavelengths are involved in detection of photoperiod.

The effect of UV-B on flowering depends on species (Petropoulou et al. 2001; Sampson and Cane, 1999). Additional UV-B had positive effects on flower size of Malcolmia maritima (Petropoulou et al. 2001). Sampson and Cane (1999) tested 5 doses of additional UV-B (ranging from 2.7 to 15.9 kJ/m^2/day) on annual species Limnanthes alba and Phacelia campanularia cultivated in a glasshouse. The effects of UV-B on these 2 species were different: L. alba plants were less likely to flower when additional UV-B was supplied, but the plants that did flower showed no delay in flowering and produced the same number of flowers. Conversely, an equal proportion of P. campanularia plants flowered under all UV-B treatments, but these same plants experienced delayed onset to bloom and produced fewer flowers at greater UV-B intensities. Also delayed flowering of pot roses was reported when excluding UV up to 350 nm (Terfa et al. 2014).

In conclusion, UV transmitting films can be beneficial for flowering of species, but the effects are species dependent.

3.3. Pollination

UV light is an important component of bee vision and orientation (Peitsch et al. 1992) and the degree of UV transmission through greenhouse coverings affects the behaviour of bees used as pollinators. Under glass with high UV transmission (up to 80%), bees behave normally. Under materials with very low UV transmission (less than 3%), they perform poorly (Guerra-Sanz, 2008).

Morandin and co-workers (2001) studied the behavior of bumble bees in a commercial tomato crop with 4 types of films: 1 with a high degree of UV transmittance and the other 3 with a low UV transmittance (around 0%). Bumble bee activity was 94% greater under the UV transmitting covering compared to the ones that transmitted less UV light. More bees were lost per colony under the covering with low UV transmittance. Also Soler et al. (2006) reported different behavior of bees under UV absorbing plastic compared to plastic without UV filters: more bees appeared at the nest entrance without flying to forage. Also Dag (2008) mentioned in a review article that bees need UV to navigate in a greenhouse. On the other hand, some researchers claim that UV is not essential for navigation (Dag 2008), because bees can learn to cope with the lack of UV and find the flowers nevertheless (Guerra-Sanz, 2008; Dyer and Chittka, 2004).

In a greenhouse in the Netherlands with 3 different types of cover differing in UV transmittance, the behavior of bees was disturbed under the cover which absorbed UV. The conclusion was that this cover was not appropriate when pollination by bees is necessary (Kempkes and van Os, 2006).

In conclusion, the presence of UV light is needed for a normal behavior (orientation, foraging) of bees for good pollination.

3.4. Metabolites

In the process of primary metabolism, the plants produce sugars and other components for growth and development: they produce acids, cellulose, hemicellulose, cutin, suberin, pectin, lignin, fatty acids, amino acids, starch, fats and proteins. The base for the primary metabolism is photosynthesis which is dependent of light. The light intensity and spectral quality both influence this primary metabolism but also have a great influence on the content and production of secondary metabolites. In the process of secondary metabolism, components are produced which enable the plant to interact with their environment. These secondary metabolites play a role in for example resilience to pathogens and pests, communications between plants, attraction of pollinators, protection against radiation and free radicals (Snel 2010). Examples are flavonoids, carotenoids, terpenoids, alkaloids, phenols, glycosides, glycosylates and hormones. Some of these components are considered as beneficial for human health like anti-oxidants (carotenoids like beta-carotene, lycopene, lutein, and zeaxanthin), anti-cancer (aliphatic glucosinalate) and vitamins.

Exposure to UV radiation tends to increase production of secondary metabolites. In order to protect cells and prevent damage by UV radiations, plants accumulate UV-absorbing compounds in their cell epidermis. These compounds can favor human health (Huché-Thélier et al. 2016) or can increase the attractiveness of for example flowers by changing the color.

Huché-Thélier et al. (2016) reported results with different effects of UV-A and UV-B on metabolites. Accumulation of flavonoids, assumed to offer UV protection (Treutter 2005, 2006) and to play a role in resilience, is induced by UV-B which is reported for several species (Rozema et al. 1997; Tsormpatsidis et al. 2008). In pepper, the effect of UV on flavonoid production was positive for plants grown under higher light intensities but no effect was observed in plants grown under low light intensities (Hoffman et al. 2015). Referenced articles were based on different experimental set-ups: additional UV radiation without sunlight and with sunlight and research was used that excluded UV radiation. This can lead to different results like was mentioned before in the chapter about the effect of UV radiation on vegetative growth. The conclusions in the next part of the text are based on research that compared effects of UV on plants grown under sunlight and excluded UV from sunlight.

Concentrations of anthocyanins in lettuce grown under UV blocking material was 8 times lower compared to lettuce (Lollo Rosso) grown under UV transmitting materials (Tsormpatsidis et al. 2008). Different UV blocking materials were used with a cut off above 320, 350, 370 and 380 nm. There was a curvilinear relationship between the anthocyanin content and UV wavelength cut off such that above 370 nm there was no further reduction in anthocyanin content (Figure 6).

Anthocyanin, flavonoid and phenolic content of lettuce (Lollo rosso) grown continuously under a UV transparent film were 7.3-fold, 2.0-fold and 2.3-fold higher, respectively, than of plants grown under a UV blocking film that blocked UV up to 380 nm (Tsormpatsidis et al. 2010). Compared with plants grown continuously under the UV blocking film, transferring the plants 6 days before the final harvest increased anthocyanin, flavonoid and phenolic content by 4.6-fold, 1.6-fold and 1.8- fold, respectively. However, this increase was more significant when plants were transferred at the transplanting stage to a UV transparent film where anthocyanin, flavonoid and phenolic content were increased by 6.5-fold, 1.9-fold and 2.1-fold, respectively. Also in research of Krizek (1998) the content of anthocyanins was increased by UV-A and UV-B, but especially UV-B increased the content of flavonoids in red lettuce.

The content of phenolic compounds like anthocyanins, flavonoids was reduced in roses by blocking UV (Terfa et al. 2014; UV up to 350 nm was blocked).

Covering branches of Alnus and Betula with UV blocking films reduced the flavonoid concentration compared to of UV transparent films (Kotilainen et al. 2008).

In conclusion, blocking UV reduces the secondary metabolite concentrations, which might lead to less intense coloring of leaves, stems and flowers, less compounds with nutritional value (like anti-oxidants), and might have a negative impact on plant resilience against pests and diseases. Transmitting a higher percentage of UV light might therefore lead to more intense plant colors and a higher plant resilience against pest and diseases.

3.5. Resilience

Resilience is considered as the capacity of plants to cope with pests and diseases (insects, herbivores, virus and pathogenic fungi). UV light (and to a lesser extent blue light) can induce the production of secondary metabolites and/or mechanisms to induce resistance to pathogens or herbivores (Huché - Théliers et al. 2016). UV-B perception by UVR8 induces its activation and triggers several processes leading to for example flavonoid synthesis and chalcone synthesis via activation HY5 and expression of several genes.

There are many studies indicating a role for flavonoids in plant resistance, while almost no firm evidence exists regarding this function. The benefit of flavonoids for plants is obvious but it is not yet quantified. It remains ambiguous whether the contribution of flavonoids to defense is the main function of flavonoids. This aspect is not easy to clarify since the multifunctional roles of flavonoids influence plant physiology in a complex manner (Treutter 2005).

Plants exposure to solar UV-B radiation tends to increase both resistance to herbivorous insects and to microbial pathogens (Demkura and Ballare 2012). It was shown that (ecologically meaningful doses of 5.5 kJ/m^2) UV-B radiation increased Arabidopsis resistance grown in a greenhouse to the necrotrophic fungus Botrytis cinerea and that this effect is mediated by the photoreceptor UVR8. UV-B radiation, acting through UVR8, increased the levels of flavonoids and sinapates (secondary metabolite) in leaf tissue.

In an experiment with soybean grown under UV-transmitting film and a UV blocking film (< 310 nm) solar UV-B exclusion resulted in a two-fold increase in the number of leaf lesions inflicted by various species of chewing insects that naturally invaded the field plots. Leaves from canopies exposed to solar UV-B showed significantly higher levels of soluble phenolics and lower levels of lignin than leaves that developed in canopies covered by polyester films. Also leaves of Arabidopsis showed more lesions caused by the diamondback moth on plants grown under UV blocking film (< 310 nm) compared to plants growing under ambient UV. These effects of natural UV-B on plant quality appear to be mediated by activation of signaling circuits in which the defense-related hormone jasmonic acid plays a functional role (Caputo et al. 2006).

Grapevines grown under UV transmitting film showed less infection of powdery mildew (after inoculation) compared to grapes grown under (98%) UV-blocking films and the concentration of flavanol-glycosides in leaves was higher (Keller et al. 2003). These data suggest that UV plays an important role in the natural regulation of powdery mildew under field conditions.

Infection of the pathogenic fungus powdery mildew on egg plants that were naturally infected was strongly reduced by lamps with extra UV-B and a background of solar radiation (Dieleman et al. 2021). This might be because of increased plant resilience, but might also be a direct effect of UV on the fungus.

In conclusion, plant resilience increases when UV is present compared to plants grown under UV-blocking material.

4. Glass and Laminated glass

During the last 50 years, architects and designers were successful in finding ways to increase the transparency of the envelope of the buildings and structures through the use of glass. As a result, laminated glass became important to ensure the safety of the occupants. The original interlayers were designed to minimize the transmission of UV to protect interiors and people from the negative effects of that radiation.

As the glazing surface increased, tailored UV transmission was needed for specific applications at both ends of the transmission range. Figure 1 illustrates the differences in UV transmission of different commercial interlayers in PVB’s and structural ionomers.

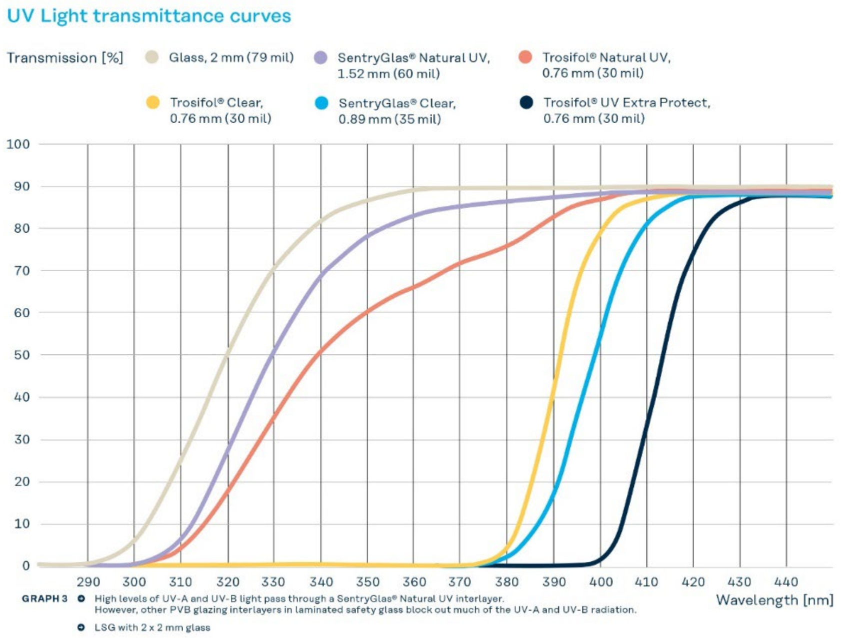

Fig. 1: UV Transmission for different glass compositions

Glass and interlayer types, thicknesses and coatings used in the laminated glass will affect UV transmission. It can be estimated with tools such as WinSLT (https://www.trosifol.com/winslt-tool/).

5. Conclusions

The conclusion of this paper is that using UV transmitting films instead of UV blocking films provides opportunities to alter plant growth and development. In the presence of higher intensities of UV, plants are more compact, have reduced growth and biomass production, improved flowering (although the effects are species dependent), and higher contents of secondary metabolites, which is positive from nutritional perspective. Furthermore, UV can positively affect appearance (color), and pollination and resilience to pests and diseases.

Table 3: Summarized effects of higher UV transmittance on plants compared to absence of UV (UV blocking material).

Process	Aspect	Effect of higher UV transmittance
Morphology	Height	Smaller plants
	Compactness	More compact
	Leaf colour	‘Red’ or ‘purple’ colour in red varieties
Growth	Biomass	Lower biomass
	Production	Lower production
Flowering		Different results: depends of the species
Pollination		Improved: better navigation of the bees
Quality		Production of secondary metabolites is stimulated which improves quality of vegetables and flowers: components that are beneficial for human health and improvement of colour and attractiveness of flowers/fruits
Resilience		Improved: less insect and fungi damage

There is potential for UV transmitting materials in botanical gardens, greenhouses and garden markets. Ornamental crops are more appreciated by the consumers when they are compact and more intensely colored. In botanical gardens, office centers and garden markets, producing biomass is not the primary goal or even unfavorable. Color of leaves and flowers is especially important in botanical gardens, and UV transmitting material improves the color (via red pigments such as anthocyanins).

6. References

Barnes, P.W., Flint, S.D., Caldwell, M.M.: Morphological responses of crop and weed species of different growth forms to ultraviolet-B radiation. Am. J. Bot. 77, 1354–1360 (1990).

Caputo,C., Rutizky, M., Ballare, C.L.: Solar ultraviolet-B radiation alters the attractiveness of Arabidopsis plants to diamondback moths (Plutella L.): impacts on oviposition and involvement of the jasmonic acid pathway. Oecologia 149: 81-90 (2006).

Dag, A.: Bee pollination of crop plants under environmental conditions unique to enclosures. Journal of Apicultural Research 47:2, 162-165 (2008).

Demkura, P.V., Ballare, C.L.: UVR8 Mediates UV-B-Induced Arabidopsis Defense Responses against Botrytis cinerea by Controlling Sinapate Accumulation. Molecular Plant 5:642-652 (2012).

Dieleman, J.A., Kruidhof, H.M., Weerheim, K., Leiss, K.: LED lighting strategies affect physiology and resilience to pathogens and pests in eggplant (Solanum melongena L.). Frontiers in Plant Science, 11 (2021). https://doi.org/10.3389/fpls.2020.610046

Dyer, A.G., Chittka, L.: Fine colour discrimination requires differential conditioning in bumblebee. Naturwissenschaften 91: 224-227 (2004).

Fehér, B., Kozma-Bognár, L., Kevei, E., Hajdu, A., Binkert, M., Davis, S.J., Schäfer, E., Ulm, R., Nagy, F.: Functional interaction of the circadian clock and UV RESISTANCE LOCUS 8-controlled UV-B signaling pathways in Arabidopsis thaliana. Plant J. Cell Mol. Biol. 67, 37–48 (2011).

Guerra-Sanz, J.M.: Crop pollination in greenhouses. In: Bee pollination in agricultural ecosystems. Rosalind R James & Theresa L Pitts-Singer (eds). Oxford ; New York : Oxford University Press (2008).

Hemming, S., Waaijenberg, D., Bot, G., Sonneveld, P., Zwart, F. de., Dueck, T., Dijk, C. van., Dieleman, A., Marissen, N., Rijssel, E. van., Houter, B.: Optimaal gebruik van natuurlijk licht in de glastuinbouw. Wageningen UR, rapport GTB-100 (2004).

Hideg, E., Jansen, M. A. K., Strid, A.: UV-B exposure, ROS, and stress: inseparable companions or loosely linked associates? Trends in Plant Science 18: 107-115 (2013).

Hoffmann, A.M., Noga, G., Hunsche, M.: High blue light improves acclimation and photosynthetic recovery of pepper plants exposed to UV stress. Enviromental and Experimental Botany 109: 254-263 (2015).

Huché-Thélier, L., Crespel, L., Le Gourrierec, J., Morel, P., Sakr, S., Leduc, N.: Light signaling and plant responses to blue and UV radiations – Perspectives for applications in horticulture. Environmental and Experimental Botany 121: 22-38 (2016).

Jansen, M.A.K., Noort, R.E. van den: Ultraviolet-B radiation induces complex lterations in stomatal behaviour. Physiol. Plant. 110: 189-194 (2000).

Kakani, V.G., Reddy, K.R., Zhao, D., Sailaja, K.: Field crop responses to ultraviolet-B radiation: a review. Agric. For. Meteorol. 120, 191–218 (2003).

Kataria, S., Guruprasad, K.N., Ahuja, S., Singh, B.: Enhancement of growth, photosynthetic performance and yield by exclusion of ambient UV components in C3 and C4 plants. J. Photochem. Photobiol. B Biol. 127: 140–152 (2013).

Keller, M., Rogiers, S.Y., Schultz, H.R.: Nitrogen and ultraviolet radiation modify grapevines' susceptibilityto powdery mildew. Vitis 42 (2): 87-94 (2003).

Kempkes, F., Os, E van: Gewasgroei en energiegebruik in kassen onder een Lexan-ZigZag kasdek in vergelijking met verschillende soorten kasdekken. Wageningen University & Research, report 428 (2006).

Kittas, C., Tchamitchian, M., Katsoulas, N., Karaiskou, P., Papaioannou, Ch.: Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. Sciencia Horticulturae 110: 30-37 (2006).

Kolb., C.A., Kaser, M.A., Kopecky, J., Zotz, G., Riederer, M., Pfundel, E.E.: Effects of natural intensities of visible and ultravolet radiation on epidermal ultraviolet screening and photosynthesis in grape leaves. Plant Physiology 127: 863-875 (2001).

Kong, S., Okajima, K.: Diverse photoreceptors and light responses in plants. Journal of Plant Research 129: 111–114 (2016).

Kotilainen, T., Tegelberg, R., Julkunen-Tiitto, R., Lindfors, A., Aphalo, P.J.: Metabolite specific effects of solar UV-A and UV-B on alder and birch leaf phenolics, Glob. Chang. Biol. 14: 1294–1304 (2008).

Krizek, D.T., Mirecki, R.M., Britz, S.J.: Inhibitory effects of ambient levels of solar UV-A and UV-B radiation on growth of cucumber, Physiol. Plant. 100: 886–893 (1997).

Krizek, D.T., Britz, S.J., Mirecki, R.M.: lnhibitory effects of ambient levels of solar UV-A and UV-B radiation on growth of cv. New Red Fire lettuce, Physiol. Plant. 103: 1–7 (1998).

Kuhlmann, F., Müller, C.: Development-dependent effects of UV radiation exposure on broccoli plants and interactions with herbivorous insects. Environ. Exp. Bot. 66, 61–68 (2009a).

Kuhlmann, F., Müller, C.: Independent responses to ultraviolet radiation and herbivore attack in broccoli. J. Exp. Bot. 60, 3467–3475 (2009b).

Lidon, F.C., Ramalho, J.C.: Impact of UV-B irradiation on photosynthetic performance and chloroplast membrane components in Oryza sativa L. J. Photochem. Photobiol. B: Biol. 104, 457–466 (2011).

Liu, B., Liu, X., Li, Y., Herbert, S.J.: Effects of enhanced UV-B radiation on seed growth characteristics and yield components in soybean. Field Crops Res. 154, 158–163 (2013).

Morandin, L.A., Laverty, T.M., Kevan, P.G., Khosla, S., Shipp, L.: Bumble bee (Hymenoptera: Apidae) activity and loss in commercial tomato greenhouses. The Canadian Entomologist 133 (6): 883 – 893 (2001).

Nedunchezhian, N., Kulandaivelu, G.: Changes induced by ultraviolet-B (280– 320nm) radiation to vegetative growth and photosynthetic characteristics in field grown Vigna unguiculata L. Plant Sci. 123, 85–92 (1997).

Petropoulou, Y., Georgiou, O., Psaras, G.K., Manetas, Y.: Improved flower advertisement, pollinator rewards and seed yield by enhanced UV-B radiation in the Mediterranean annual Malcolmia maritima. New Phytol. 152, 85–90 (2001).

Peitsch, D., Fietz, A., Hertel, H., Souza, J. de, Ventura, D.F., Menzel, R.: The spectral input systems of hymenopteran insects and their receptor-based colour vision. J Comp Physiol A 170: 23-40 (1992).

Rozema, J., van de Staaij, J., Björn, L.O., Caldwell, M.: UV-B as an environmental factor in plant life: stress and regulation. Trends Ecol. Evol. 12, 22–28 (1997).

Sakalauskaite, J., Viskelis, P., Dambrauskiene, E., Sakalauskiene, S., Samuoliene, G., Brazaityte, A., Duchovskis, P., Urbonavicien 9 e, D.: The effects of different UV-B radiation intensities on morphological and biochemical characteristics in Ocimum basilicum L. J. Sci. Food Agric. 93, 1266–1271 (2013).

Sampson, B.J., Cane, J.H.: Impact of enhanced ultraviolet-B radiation on flower, pollen, and nectar production. Am. J. Bot. 86, 108–114 (1999).

Singh, S., Kumari, R., Agrawal, M., Agrawal, S.B.: Modification in growth, biomass and yield of radish under supplemental UV-B at different NPK levels. Ecotoxicol. Environ. Saf. 74, 897–903 (2011).

Snel, J.: Literatuuronderzoek naar het effect van teeltmaatregelen op gehaltes aan gezonde inhoudsstoffen in glasgroenten. Interne Publicatie Wageningen University, BU Glastuinbouw (2010).

Soler, A., Blom, J. van der, Lopez, J., Cabello, T.: The effect of the absorbent UV plastic on the behaviour of Bombus terrestris in greenhouses: results of a bioassay. In. Second short course on pollination of horticulture plants (258-261). J.M. Gurra-Sanz, A. Roldan Serrano, A. Mena Granero 9eds). Almeria, Spain: CIFA la Mojonera (2006).

Terfa, M.T., Roro, A.G., Olsen, J.E., Torre, S.: Effects of UV radiation on growth and postharvest characteristics of three pot rose cultivars grown at different altitudes. Sci. Hortic. 178, 184–191 (2014).

Tezuka, T., T. Hotta, I. Watanabe: Growth promotion of tomato and radish plants by solar UV radiation reaching the Earth's surface, J. Photochem. Photobiol. B Biol. 19: 61–66 (1993).

Tezuka,T., F. Yamaguchi, Y. Ando: Physiological activation in radish plants by UV-A radiation, J. Photochem. Photobiol. B Biol. 24: 33–40 (1994).

Torre, S., Roro, A.G., Bengtsson, S., Mortensen, L., Solhaug, K.A., Gislerød, H.R., Olsen, J.E.: Control of plant morphology by UV-B and UV-B-temperature interactions. Acta Hortic. 956, 207–214 (2012).

Treutter, D.: Significance of flavonoids in plant resistance and enhancement of their biosynthesis. Plant Biol. 7, 581–591 (2005).

Treutter, D.: Significance of flavonoids in plant resistance: a review. Environ Chem Lett 4: 147-157 (2006).

Tsormpatsidis, E., Henbest, R.G.C., Davis, F.J., Battey, N.H., Hadley, P., Wagstaff, A.: UV irradiance as a major influence on growth, development and secondary products of commercial importance in Lollo Rosso lettuce 'Revolution' grown under polyethylene films. Environmental and Experimental Botany 63: 32-239 (2008).

Tsormpatsidis, E., Henbest, R.G.C., Battey, N.H., Hadley, P.: The influence of ultraviolet radiation on growth, photosynthesis and phenolic levels of green and red lettuce: potential for exploiting effects of ultraviolet radiation in a production system. Ann. Appl. Biol. 156, 357–366 (2010).

Verdaguer, D., Jansen, M.A.K., Llorens, L., Morales, L.O., Neugart, S.: UV-A radiation effects on higher plants: Exploring the known unknown. Plant Science 255:72-81 (2017).

Wargent, J.J., Taylor, A., Paul, N.D.: UV supplementation for growth and disease control. Acta Hortic. 711, 333–338 (2006).

Zhang, L., Allen, L.H., Vaughan, M.M., Hauser, B.A., Boote, K.J.: Solar ultraviolet radiation exclusion increases soybean internode lengths and plant height, Agric. For. Meteorol. 184: 170–178 (2014).

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