

Ultraviolet-Blocking Materials as a Physical Barrier to Control Insect Pests and Plant Pathogens in Protected Crops

Beatriz M. Diaz • Alberto Fereres*

Departamento de Protección Vegetal, Instituto de Ciencias Agrarias, Centro de Ciencias Medioambientales-CSIC, C/Serrano 115 dpdo., Madrid 28006, Spain

Corresponding author: * afereres@ccma.csic.es

ABSTRACT

New types of ultraviolet (UV)-blocking materials, such as polyethylene films and nets, have been developed in recent years as a very promising tool to control insect vectors of plant disease threatening greenhouse crops. UV-blocking materials have properties to filter the UV radiation (280-400 nm) interfering with the vision of insects and in consequence, their behaviour related with movement, host location ability and their population parameters. The exclusion of part of the UV radiation within the greenhouse environment has a dramatic incidence on insect orientation, movement and on the spread of insect-transmitted viral diseases. In the same way, the impact of UV-absorbing materials on population dynamics of natural enemies, pollinators and crop yield needs further investigation. The level of protection of the different UV-blocking materials may vary among different designs of greenhouses and the geographic location that determines different internal climatic conditions and the amount of UV and visible light absorbed and transmitted within the covered structures. In this review, we will discuss the current knowledge about the impact of UV-absorbing films on insect pests, plant pathogens and beneficial organisms, with special attention to insects acting as vectors of plant disease. Also, the new perspectives, limitations and advantages of using UV-blocking materials together with other control strategies under Integrated Pest Management (IPM) production systems will be discussed.

Keywords: cover materials, greenhouse, insect vectors, Integrated Pest Management, plant diseases

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INTRODUCTION

Agriculture has played a major contribution to the maintenance of natural resources and biodiversity and plays an important social and environmental role. It is clear that technology and innovation plays a major role in increasing yields and profit of lands and therefore, reduces the withdrawal of agricultural activities.

The contribution of plastic materials to agriculture has been a real revolution to traditional agriculture that has made possible the increases of productive areas of the world with the incorporation of areas with unfavourable climatic conditions.

Protected crops include horticulture and ornamental

flower production (cut flower, potted floral and foliage plants). Protected production has increased in the last decade with the development of new types of plastic films which have achieved a high degree of specialization with different applications and properties (anti-dripping, anti-thermal, anti-pest). At present, greenhouses are mainly distributed in two regions of the world; one of these is Asia, especially in China, Korea and Japan, with almost 80% of the total area, and in the Mediterranean region covering about 15% of the world (Espi *et al.* 2006). This protected production requires the use of 1.000.000 t/year of plastic films to cover all the protected crops grown worldwide (Espi *et al.* 2006).

In protected agriculture crops suffer important econo-

mic damage from insect pests as well as diseases caused by viruses (e.g. CMV, TSWV, TYLCV) and their vectors (e.g. aphids, thrips, whiteflies), fungi (e.g. *Botrytis cinerea*, powdery mildew), and bacteria (e.g. *Clavibacter michiganensis* and *Pectobacterium* spp.). The most extended and common practice to control insect pests and plant pathogens is the application of large amount of pesticides.

However, pesticides have a negative impact on farmers, consumers and the environment (Pimentel and Greiner 1997). Currently the situation is unsustainable and other alternative control measures need to be implemented because many of the active ingredients are being banned in the European Union (DOUCE 2002) and elsewhere, and also pesticide efficacy is also not enough to control many of the key pests and diseases because resistance build-up to insects and pathogens often occurs (Urech *et al.* 1997). In addition, consumers are very sensitive to environmentally friendly agricultural systems (organic agriculture, integrated production, etc.), and are demanding pesticide-free high quality and low cost food products. All these demands require the investigation of new control tactics for pest and disease control.

Photosensitive plastics are a quite recent development that can block or modify the transmitted light to obtain specific benefits (Catalina *et al.* 2000). Nakagaki *et al.* (1982) reported the first evidence of the inhibitory effect of UV blocking materials on the invasion of greenhouses by insects. An environment with a low level of UV light modifies insect vision and in consequence its behaviour. Several studies have been conducted to evaluate the effect of this plastic materials used as nets and films to reduce insect population in protected crops and these will be discussed in this review.

In addition, changing the light spectrum underneath the film cover may alter plant morphogenesis, and consequently produce changes in herbivory responses. In the same way the manipulation of greenhouse light quality was used as a non-chemical alternative method for growth regulation of ornamental crops (Rajapakse and Kelly 1995). Crop yield and quality can be increased at the time that pest and disease damage is significantly reduced by changing the colour physicochemical characteristics of plastic films. Photosensitive plastic barriers have also shown good efficacy in the control of plant pathogenic fungi (Honda *et al.* 1977). At the same time these types of barriers have proved positive effects by increasing the persistence and viability of the entomopathogenic fungi, *Beauveria bassiana* (Costa *et al.* 2001) and of baculoviruses (Lasa *et al.* 2007) used as biological control agents.

The aim of this review is to update the information available on the use of the UV-blocking plastic materials used in protected environments to control insect pests and diseases, with special attention to their impact on insect vectors of plant diseases, their natural enemies and other beneficial organisms. In addition, the use of the UV blocking materials as a tool in Integrated Pest Management (IPM) programs will be discussed.

RESPONSE OF INSECTS, PATHOGENS AND PLANTS TO UV RADIATION

Effects of UV radiation on insect vision and behaviour

Vision is defined as the ability to perceive spatial patterns. Vision of insects is due to the photoreceptors present in the ocelli and the compound eyes (Fig. 1B, 1C). Compound eyes are formed of aggregations of separate visual elements known as ommatidia, each ommatidium corresponding with a single facet of the cornea (Fig. 1B). The ommatidium is composed by different parts, such as, the cornea, the crystalline cone cells, the primary and secondary iris cells and the retinula (Fig. 1C). The retinula forms the basal portion of an ommatidia and is composed of a group of pigmented cells, each of the latter being continuous with a post-retinal

fibre. The visual cells collectively secrete an internal optic rod or rhabdom. The rhabdom forms the central axis of the retinula and is in contact with the extremity of the crystalline cone (Imms 1957). Dorsal ocelli and stemmata (lateral ocelli) are poor image formers relative to compound eyes, detecting mainly the light and dark expanses, the fluctuating light intensity or polarized light (Prokopy and Owens 1983). True image formation in insects is a property solely of the compound eyes, which are able to mediate the discrimination of form with various degrees of visual acuity and to perceive the movement and spatial location of distant objects (Imms 1957). The compound eye is a unique structure with enormous flexibility for selective adaptation. They vary in external (size, shape, color, facet number, surface texture and position) and internal (morphology of innervation and physiology of photoreceptor function) characteristics and these differences determine visual capability (Prokopy and Owens 1983).

It is known that insects have ocular photoreceptors in a bandwidth of ultraviolet (200-400 nm), visible or photosynthetically active radiation (PAR), 400-700 nm and the far red (700-800 nm) part of the electromagnetic energy spectrum (Fig. 1A). Wavelength in the UV region have incidence on insect behaviour, such as, orientation, navigation, host finding and feeding (Antignus and Ben-Yakir 2004) (Fig. 1D).

However, to optimize detection of ground pattern movement, insect motion detectors in the ventral half of the eye are most sensitive to long wavelengths (greater than 500 nm) which are in the region of earth's reflecting energy, and are least sensitive to short wavelengths (less than 500 nm), which are in the region of greatest visible sky energy (Prokopy and Owens 1983).

In many herbivorous insects, plant spectral quality appears to be the principal stimulus eliciting alightment on living plants. In this way, special attraction is elicited by foliage-like hues, such as the wavelengths reflecting between 500-580 nm causing maximum reaction of aphids to yellow (Klingauf 1987).

The spectral discrimination requires a minimum of two photoreceptor types located in different parts of the compound eyes. Insects are able to distinguish between vegetation and sky by the presence of two receptor types, one absorbing maximally before ca. 500 nm and one absorbing maximally beyond this point. Discrimination between foliage and bare soil theoretically require one additional receptor for detection differences above 580 nm (Prokopy and Owens 1983). Using the electroretinogram technique Kirchner *et al.* (2005) determined that alate female summer migrants of *Myzus persicae* have three types of photoreceptors in the compound eye, the first in the green region around 530 nm, the second peak was registered in the blue-green region (490 nm) and the third peak was registered in the near UV (330-340 nm). However, *Frankliniella occidentalis* showed two peaks of spectral efficiency, the primary in the UV range and a secondary in the visible region around 540 nm (Mattesson *et al.* 1992). Mellor *et al.* (1997) observed a similar spectral efficiency between the whitefly *Trialeurodes vaporariorum* and its parasitoid *Encarsia formosa*, the primary peak is in the blue-green-yellow region (520 nm) and a secondary peak in the UV region. Also, they observed a difference in the response to UV light between the dorsal and the ventral region of the compound eye of *T. vaporariorum*. Doukas and Payne (2007b) found that compartments clad with films that blocked LTV below 375 nm attracted significantly more whiteflies than films that blocked UV below 385 nm, whereas the absorption of LTV wavelengths above 385 nm did not show any further effect on whitefly numbers. Another recent work conducted by Doukas and Payne (2007a) revealed that under UV-blocking films with similar UV-absorbing properties, *E. formosa* showed preference to disperse into compartments clad with films that had high diffusion properties. However, adults of *T. vaporariorum* did not discriminate between direct and diffused-light environments. The positive response of the

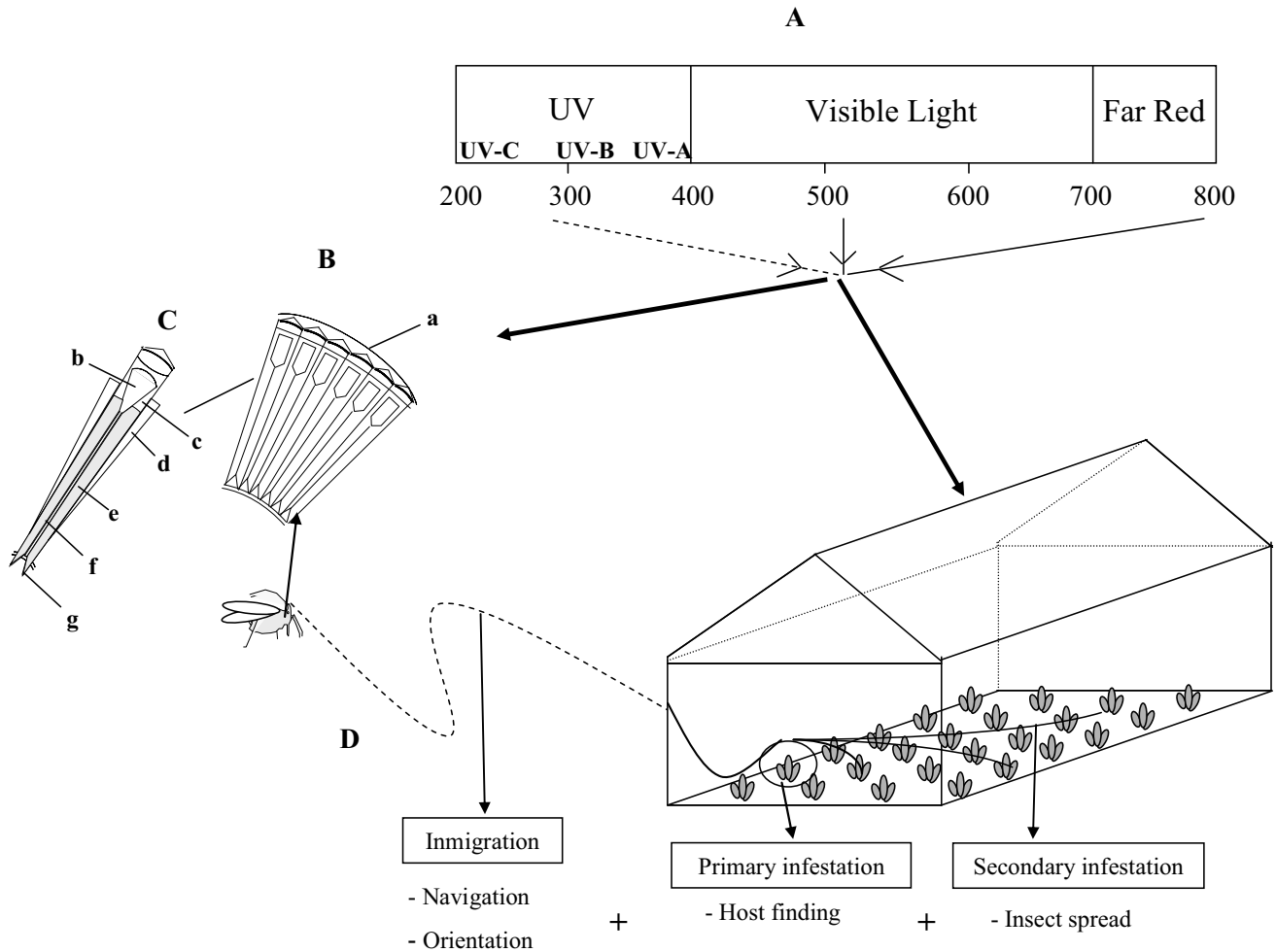


Fig. 1 Incidence of the different types of wavelengths of the electromagnetic energy spectrum (A) on insect vision organs (B, C) and on insect colonization of a protected crop (D). (A) Wavelengths are expressed in nanometers (nm). (B) Section of the compound eye showing a group of ommatidia and the cornea (a). (C) Diagram of a standard ommatidium showing its different parts, the crystalline cone (b), primary iris cells (c), secondary iris cells (d), retinulla (e), rhabdom (f) and nerve fiber (g). (D) UV-blocking materials affecting insect orientation, navigation, host finding and the spread within a greenhouse structure.

parasitoid *E. formosa* to diffuse light could be a result of the better illumination of all ommatidia than in its whitefly host, and the different response between both species to diffused light.

Dispersal difference between *T. vaporariorum* and *E. formosa* under poor UV-light environments could be explained not only by the position of the photoreceptors in the compound eye, but also by the differences in the structure of the compound eye in the two insect species (Doukas and Payne 2007a). Mellor *et al.* (1997) observed that *E. formosa* has more light receptors than its whitefly host, and therefore, the radiance perceived under the same light intensity will be greater for the parasitoid, because more photons will be received by its compound eye (Doukas and Payne 2007a).

Different groups of insects are able to support a different amount of UV light depending on their habits, either nocturnal or diurnal. Antignus *et al.* (1996) suggested that the ability of UV-absorbing plastic sheets to protect crops from *Bemisia tabaci*, *Aphis gossypii* and *F. occidentalis* indicates a common response of diurnally active insects to UV light probably caused by the presence of similar photoreceptors in their compound eyes.

In the same way, the amount and quality of sunlight radiation vary with latitude; the compound eyes of insects have a different capacity to react to UV light exposure. Meyer Rochow *et al.* (2002) studied the UV-induced damage in photoreceptors in four species of insects from higher and lower geographic latitudes. They found two kinds of reaction in the photoreceptive cells of the insect's eyes. The diurnal butterflies, *Papilio xuthus* (from Japan) and *Pieris*

napi (from northern Finland) exhibited changes only in the cell bodies of retinulla cells identified as short wavelength receptors, but not their corresponding rhabdomeres, exhibit damage with apoptotic features. The UV-vision in bright sunlight is important to these butterflies for intraspecific communication and for recognizing UV-nectar guides on the petals of flowers. However, rhabdomeres of cells of the adult crickets, *Gryllus bimaculatus* (from Japan) exhibit signs of severe membrane disruption when exposed to UV radiation. These effects can be explained by the nocturnal habits of the crickets and in consequence, their UV receptors could not play a role in communication or food identification. No signs of damage occurred in the photoreceptors of the eyes of the bumble bee, *Bombus hortorum* because their rhabdoms are voluminous and are able to see under relatively low light environments. This fact has implications for this bumble bee species that lives in northern Finland, where they are able to visit flowers 24 h a day during the short summer season.

Within the UV portion is possible to distinguish three types of wavelengths: UV-C (200-290 nm), UV-B (290-320 nm) and UV-A (320-400 nm) (Fig. 1A). UV-B radiation reduce the infestation of different species of thrips, such as *F. occidentalis* (Antignus 1996) and *Calliothrips phaseoli* (Mazza *et al.* 1999). Behavioural experiments conducted on *Pieris brassicae* using a monochromatic light as stimuli, demonstrated that the open-space reaction corresponds to UV-A wavelengths, while the feeding, egg laying and drumming reactions correspond to wavelengths higher (420-590 nm) than the UV-radiation (Scherer and Kolb 1987).

Effect of UV radiation on plants and their relationship with insect herbivores

Three photoreceptors have been described that have a direct effect on green plants: Phytochrome, that absorbs visible light in the red or far red interval, 600-800 nm, Cryptochrome, that absorbs light in the blue and ultraviolet A interval, 320-450 nm and, a Photoreceptor that absorbs in the UV-B, in the 280-320 nm interval. Many microbes, plants and animals use UV-B and UV-A radiation as a source of information about their environment affecting many ecological processes (Paul and Gwynn-Jones 2003). Long exposure to UV radiation may damage plants and other living organisms because the UV photons have enough energy to destroy chemical bonds causing photochemical reaction, that induces structural and biochemical changes (Kovács and Keresztes 2002; Jacobs *et al.* 2007). A large number of experiments where solar UV-B has been attenuated using wavelengths-selective filters, such as polyester, show a range of significant responses across many plant species and locations (Paul *et al.* 2005).

In this way, responses to UV attenuation by selective filters include increased growth and yield of an eggplant soilless crop (Kittas *et al.* 2006). Also, changing in quality, such as pigmentation and taste of lettuce was found when plants were grown under UV-opaque film, which absorbed 50% of UV-A and 95% of UV-B light (Paul *et al.* 2005).

Plants need UV light for the synthesis of specific pigments such as anthocyanins which are required for colouring of vegetables such as red cabbage. Therefore, UV-blocking films should not be used to protect crops in which anthocyanin pigmentation is a determinant of their quality (Antignus and Ben-Yakir 2004).

Also, in cut flower production flowering is affected by the use of spectral filters. The light quality altered by the use of different colour filters (blue and red absorbing, blue absorbing, two partially blue absorbing and red absorbing) influenced the time of flowering of chrysanthemum (*Dendranthema grandiflorum*) plants. Time of flowering was affected by a combined action of phytochrome and cryptochrome since filters with blue transmission and high phytochrome photoequilibrium resulted in early flowering (Khat-tak and Pearson 2006).

Plastic films with different transmission of UV radiation were used to investigate the changes of leaf and flower colours of ornamental plants showing that UV-B causes a decrease of the chlorophyll content of *Coleus × hybrida*, but no loss of plant quality was recognised as a result of chlorophyll gradation. Therefore yellow pigments of a green cultivar and the red pigments of a red-green cultivar emerged. UV-A induced the synthesis of anthocyanins in flower and leaves of *Kalanchoe × hybrida* 'Colorado' increased by UV-B (Hoffman 1999).

These structural and biochemical changes on plants due to UV radiation affect their relationship with herbivores. Several studies reported that phytophagous insects show direct effects as well as indirect behavioural responses to solar UV-B wavelength induced by changes in plant tissue quality.

The direct effect of the UV-light on insect herbivores was reported by Mazza *et al.* (1999), who observed a negative effect of the UV-B radiation on the density of the thrips, *C. phaseoli* and the amount of leaves damage caused by this insect on field-grown soybean crops. Also, in laboratory and field experiments thrips preferred leaves from plants they were not exposed to solar UV-B light than those exposed to supplemental UV-B radiation produced by artificial UV-B bulbs. Using behavioural experiments with *C. phaseoli* in experimental tunnels Mazza *et al.* (2002) demonstrated that thrips can sense and respond to solar UV-B under natural background levels of UV-A and human visible radiation. This work provided the first demonstration of a specific behavioural sensitivity to ambient UV-B of an insect.

The indirect responses are mediated by chemical chan-

ges in the plant host that are induced by UV-B exposure, which can modify the abundance of a number of secondary metabolites, including phenolic compounds with potential impact on insect herbivores, as shown by Izaguirre *et al.* (2007). They demonstrated that the anti-herbivore effect induced by UV-B on two wild species of *Nicotiana* may be mediated at least in part by the accumulation of phenylpropanoid derivatives, such as chlorogenic acid and phenolic compounds (flavonoids) that are similar to those induced by the plant in response to insect herbivory.

Hatcher and Paul (1994) showed that leaves of pea (*Pisum sativum*) exposed to UV-B radiation increases concentration of phenolic compounds and this change had a little effect on the last instar larvae of *Autographa gamma*. However, tissue nitrogen level also increased with increasing UV-B light and this increase was correlated with an increase in the efficiency of the larvae to utilize their food and on the larval growth rate, but in a reduction in the plant consumption. Similar results were observed in the consumption by the soybean worm *Anticarsia gemmatalis*, feeding on soybean leaves previously damaged by thrips exposed to supplementary UV-B radiation.

Effect of UV radiation on plant diseases

Diseases are influenced by a range of interacting responses to UV light, including altered plant growth, canopy microclimate, altered host plant resistance and changes in the survival of fungal pathogens (Paul *et al.* 2005). The effect of the UV-light on pathogens that cause plant diseases are well covered in a recent review by Raviv and Antignus (2004). There are very few new contributions on the relationship between UV-light and plant fungal diseases.

Vakalounakis (1992) has shown that films absorbing infrared radiation increases night temperatures and reduce relative humidity producing a less favourable environment for fungal diseases. Also, the UV-absorbing films may reduce the sporulation of *Botrytis cinerea* in greenhouse-grown tomato and cucumber plants (Reuveni *et al.* 1989; Reuveni and Raviv 1992, 1997; Nicot 1996). A dose of 0.88 KJ m⁻² of UV-C light was found to be highly germicidal to *B. cinerea* conidia in bell pepper (*Capsicum annum* L., var. *annuum*). Also, when pepper fruits were exposed to UV-C 24 hours before inoculation with *B. cinerea* a lower percentage of infections were recorded, concluding that UV-C radiation was effective for inducing resistance to this fungal pathogen in fruits at various stages of maturity (Mercier *et al.* 2001).

In addition, Paul *et al.* (2005) observed that *B. cinerea* and its biological control agent, the fungus *Trichoderma harzianum* are both sensitive to UV radiation in experiments conducted on lettuce crops covered with a UV-opaque film (PAR transmission: 95%, UV-A transmission: 10% and UV-B transmission: 0%).

Differences in survival among fungus species was observed when they were exposed to UV-light, varying from 7 days for *Sclerotium rolfsii* to approximately 50 minutes for *Mycosphaerella pinodes* and 3 minutes for *B. cinerea* (Rotem and Aust 1991).

The effect of solar UV-radiation alters phyllosphere bacterial community of peanut leaves in field studies using plants grown under UV-B transmitting or UV-B excluding plastic filters. Other studies using *C. michiganensis* determined that strains which produce pigments are characterized as UV-tolerant, enhancing the ability of bacterial strains to maintain population size in the phyllosphere (Jacobs and Sundin 2001; Jacobs *et al.* 2005).

PHYSICAL AND SPECTRAL CHARACTERISTICS OF UV-BLOCKING MATERIALS

Plastic films used in agriculture and horticulture have been modified over the years to enhance their performance and useful lifespan by the incorporation of different additives that alter the physical and spectral properties of these mate-

Table 1 Different types of UV-absorbing plastic films used for controlling insect vectors and virus diseases under enclosed environments.

Type of UV-plastic film and manufacturer	Spectral absorption of UV light	Type of greenhouse	Country	Crop	Insect pests and natural enemies	Virus diseases	Reference
IR-Veradim ⁽¹⁾	some light transmittance between 250-400 nm	walk-in tunnel	Besor (Israel)	tomato	<i>B. tabaci</i> <i>F. occidentalis</i> <i>A. gossypii</i>	TYLCV	Antignus <i>et al.</i> 1996
		walk-in tunnel	Besor (Israel)	tomato	<i>B. argentifolii</i>	TYLCV	Antignus <i>et al.</i> 1998
		walk-in tunnel	Arava Valley (Israel)	sweet pepper	<i>M. persicae</i> <i>A. matricariae</i>	---	Chyzik <i>et al.</i> 2003
Solarig ⁽²⁾	some light transmittance between 250-400 nm	greenhouse	Besor (Israel)	sweet pepper	<i>A. colemanii</i> <i>D. isaea</i> <i>E. mundus</i>	---	Chiel <i>et al.</i> 2006
		walk-in tunnel	Besor (Israel)	tomato	<i>B. tabaci</i> <i>F. occidentalis</i> <i>A. gossypii</i>	TYLCV	Antignus <i>et al.</i> 1996
		walk-in tunnel	Besor (Israel)	tomato	<i>B. tabaci</i> <i>F. occidentalis</i> <i>A. gossypii</i>	TYLCV	Antignus <i>et al.</i> 1996
Rav- Hozek ⁽³⁾	no light transmittance between 200-370 nm	walk-in tunnel	Besor (Israel)	tomato	<i>B. tabaci</i> <i>F. occidentalis</i> <i>A. gossypii</i>	---	Costa <i>et al.</i> 1999
DuraGreen-Insulator FI ⁽⁴⁾	<380nm+IR component	small scale experimental tunnels	San Diego County (USA)	no plants	<i>B. argentifolii</i> <i>F. occidentalis</i>	---	Costa <i>et al.</i> 1999
		commercial greenhouse	San Diego County (USA)	cut-flowers	aphids, thrips and whiteflies	---	Costa <i>et al.</i> 2002
DuraGreen-Custom FI	<380 nm	small scale experimental tunnels	San Diego County (USA)	no plants	<i>B. argentifolii</i> <i>F. occidentalis</i>	---	Costa <i>et al.</i> 1999
Klerk's Rose ⁽⁶⁾ (K-Rose)	<380 nm	small scale experimental tunnels	San Diego County (USA)	no plants	<i>B. argentifolii</i> <i>F. occidentalis</i>	---	Costa <i>et al.</i> 1999
		small enclosed tunnels	Hannover (Germany)	no plants	<i>T. vaporariorum</i>	---	Mutwiwa <i>et al.</i> 2005
Klerk's Kool-lite 380 (K-380) ⁽⁶⁾	<380 nm	small scale experimental tunnels	San Diego County (USA)	no plants	<i>B. argentifolii</i> <i>F. occidentalis</i>	---	Costa <i>et al.</i> 1999
High UV-absorbing plastic film ⁽⁴⁾	<380 nm	small enclosed tunnels	San Diego County (USA)	no plants	<i>T. vaporariorum</i>	---	Costa <i>et al.</i> 2002
Klerk's Plastic Product ⁽⁵⁾	<360 nm+IR component	commercial greenhouse	San Diego County (USA)	cut-flowers	aphids, thrips and whiteflies	---	Costa <i>et al.</i> 2002
AD-IR AV clear ⁽¹⁾	---	walk-in tunnel	Navarra (Spain)	lettuce	<i>M. euphorbiae</i> <i>A. lactucae</i> <i>F. occidentalis</i> <i>T. vaporariorum</i> <i>A. gamma</i>	Potyvirus TSWV	Diaz <i>et al.</i> 2006
Sun Selector diffused Antivirus ⁽¹⁾	<380 nm	greenhouse	Bangkok (Thailand)	tomato	<i>B. tabaci</i> <i>C. claratris</i> <i>A. gossypii</i>	CaCV	Kumar and Poehling 2006
Luminance UVX ⁽⁷⁾	< 370 nm	choice-chambers	United Kingdom	cucumber	<i>T. vaporariourum</i> <i>E. formosa</i>	---	Doukas and Payne 2007a, 2007b
Antibotrytis ⁽⁷⁾	< 400 nm	choice-chambers	United Kingdom	cucumber	<i>T. vaporariourum</i> <i>E. formosa</i>	---	Doukas and Payne 2007a, 2007b
XL Sterilite ver. 1 (XL-375) ⁽⁸⁾	< 375 nm	choice-chambers	United Kingdom	cucumber	<i>T. vaporariourum</i> <i>E. formosa</i>	---	Doukas and Payne 2007a, 2007b
XL Sterilite ver. 2 (XL-385LD) ⁽⁸⁾	< 385 nm	choice-chambers	United Kingdom	cucumber	<i>T. vaporariourum</i> <i>E. formosa</i>	---	Doukas and Payne 2007a, 2007b
XL Sterilite ver. 3 (XL-385) ⁽⁸⁾	<385 nm	choice-chambers	United Kingdom	cucumber	<i>T. vaporariourum</i> <i>E. formosa</i>	---	Doukas and Payne 2007a, 2007b

Plastic films supplied by:

⁽¹⁾ Ginegar Plastic Products Co., Ginegar, Israel⁽²⁾ Palrig, Neot Mordecha, Israel⁽³⁾ Erez, Thermoplastic Products, Erez, Israel⁽⁴⁾ DuraGreen Marketing USA, Mount Dora, FL, USA⁽⁵⁾ Klerk's Plastic Product Manufacturing, Richburg, SC, USA⁽⁶⁾ Hyplast Ltd., Hoogstaten, Belgium⁽⁷⁾ BPI Agri, UK⁽⁸⁾ Plastika Kritis, GreeceVirus abbreviations: *Tomato Yellow Leaf Curl Virus* (TYLCV), *Tomato Spotted Wild Virus* (TSWV), *Capsicum Chlorosis Virus* (CaCV).

rials. The first additives incorporated into polyethylene films were UV stabilizers to protect them from fast degradation. Later, thermal stabilizers were also incorporated and the introduction of antifog and antidrip agents were applied to diminish the negative effects of the condensation which reduce the amount of light transmission into the greenhouse and reduce the risk of fungal diseases (Cemek and Demir

2005). Nowadays a new family of additives for agricultural films has been developed to manipulate their optical properties. Optical properties include the manipulation of different regions of the light spectrum that are necessary for photosynthesis and in consequence to enhance the process of plant growth and crop yield (Winsel 2002). The same principle was used to manipulate the light spectrum in the UV

region to improve pest and disease management. These types of materials act as a photoselective barrier by blocking the transmission of the UV radiation (280-400 nm) to the interior of the greenhouse (Espí *et al.* 2006). The lack of UV radiation has a positive effect on plant growth and contributes to reduce the damage due to insect pests and plant diseases.

The name "UV-blocking materials" includes different plastic films and nets available in the market provided by various manufacturers with different capacities to absorb UV wavelength below 380 nm and with a proved action for reducing the damage caused by insect pests.

Different types of UV-blocking plastic films and types of structures have been tested under different climatic conditions and regions of the world mainly against the three main groups of insect vectors of virus diseases (aphids, whiteflies and thrips) (Table 1). Also, there are some studies on the impact of these types of films on the natural enemies of insect vectors and other beneficial organisms (reviewed in the Section COMPATIBILITY OF UV-BLOCKING MATERIALS WITH BENEFICIAL ORGANISMS). Krizek *et al.* (2005) compared the spectral properties of UV-selecting and UV-transmitting plastic materials by means of a UV-VIS spectroradiometer or a UV-VIS spectrometer to provide growers some guidelines for selecting appropriate covering materials, showing that plastics have different spectral transmittance capacity. For example, cellulose diacetate (CA) excludes UV-C wavelength, but transmits UV-B and UV-A wavelengths.

Polyester films block the transmission of UV-B, but are able to transmit UV-A wavelengths, and are commonly used in UV-enhancement studies as a control when using CA to exclude UV-B radiation. Also, Teflon transmits radiation at 245 nm and above. When using these three types of plastics, CA should be used with caution in UV exclusion studies because it may have a phytotoxic effect on sensitive plants such as cucumber (Krizek and Mirecki 2004).

The kind of UV-blocking plastic used in a structure determines the level of protection and can affect the population levels of some insect species. In this way, Costa *et al.* (2002) found that UV-absorbing components that block the majority of UV-light at wavelengths below 380 nm had more influence in reducing insect numbers than those that blocked light at wavelengths below 360 nm. Antignus *et al.* (1996) found a positive correlation between the level of protection and the capacity of the sheets to absorb UV light.

In addition, the design of the greenhouse and the amount of unfiltered light that enters the system appear to be an important component in determining the level of protection provided by UV-blocking films (Costa *et al.* 2002). It is important to consider that most works have been conducted in enclosed greenhouses or tunnels obtaining in some cases contradictory results compared with those obtained from open-side greenhouse structures (Table 1). For example, UV-blocking materials were not able to reduce the population density of *T. vaporariorum* in open-side greenhouses, while a positive effect of the film in reducing insect density was observed in enclosed tunnels (Costa *et al.* 2002; Mutwiwa *et al.* 2005; Diaz *et al.* 2006). In this last case, it was not possible to evaluate the effect of UV films on the attraction to insect invasion into the protected structure which is the first phase in the process of infestation by insects in a greenhouse crop (Fig. 1D).

Habitats with significant UV levels can be found at high altitudes, where solar radiation has to penetrate a thinner layer of the atmosphere. Consequently, UV-blocking films will be more adequate to use under these types of high intensity UV-light conditions and in geographical locations closer to the equator, where UV-light differences within the greenhouse and the outside light environment are greater (Doukas and Payne 2007b).

As shown in Table 1, most of the pioneer experiments to evaluate the efficacy of UV-blocking plastic films were done in desertic areas from southern Israel (mainly in the

Negev dessert), but the latest works on this subject were conducted in other Mediterranean and temperate regions, with higher relative humidities which demands a different design of greenhouses structure and specific management tactics, such as strategies to increase ventilation over the crop canopy.

In general, physical barriers such as plastic films or nets reduces the efficiency of natural ventilation with the consequent increase of temperature inside the covered structure, although this principle is not applicable to UV-plastic films, because the heat load depends on the overall energy transmittance and not on the different spectral properties of the films (von Elsner and Xie 2003). However, the specific external climatic conditions of a given region determines the need for ventilation inside the cover structure as has been described by Kumar and Poehling (2006) in studies conducted in the humid tropics (Thailand). These high humidity external conditions reduced the efficiency of UV-plastic films to mitigate insect immigration because side wall ventilation is a pre-requisite under such climatic conditions. Conversely, the efficiency of UV-absorbing barriers is much higher in dry regions of Germany where crops can be grown under closed tunnels, as shown by Mutwiwa *et al.* (2005).

TYPES OF PHOTOSELECTIVE BARRIERS USED FOR INSECT PEST MANAGEMENT

Habitat manipulation is an insect pest management strategy that provides an unfavourable environment for insect pests and more favourable habitat to their natural enemies. In this way, physical barriers are one of the oldest tactics used to control insect pests and had a significant role in Integrated Pest Management Programs in the last few decades (Boiteau and Vernon 2001). Different kinds of physical barriers have been used in the past to exclude insects, modify their behaviour and provide a deleterious environment for their development and population increase. For example, insect screens act as an exclusion physical method between the plants and the pest and have been successfully adopted by many growers around the world.

Vision and olfaction are the primary cues used by insects to orient to their host plants; sometimes the two cues work in concert (Prokopy and Owens 1983). Some physical barriers are often based on manipulating insect vision dependent behaviours by using UV-blocking or UV-reflective materials to interfere with host finding, landing and orientation (Antignus 2000). These materials have been used commonly in three different forms, such as mulches for open-grown crops, and as plastic sheets or screen/nets for protected crops.

Reflective mulches

Plastic mulches act among other purposes as deflecting insect pest populations. Depending of the mulch colour they may also have repellent effects on insects. Therefore different types of plastic mulches have been used specially to control insect vectors, such as aphids, thrips and whiteflies.

Plastics mulches are now being manufactured either as with a high absorption or with a high reflection for certain wavelengths of light (Weintraub and Berlinger 2004).

One of the first reports on the use of reflective mulches and plastic sheets to control plant viruses transmitted by insect vectors is the work by Lobenstein *et al.* (1975). They found that aluminium foil and coloured plastic sheets were a very good strategy to protect pepper crops from aphid-transmitted viruses such as *Cucumber mosaic virus* (CMV) and *Potato virus Y* (PVY).

UV-reflective plastic mulches combined with the insecticide spinosad reduced early season abundance of adult thrips, *F. occidentalis*, in field-grown pepper and the consequent primary infection of *Tomato spotted wild virus* (TSWV) compared to plots covered with a black mulch (Reitz *et al.* 2003). Similar results were obtained by Sta-

visky *et al.* (2002) using UV-reflective mulches on the population of *F. occidentalis*, *Frankliniella tritici* and *Frankliniella bispinosa* and TSWV in field-grown tomato as a unique control measure, or when UV-reflective mulch was combined with a plant activator (acibenzolar-*S*-methyl) and insecticides to control the same species of thrips (Momol *et al.* 2004).

Other works confirm that UV-reflective plastic mulches are a good tool for reducing silverleaf whitefly, *Bemisia argentifolii* populations and the incidence of silverleaf in cucurbits (Summers and Stapleton 2002; Summers *et al.* 2004). Also, UV-reflective mulches provided a higher reduction in the incidence of *Tomato mottle virus* (ToMoV) when compared with wheat straw mulch in fresh-market tomato (Csizinszky *et al.* 1999).

No effects were observed on the number of leafminers and mite colonies on tomato foliage from field-grown commercial tomato covered with aluminium-painted plastic mulch compared to non-painted mulch (Kring and Schuster 1992).

Aphid landing preference is determined by the colour of the background, mainly by the degree of contrast between a green target (e.g. the plant) and the colour of the soil (background colour) (A'Brook 1968).

In an experiment using water traps located on soil covered by different coloured plastic sheets, aphid catches were highest in the traps placed on the uncovered background and lowest in the traps placed on white or silver backgrounds (Doring *et al.* 2004). Similar trends were observed by Kring and Schuster (1992) capturing lower number of aphids in water dish traps and on tomato foliage when a tomato field crop was covered with an aluminium-painted plastic film. As a consequence, fewer tomato plants infected with aphid-transmitted viruses were recorded.

Also, a significant reduction in the incidence of aphid-borne viruses was obtained in a zucchini squash crop (*Cucurbita pepo* L.) using plastic UV reflective mulches (metallized mulch) as a crop cover (Summers *et al.* 2004).

UV-blocking insect nets or screens

Insect exclusion screens (50 mesh) were first used against *B. tabaci* to prevent primary infestation of this pest and the spread of whitefly-transmitted viruses in fresh-market tomato production in Israel. Later, a new product was developed by combining the physical barrier provided by the conventional insect-proof net with optical properties, developing a new screen that is able to absorb UV-radiation in the UV-A and UV-B range (Bionet[®]) (Antignus *et al.* 1998). Experiments conducted in Israel showed that Bionet[®] screen with a density of 50-mesh was effective to protect the invasion of *B. argentifolii* and the spread of *Tomato Yellow Leaf Curl Virus* (TYLCV), red spider mites (*Tetranychus telarius*), and leafminers (*Liriomyza trifolii*) in tomato greenhouses. Also, the 50-mesh screen was able to protect cucumber from aphids very effectively.

However, this positive effect disappeared when the hole size of the screen was reduced to 30-mesh and 16-mesh, because a considerable amount of UV-light was transmitted through the screen compared with that of the 50-mesh screen (Antignus *et al.* 1998). However, due to the small size of the holes of the 50-mesh screens, they do not provide a good solution for regions that require high ventilation such as those with hot and humid climate.

Greenhouses ("parral type") in southeastern Spain (Almería) covered with Bionet[®] at the roof and their sides provided good control of *B. tabaci* and reduced the incidence of TYLCV of tomato crops with similar results to those obtained in Israel (Tico Maluquer *et al.* 2002).

However, in all of the experiments carried out in Israel and Spain, Bionet[®] screen failed to prevent the invasion of *F. occidentalis* into the protected structures (Antignus 1998; Tico Maluquer *et al.* 2002). In a recent work, Kumar and Poehling (2006) combined the use of UV-blocking nets and plastic films to study the movement of the whitefly, *B.*

tabaci, the thrips, *Ceratothripoides claratus* and the aphid, *A. gossypii* in tomato protected crops located in a humid tropic region in southeastern Asia. Results showed that a greenhouse structure completely covered with UV-blocking materials (plastic and nets) significantly reduced the entry and attraction of whiteflies, winged aphids and thrips into the greenhouse interior and the outside sidewalls compared with those made from UV-transmitting materials, and this protection was independent of the length of the time that greenhouses gates were opened for ventilation.

UV-blocking plastic films

Pest invasion is the first phase in the process of host plant infestation by insects in a greenhouse crop (Fig. 1D). In greenhouses and walk-in tunnels conditions, the first level of protection provided by UV-plastic films is determined by the reduction in the number of invading insects through the opening of the structures from the covered environment, as was observed by Costa and Robb (1999) on *B. argentifolii* and *F. occidentalis* in small scale experimental tunnels (≈0.5 by 0.5 by 1.8 m). Also, Costa *et al.* (2002) found a significant reduction in the number of aphids and thrips captured on yellow sticky traps (YST) in greenhouses covered by UV-plastic films in a commercial cut-flower greenhouse. Antignus *et al.* (2001) found that penetration of the whitefly *B. tabaci* into walk-in tomato tunnels covered with UV-absorbing films was strongly inhibited as well as the attraction of whiteflies to these types of structures. Also, a reduction in the number of aphids captured on YST, a delay in aphid immigration and colonization were recorded in lettuce grown in walk-in tunnels under UV-blocking plastic films (Diaz *et al.* 2006). Also, they found that UV-absorbing plastic films were effective in reducing the population density of *F. occidentalis* (Pergande) and the spread of TSWV as well as the population density of the lepidopteran pest, *A. gamma* (L.). *T. vaporariorum* showed a distinctive preference to penetrate and disperse in UV-rich tunnels, both without and with tobacco plants (Mutwiwa *et al.* 2005). Similar results were obtained with *B. tabaci*, *Ceratothripoides claratis* and *A. gossypii* that showed a reduction in their immigration rate into a tomato greenhouse covered with UV-blocking plastic films (Kumar and Poehling 2006).

Once the invading insects entry into the protected crop, they must recognize and locate their host plants. As a result, insects begin the second phase of the process of host plant infestation, which is primary infestation (Fig. 1D). Studies conducted by Antignus *et al.* (1996) show that *B. tabaci* is attracted by 254-366 nm when exposed to monochromatic UV sources as well as to full-spectrum light, explaining the inability of this whitefly to recognize the host plants under UV-blocking materials. Also, Antignus *et al.* (1996) observed that walk-in tomato tunnels covered by UV-absorbing plastics reduce the landing rate of *B. tabaci*, *F. occidentalis* and *A. gossypii*. The same effect was observed on the landing rate of, *M. euphorbiae* and *F. occidentalis* on lettuce plants grown under a UV-light deficient environment.

The third phase of greenhouse infestation by insects consists in the secondary spread of the insects within the greenhouse, by the movement of insects by walking or flying from plant to plant (Fig. 1D). UV-blocking materials have a positive effect on the movement of insects within the protected environment, not only by reducing the secondary spread of the pest, but also by reducing the incidence of insect-transmitted virus diseases. In this way a positive effect of the UV-light deficient environment was observed on the population growth and spread of *M. persicae* (Chyzik *et al.* 2003) and on the movement of *M. euphorbiae* and *F. occidentalis* across lettuce plants, reducing the percentage of lettuce plants affected with Potyvirus and TSWV, respectively (Diaz *et al.* 2006). In addition, a delay of *Capsicum chlorosis virus* (CaCV) symptoms on tomato plants was observed in a greenhouse covered with UV-blocking plastic films and nets (Kumar and Poehling 2006). Other works ex-

plain a reduction on virus spread not only because a reduction of insect movement, but also due to changes in insect physiology under deficient UV-light environments (Antignus *et al.* 2001). They suggested that feeding behaviour of insect vectors change in a way that reduces their transmission ability under UV-blocking plastic films (IR-Veradim), and in consequence a dramatic reduction in virus disease incidence was observed (Antignus *et al.* 1996).

COMPATIBILITY OF UV-BLOCKING MATERIALS WITH BENEFICIAL ORGANISMS

Photoselective plastic films should be compatible with natural enemies of pests and other beneficial organisms such as pollinators because biological control is one of the most widely used strategies in vegetable production due to its well known environmental benefits (Viñuela 2005).

Impact of UV-light on parasitoids

Parasitization mechanisms begin with the host habitat locations by the female parasitoids, and then followed by its host location. In each of these steps, different cues are perceived from the natural habitat (shape, color, texture) and from the target host itself (Willis 1997). These stimuli may be visual, olfactory, gustatory, or chemosensory. Some species of parasitoids locate their host through very specific cues making a unique host-parasitoid relationship (Harris and Bautista 2003). These considerations should avoid any generalization made about any possible effects of UV-blocking materials on parasitoids, and therefore each specific host-parasitoid relationship must be considered in any given environment. In this way, Chiel *et al.* (2006) studied the effects of UV-absorbing plastic sheets on the host location ability of three parasitoids that are available commercially and commonly released by the growers under greenhouse conditions, such as, *Aphidius colemani* a parasitoid of *M. persicae*, *Diglyphus isaea* a parasitoid of *Lyriomyza bryoniae*, and *Eretmocerus mundus*, a parasitoid of *B. tabaci*. Two types of experiments were carried out, under laboratory choice conditions and in greenhouse trials. In laboratory experiments, in which only the visual stimuli were evaluated, the three species showed a strong attraction to environments with high levels of UV-light. However, greenhouse trials showed significant differences in their host location ability among the three species under the UV-blocking cover. *A. colemani* and *D. isaea* were not affected by UV-low light environment to find their hosts, because apparently they do not use visual stimuli for host finding or their visual capability is not significantly affected by UV-deficient light. For *E. mundus* UV wavelengths were necessary for long range host location, because this process is driven by visual stimuli, but were not essential for the close range host location probably because they use non-visual stimuli (Chiel *et al.* 2006). These results provide practical information for growers about the release of these parasitoids in greenhouses covered by UV-blocking materials. For example, they propose that *E. mundus* should be introduced in multiple release points or as close as possible to the *B. tabaci* infected plants.

Chyzik *et al.* (2003) showed that UV-blocking films suppressed both the propagation and flight activity of *M. persicae* within walk-in tunnels, without effects on the host-finding activity and fecundity of its parasitoid *Aphidius matricariae*. The mechanisms of the inhibitory effect on the aphid biology are still unknown, whereas, the parasitoid behaviour under UV-deficient environment may be explained by the hypothesis that the attraction of this wasp to its aphid host is controlled by olfactory rather than by visual cues.

Doukas and Payne (2007a) confirmed that *E. formosa* dispersal is not affected by environments with low UV-light, while this wavelength radiation is necessary for their whitefly host flight activity and dispersal. From a practical point of view, these authors concluded that the number of parasitoids to be released could be lowered under UV-blocking

films to achieve the same level of protection against *T. vaporariorum*.

Impact of UV-light on predators

To date no experiments were carried out to evaluate the effects of the UV-blocking greenhouse covering materials on the predators commonly released by growers. Reitz *et al.* (2003) studied the impact of different plastic soil mulches, insecticides and predator releases for the control *Frankliniella* thrips in field-grown pepper. The results showed that the abundance of the predator *Orius insidiosus* was significantly reduced in UV-reflective mulch compared to a black mulch treatment.

Effects of UV-light on pollinators

Most of the flower-visiting Hymenoptera are trichromatic, with photoreceptor spectral sensitivity peaks in the UV, blue and green regions of the spectrum (Skorupski *et al.* 2007).

The effects of enhanced UV-B radiation on reproductive and pollination success were investigated in the Mediterranean annual *Malcolmia maritima*. Plants were exposed in the field to ambient or ambient plus supplemental UV-B radiation. UV-B radiation had no effect on stem and fruit biomass, anthesis time and duration and flower number. However, flower diameter, nectary volume and nectar amount per flower (but not nectar concentration) were significantly increased by supplemental UV-B radiation. In addition, UV-B treated plants showed higher reproductive success and a trend to higher pollination success (i.e. increased number of seeds per fruit). As a result, the seed yield was increased. This work suggests that the UV-B induced changes in flower attributes might have affected pollinators' behaviour in a way that improved the fitness of *M. maritima* (Petropoulou *et al.* 2001).

Another study was carried out to study the response of insect pollinators to the UV-reflectance of flowers independently of other wavelengths. Flower corollas of *Hypoxis hemerocallidea* were painted with human sunscreen able to absorb UV wavelengths. The results showed that honeybees (*Apis mellifera scutellata*) foraged on the strongly UV-reflecting flowers of *H. hemerocallidea*, rejected flowers that had UV reflectance eliminated by the sunscreen coating, but continued to visit control flowers painted with sunscreen solution that did not contain the UV absorbing compound. The sunscreen technique could be useful for determining the response of a wide range of pollinators to the UV component of spectral reflectance in flowers and could be used to test the functional significance of UV-contrasting "nectar guide" patterns (Johnson and Andersson 2002).

The incorporation of the bumblebee (*Bombus terrestris*) hives into the greenhouses is a usual practice by growers in many regions, because they play an important role on the yield of high-value crops, such as tomato and cucurbits. For this reason, the effects of UV-light blocking materials on pollinator's behaviour must be carefully considered. In this way, Morandin *et al.* (2001) observed that the activity of *B. terrestris* measured in commercial tomato greenhouses was higher (94%) under UV-transmitting covering materials than under UV-blocking films. However, there was no difference in bumblebee activity based on different types of covering, when measured in small experimental greenhouses (Morandin *et al.* 2002). In both, commercial and experimental greenhouses bumblebee activity had a positive linear relationship with the internal greenhouse temperature. In the same experiments, the authors observed that under UV-transmitting plastics there was a lower loss of bumblebees through the greenhouse ventilation systems, showing that bees were more attracted to UV-transmitting than to UV-blocking materials.

It is known that ultraviolet-sensitive photoreceptors have an important role in a variety of visual tasks performed by bees, such as orientation, colour and polarization vision. Ultrastructural studies have shown that the bumble

bee (*B. hortorum*) eye is similar to that of the honeybee *Aphis mellifera* concluding that bumble bee, like honeybees, make use of shapes and colours of flowers, the polarization pattern of the sky in navigation and retain fine details of their environment (Meyer Rochow 1981). A recent work conducted by Spaethe and Briscoe (2005) have shown the location of UV-pigments bumblebee brains by molecular characterisation and expression of the UV opsin from *Bombus impatiens*. They found UV opsin expression in the retina of ommatidia, ocelli and various brain parts, particularly in the optic and antennal lobes, the regions that process vision and olfaction. They also found that bumblebees express a circadian clock protein, in the optic and antennal lobes. Since period and the UV opsin are both expressed in the optic and antennal lobes, they concluded that UV light might play a role in bumblebee circadian rhythm regulation, mediated through these two brain regions.

Impact of UV-light on entomopathogens

The low survival and persistence of microbial organisms used for pest control exposed to UV radiation is one of the limitations for its wider use as microbial insecticides in field or greenhouse conditions.

Several works showed the detrimental effects of UV radiation on germination and survivorship of different entomopathogenic fungi genera. Fargues *et al.* (1997) observed that UV-B light appeared to be the most detrimental part of the natural radiation on the survival of conidia of *Paecilomyces fumosoroseus*. Similar results showing a strong delay in germination of conidia of *Metarhizium anisopliae* (Braga *et al.* 2001), *Verticillium lecanii* and *Aphanocladium album* strains were obtained after exposure to UV-B radiation (Braga *et al.* 2002).

New formulations of entomopathogenic fungi are available commercially or in experimental phase that provide UV protectant agents to enhance the survival of conidia exposed to high levels of UV radiation. Among several montmorillonites-containing formulations of *V. lecanii*, the SCPX-1374 (hydrogenated tallow and trimethyl quaternary ammonium) protects spores with a survival rate >90% after 30 min expose to UV-C light versus no conidia survival without this type of clay (Lee *et al.* 2006). Also this selected *V. lecanii* formulation was tested against *A. gossypii* in a greenhouse with natural sunlight reducing cotton aphid density to 60% of the initial level, while the cotton aphid densities increased 3-fold in 15 d for the untreated spores of *V. lecanii*.

Under field conditions, Costa *et al.* (2001) found that the persistence of viable spores from a commercial formulation of the entomopathogenic fungi *Beauveria bassiana* was significantly increased under a plastic that blocked UV-light wavelengths below 380 nm compared to that with plastics that blocked UV-light wavelengths below 360 nm.

Other microbial organisms used for pest control, such as the bacteria *Bacillus thuringiensis* or baculoviruses, need formulations to protect them from the negative effects of sunlight ultraviolet radiation that reduce their persistence in the field (Behle *et al.* 1997). Lasa *et al.* (2007) observed that the mixture of *Spodoptera exigua* multiple nucleopolyhedrovirus (SeMNPV) with an optical brightener increased the prevalence of infection in larvae of *S. exigua* during the first two days post-application of the baculovirus formulation in grown sweet pepper greenhouse covered with UV-B (280-315 nm) absorbing films. The use of microbial insecticides combined with UV-blocking materials could be an effective and very promising strategy to enhance pest control in protected crops.

CONCLUDING REMARKS

We can conclude that UV-blocking plastic materials are a very effective tool to reduce the incidence of pests and diseases, especially under organic and integrated production. But due to the fact that all the strategies to be developed are

based on films or nets made out of polyethylene, it is important to have a technology for the correct disposal of such material to avoid its accumulation in the environment. In this way, biodegradable and photodegradable plastics will be developing and will become more important in the near future. The result of photochemical degradation is the production of small film fragments that can disappear from the soil surface due to the activity of soil inhabitant organisms.

On the other hand more studies must be developed for a better understanding of the effects of UV-blocking materials on plant diseases, especially on several physiological aspects of fungal pathogens infecting vegetable crops, as well as, their effects on fungal antagonists and their influence on disease development. Also, more studies are needed to understand the biological effects of different solar wavelength radiation on microbial ecology, especially on plant pathogenic bacteria. It is important to note that the UV-blocking materials may have a direct or indirect effect on plant pathogenic bacteria, affecting the degree of susceptibility of plants to these organisms. The situation may be complex because there is a series of factors that may interfere with the effect of light on microbial development.

At present, few works on the effects of UV-blocking films on natural enemies of insect vectors have been conducted. Future works should be focused on the effects of UV-light on the behaviour of commercial parasitoids and predators. The effects of UV-blocking materials on predators, such as syrphid flies, mirid bugs, *Orius* spp., ladybeetles and lacewings have never been well established. In the same way, the compatibility of UV-blocking materials with other control tools such as microbial or botanical insecticides needs further investigation.

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