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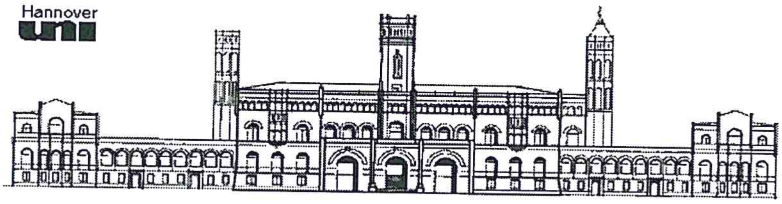

Department of Horticulture
Institute of Horticultural and Agricultural Engineering

Effects of UV-absorbing plastic films on the behaviour of the greenhouse whitefly

Thesis submitted in partial fulfilment for the requirements of the degree of
Master of Science in International Horticulture
Major in Horticultural and Agricultural Engineering

By

Urbanus Ndungwa Mutwiwa

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September 2004

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Dedicated to

my mother, Sophia,

my wife, Mercy and our children, Anita and Mwendwa

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Above all, thanks to God the Almighty for giving me the strength, wisdom and courage that has brought me this far.

ABSTRACT

Studies were conducted to investigate the effects of ultraviolet (UV) absorbing plastic films, on the flight behaviour of the greenhouse whitefly *Trialeurodes vaporariorum* Westwood (Hom.: Aleyrodidae), in Hannover, Germany. In field and greenhouse experiments, we investigated the effects of two plastic films, i.e. Thermilux (UV-transmitting) and K-Rose (UV-absorbing), on two flight-related aspects, i.e., (i) the orientation and initial attraction of *T. vaporariorum* into greenhouses, and (ii) the colonization and distribution of *T. vaporariorum* once inside the greenhouse. Orientation and invasion behaviour were studied in choice experiments involving the release of whiteflies from a black compartment at the centre of four tunnels with different UV intensities. Results from experiments performed using either natural or artificial UV-sources showed that over 90% and 70%, using natural and artificial UV sources, respectively, of the total proportion of whiteflies recaptured were recorded in the tunnels with the highest UV intensity. No-choice experiments were conducted to study the effects of UV intensity on the colonization and distribution of *T. vaporariorum*. When whiteflies were released from one end of the tunnel and their penetration into the tunnel monitored by recapturing them at various points, results show that whitefly penetration was greatly limited in K-Rose-covered tunnels. Furthermore, when whiteflies were released from the centre of the tunnel and their dispersion monitored by recapturing them using yellow sticky traps positioned at different radii from the central release point, whitefly dispersion inside K-Rose-covered tunnels was significantly reduced. These results show a distinct UV-preference by *T. vaporariorum* and indicate that the type of plastic film used for greenhouse covers may have a significant influence on the initial attraction (immigration) and distribution of *T. vaporariorum* into greenhouses. In addition, the orientation of the greenhouse appears to be an important factor in determining the level of these effects. The possibilities of using UV-absorbing plastic films for IPM of whiteflies in greenhouses are discussed.

Keywords: *Trialeurodes vaporariorum*, invasion, colonization, behaviour, ultraviolet light, UV-absorbing, greenhouse, plastic films.

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ABBREVIATIONS AND INDICES

ANOVA	Analysis of variance
BPYV	Beet pseudo-yellow virus
CCI	Centre for Computational Intelligence
CI	Confidence interval
CIE	International Commission on Illumination
CO_2	Carbon dioxide
df	Degrees of freedom
ERG	Electroretinogram
F	F-value
Fig.	Figure
HALS	Hindered Amine Light Stabilizers
I_F	Impact Factor
IPM	Integrated pest management
IPP	Institute of Plant Diseases and Plant Protection
IR	Infra red
ITG	Institute of Horticultural and Agricultural Engineering
KR	K-Rose
NiQ	Nickel Quenchers
NIR	Radiation with wavelength from 700 to 3000 nm
nr	Not recorded
NS	Non-significant
P	P-value
PAR	Photosynthetic Active Radiation (wavelength 400-700 nm)
PVC	Polyvinylchloride
RH	Relative humidity (%)
SAS	Statistical Analysis System
SE	Standard error of the mean
Tlux	Thermilux
TYLCV	Tomato yellow leaf curl virus
UV	Ultraviolet radiation (wavelength 100 to 400 nm
UVA	UV with wavelength from 315 to 400 nm

UVB	UV with wavelength 280-315 nm
UVC	UV with wavelength 100-280 nm
UVAs	UV radiation absorbers
VIS	Visible radiation (wavelength 400-700 nm)
λ	Wavelength (nm)
α	Level of confidence
χ^2	Chi-square

1 INTRODUCTION

The main purpose of greenhouse covering is to create an internal climate that is conducive to plant growth regardless of the external environment, and to allow optimal control of plant production factors. The capability of the covering material to transmit light in wavelengths useful to plants is therefore extremely important since it has a tremendous influence on the crop production capability of the greenhouse (GIACOMELLI & ROBERTS, 1993). The availability of new types of covering materials, and enhancements of previously existing ones, as well as the demand for technological improvements within greenhouse agriculture has led to an increase in the diversity of greenhouse covers over the past four decades (MOENS, 1990; GIACOMELLI & ROBERTS, 1993; ASHEKANZI, 1996).

The greenhouse whitefly, *Trialeurodes vaporariorum* Westwood (Homoptera: Aleyrodidae) is worldwide one of the most important greenhouse pests on vegetable and ornamental crops (VAN LENTEREN & NOLDUS, 1990; COOMBE, 1982; MANZANO, 2002). Whiteflies damage the attacked plants through direct sap feeding (RUSSEL, 1997; STANSLY, 2004), and indirectly through the excretion of honeydew and transmission of plant pathogenic viruses (STONOR et al., 2003). Despite important advances in knowledge of the biology of the insect, only limited control measures are available (SKROBEK, 2001). Chemical control of whiteflies has become unreliable because of widespread development of resistance to insecticides in *T. vaporariorum* (FASULO et al., 2003). Additionally, biological control, mainly through inundative releases of natural enemies like the parasitoid *Encarsia formosa* Gahan (Hym.: Aphelinidae), may not achieve the level of efficacy needed by growers, particularly in case of virus transmission by *T. vaporariorum*. Recent quests for effective, environmentally safe and sustainable pest management programs have been targeted primarily towards the development of new and less hazardous products to replace conventional often highly toxic pesticides (LEWIS et al., 1997) and has led to an increased interest in environmentally friendly control strategies that are compatible with biological control in greenhouses (VON ELLING et al., 2000).

Previous studies by COOMBE (1981, 1982) reported wavelength specific behaviour in *T. vaporariorum* at 400 and 500 nm wavelengths. Thus, in nature flying adults would orient towards the sky but would tend to land on a green plant because plants reflect maximally at a wavelength (λ) of 550 nm. Most greenhouse polyethylene plastic films contain ultraviolet light (UV), (λ: 200-400 nm) absorbing components added to prolong the life of the material while maintaining high levels of photosynthetic active radiation (PAR) (λ: 400-700 nm) transmission (COSTA & ROBB, 1999).

Crops grown in walk-in tunnels covered with UV-absorbing plastic films were highly protected from infestation with sweet potato whitefly, *Bemisia tabaci* (Gennadius) and had reduced incidences of *Tomato Yellow Leaf Curl Virus* (TYLCV) (ANTIGNUS et al., 1996). The same results were obtained in tomatoes grown in tunnels covered with UV-absorbing screens (ANTIGNUS et al., 1997, 1998). ANTIGNUS et al. (2001) reported that the rate of TYLCV spread to tomato plants grown under walk-in tunnels covered with regular greenhouse plastic films increases sharply with time, whereas the virus infection-rate under UV-absorbing plastic sheets increased at a slower pace. Fewer Poinsettia whiteflies *B. argentifolii* (Bellows & Perring) were recorded on yellow traps inside tunnels covered with UV-absorbing plastic films as compared to tunnels covered with regular plastic (COSTA & ROBB, 1999; ANTIGNUS et al., 2001). However, field studies conducted to compare insect population levels in crops grown in greenhouses covered with UV-absorbing and UV-transmitting plastics reported insignificant differences in numbers of *T. vaporariorum* under both plastic types (COSTA et al., 2002). In choice experiments using small tunnels, DOUKAS (2002) reported *T. vaporariorum* preference for tunnels covered with UV-transmitting plastic films, and observed that inside these tunnels whiteflies were more active in flight, as compared to tunnels covered with UV-blocking films.

So far all previous studies, save DOUKAS (2002), were conducted in regions with high levels of UV like Israel and California. It is not known whether UV-absorbing plastic films would be effective in reducing insect pest populations in areas with lower levels of UV, like central Europe. Moreover, in most of the previous experiments *B. tabaci* was used as model whitefly species. Finally none of the previous studies quantified the effects of the quantity and quality of UV on the behaviour of *T. vaporariorum*. Hence the objectives of this study were therefore to investigate the effects of UV-absorbing plastic films on the behaviour of *T. vaporariorum* under the low light intensities prevalent in northern Germany (latitude 52 °N). The flight behaviour of *T. vaporariorum* was investigated using both natural and artificial UV sources.

2 LITERATURE REVIEW

2.1 Greenhouse covers

Greenhouses offer an excellent opportunity to grow high-quality products in large quantities on a small surface area. The total world area covered by greenhouses is about 280,000 ha; 50,000 of which is covered with glass, and 230,000 with various plastic materials, with vegetable crops grown on about 65% of this area and ornamentals on 35% (PARRELLA et al., 1999). The type of cover material influences the amount and type of solar radiation at the plant canopy. This directly affects plant growth and indirectly affects the microclimatic factors such as relative humidity (RH), carbon dioxide (CO_2) (GIACOMELLI & ROBERTS, 1993; VON ELSNER & XIE, 2003; ZANON, 1990) and to some extent the population of some insect pests (ANTIGNUS et al., 1996, 1997; COSTA & ROBB, 1999; COSTA et al., 2002; GONZALEZ et al., 2001) and behaviour of fungi (ELAD, 1997; COSTA et al., 2001; REUVENI & RAVIV, 1997; VAKALOUNAKIS, 1992). Various authors have discussed the considerations for designing and selecting a covering system (ASHEKANZI, 1996; GIACOMELLI et al., 1990; GIACOMELLI & ROBERTS, 1993; MOENS, 1990; VON ZABELTITZ, 1990; ZANON, 1990).

Energy from the sun (both direct and diffuse) is transmitted through the transparent greenhouse covering to the plant environment where it provides energy for photosynthesis and acts as a signal for plants for, among others, identifying the surrounding environmental conditions (GIACOMELLI & ROBERTS, 1993). This energy is composed of UV, visible radiation (VIS or PAR, λ: 400-700 nm) and infrared (IR) (λ: 700-3000 nm). The percentage distribution of the three ranges is approximately 7%, 71% and 22% for UV, PAR and IR, respectively (ZANON, 1990). The UV radiation is further composed of 3% UVC (λ: 200-280 nm), 9% UVB (λ: 280-315 nm) and 88% UVA (λ: 315-400 nm). UVC is absorbed by the atmosphere and is highly phototoxic (SON & SMITH, 1992). On the other hand, UVB is responsible for sporulation of fungal spores (REUVENI & RAVIV, 1997) and may repel some insects (MAZZA et al., 1999, 2002), while UVA has formative effects to many plants and is important for insect vision (ZANON, 1990; GLASER et al., 2000).

The intensity of PAR directly influences growth and development of plants. It has two main bands. The first band (λ: 400-510 nm) is a region of strong absorption by chlorophyll and the yellow plant pigments with relatively strong photosynthetic activity. The second band (λ: 610-700 nm) is the region of maximum absorption by chlorophyll and strong photosynthetic activity (MOENS, 1990; RAJAPAKSE et al., 2001).

2.1.1 Photo-selective films

The incorporation of additives and coextrusion techniques in film manufacture offers a variety of benefits, among them protection of the film from detrimental effects of UV radiation and agrochemicals (ASHEKANZI, 1996; CIBA, 2004; RUIZ et al., 2003), selective management of different wavelengths of light to optimise crop growth, keeping the films clean and algae-free in dusty/humid environments to assure optimal light transmission, keeping the films condensate free under high humidity conditions, and management of film wastes by timely degradation (ANGUS & MORRISON, 1998; CASTILLA, 2003; GHOSH & LELLI, 2003; MOENS, 1990; SCHULTZ, 1997).

The advantages of wavelength selective films for plant growth and enhancement include the possibility of improving the quantity and quality of radiation transmission (GBIORCZYK, 2003), growth enhancement of plants (ANGUS & MORRISON, 1998; ZANON, 1990; GLASER et al., 2000), control of plant height by controlling the ratio of red to far red light (ANONYMOUS, 2002; FRIEND & DECOTEAU, 1990; RAJAPAKSE et al., 2001), and temperature or climate regulation (ANGUS & MORRISON, 1998; VERLODT & VERSCHAEREN, 1997; VON ELSNER & XIE, 2003; ZANON, 1990). Previous research has reported that the incorporation of UV-absorbing additives in the plastic film not only increases the useful lifetime of the film, but may also improve some quality characteristics of some greenhouse crops, e.g. colour in roses and strawberries, prevention of petal darkening in roses (ASHEKANZI, 1996; GLASER et al., 2000; RAVIV, 1989), and extension of shelf life in peppers (GLASER et al., 2000). Moreover it improves the management of fungal diseases (ANGUS & MORRISON, 1998; REUVENI & RAVIV, 1992, 1997), insect pests (COSTA & ROBB, 1999, COSTA et al., 2002; ANTIGNUS et al., 1996, 1998), and insect-transmitted viral diseases (ANTIGNUS, 2000).

2.1.2 Stabilization of plastic films

When a plastic film (polymer) is exposed to light, chemical reactions start in the polymer backbone, which have a net result of changing the chemical composition and the molecular weight of the polymer, and in turn lead to a change in the physical and optical properties of the polymer (CIBA, 2004; SWASEY, 1992). Once the oxidation starts, it sets off a chain reaction that accelerates degradation unless stabilizers are used to interrupt the oxidation cycle (CIBA, 2004; RUIZ et al., 2003).

There are three main categories of light stabilizers, namely Nickel quenchers (NiQ), UV-Absorbers (UVAs) and Hindered Amine Light Stabilizers (HALS) (AMIN et al., 1990; CIBA 2004; RUIZ et al., 2003; WEIHOFEN & SPINATSCH, 2003). UVAs have an impact factor (I_F) of 2 (i.e. they double the life of the film) and function by absorbing UV energy then dissipating it as non-destructive thermal energy. However, they cannot be applied to greenhouse covering films because high concentrations are needed and the undesirable colour change of the film after UV absorption. NiQ have I_F of 4-5 and act as weak absorbers (radical scavengers), thereby dispersing UV energy before it causes polymer molecules to break. However, they are weak thermal stabilizers, environmentally unsafe and their green colour may reduce light transmittance if they are used in high concentrations (RUIZ et al., 2003; WEIHOFEN & SPINATSCH, 2003). The combination of UVAs/NiQ blend is very resistant to pesticides (RUIZ et al., 2003). HALS have an I_F of 10, hence, they are extremely efficient stabilizers against photo-degradation. HALS protect the film by immediately reacting with the free radicals, rendering them chemically inactive. They do not absorb UV, but act to inhibit the degradation of the polymer by slowing down the photo-chemically initiated degradation reactions. They are well suited for agricultural films because the catalytic radical mechanism makes them highly effective even in thin cross section materials (RUIZ et al., 2003), the ability of the stabilizer to regenerate itself immediately and their neutrality in colour (WEIHOFEN & SPINATSCH, 2003). However, the deleterious effects of many agrochemicals on conventional HALS-stabilized films are much greater than on UVAs/NiQ-stabilized film (RUIZ et al., 2003). As with nickel quenchers, HALS are often used in combination with UVAs to improve their performance through synergism (SON & SMITH, 1992).

2.1.3 Crop protection using photo-selective plastic films

UV-reflective mulches have been reported to protect crops against infestations and infections by certain insects and insect-transmitted viral diseases (CSIZINSZKY et al., 1999; BENOIT & CEUSTERMANS, 2000; McLEAN et al., 1982; DELGADILLO et al., 2002; GONZALEZ et al., 2001). In addition, filtration of UV from the greenhouse environment has been applied to manage fungal diseases such as grey mould caused by *Botrytis cinerea* (de Bary) Whetzel and downy mildew caused by *Pseudoperonospora cubensis* (Berk. & M.A. Curtis) Rostovtzev (ELAD, 1997; REUVENI & RAVIV, 1992, 1997), and to increase the persistence of the spore viability in the entomopathogenic fungus *Beauveria bassiana* (Bals.-Criv.) Vuill. (COSTA et al., 2001). GOULSON et al. (2003) suggested the incorporation of optical brighteners (compounds that absorb UV and emit visible blue wavelengths), into baculoviruses in order to enhance their infectivity, rendering the viruses more efficient as control agents of insect pests.

COSTA & ROBB (1999) conducted choice experiments using small tunnels with a black compartment in the centre to examine the effects of four high UV-blocking plastic films on the flight behaviour of *B. argentifolii*, and the western flower thrips *Frankliniella occidentalis* (Pergande). In choice experiments, both pests showed distinct preference for the tunnels with UV, an indication that UV-absorbing plastic films significantly influence the initial attraction of insects to greenhouses. Crops grown in walk-in tunnels covered with UV-absorbing plastic sheets were highly protected from infestations with sweet potato whitefly, *B. tabaci, F. occidentalis* and cotton aphids *Aphis gossypii* (Glover) (ANTIGNUS et al., 1996, 1997). In addition, there was a dramatic reduction in the spread of TYLCV, with a pronounced delay in infection and disease severity. UV-absorbing plastic screens (so-called Bionets) significantly reduced the penetration of *B. argentifolii* into tunnels as well as the spread of TYLCV (ANTIGNUS et al., 1998). Compared to ordinary insect screens, these UV-absorbing screens were significantly more effective, in protecting tomatoes against leaf miners (*Liriomyza trifolii* Burgess) and red mites (*Tetranychus telarius* L.) as well as in protecting cucumbers against *A. gossypii*. Previous studies on the effect of a UV-deficient environment on the attraction and dispersion of *B. tabaci*, and transmission of TYLCV, reported a sharp increase with time in the virus infection-rate in tomato plants grown under regular plastic film as compared to UV-absorbing films (ANTIGNUS et al., 2001). More whiteflies were recorded in UV-rich tunnels, and whitefly dispersion was higher inside these tunnels, as compared to UV-deficient ones. DOUKAS (2002) reported similar results for *T. vaporariorum* and observed an increased flight activity by *T. vaporariorum* inside tunnels covered with UV-transmitting plastic film as compared with UV-absorbing tunnels.

2.2 The greenhouse whitefly *T. vaporariorum*

T. vaporariorum is a cosmopolitan, extremely polyphagous plant pest. It has reached the status of a major pest in both greenhouse and field cultures as a consequence of intensified crop production (VAN LENTEREN & NOLDUS, 1990; DITTRICH et al., 1990; SUCCOP, 1997).

GILL (1990) described the lifecycle of *T. vaporariorum* as follows: Reproduction is all year round. It can have a generation time of 28 days depending on the environmental conditions (approximately 26°C). Adult longevity is about 10 to 22 days, and fecundity is high with about 30 to 300 eggs per female. Eggs are attached by a stalk to the undersides of leaves where they are usually clustered in groups. Egg hatching takes place after 8 to 12 days depending on the environmental conditions. *T. vaporariorum* has six life stages, namely the egg, the crawler (1st nymphal instar), two sessile nymphal instars (2nd and 3rd instar nymphs), the pupa (4th instar) and the adult. The adult leaves a distinctive T-shaped split on the pupal case after emergence and appears white owing to the white powdery wax secretions. Only the crawler and the adult are mobile.

Research on dispersal and distribution of *T. vaporariorum* adults reported preference for young (upper) leaves, since they have lower water and higher sugar and nitrogen contents (NOLDUS et al., 1986; VAN ROERMUND et al., 1997; SÜTTERLIN et al., 1991; MARTIN et al., 1991). Colour is the most important factor in the host-plant selection from a distance, but host plant discrimination occurs only after landing. Through a process of probing, and horizontal plus vertical movements, whiteflies are able to select host plants in a mixture of plant species, and to select certain leaves for simultaneous feeding and oviposition within a plant (VAN LENTEREN & NOLDUS, 1990), while within plant-leaf selection is controlled by chemical differences.

Direct damage occurs when whitefly larval instars and adults suck the phloem sap; thereby removing assimilates leading to, among others, reduced plant vigour (BYRNE et al., 1990). The host range comprises about 200 plant species, mostly in the families Cruciferae, Leguminosae, Malvaceae, and Solenaceae (FASULO et al., 2003). At high population levels *T. vaporariorum* infestations can cause leaf drop, inhibit fruit maturity and eventually leading to the death of the plants (RUSSEL, 1997). Indirect damage results from the excretion of honeydew on leaves and fruits, which serves as a suitable medium for fungi (sooty mould), thereby interfering with photosynthesis and lowering product quality (VAN LENTEREN & NOLDUS, 1990). Furthermore, sooty mould may increase thermal absorption and raise leaf temperature; this in turn reduces leaf efficiency, and may even cause premature death of tissues (BYRNE at al., 1990). In some hosts, damage can result from whitefly feeding toxins that can cause plant disorders such as silver leaf of squash and irregular ripening of tomatoes (FASULO et al., 2003). Whiteflies in general and *T. vaporariorum* in particular are vectors of geminiviruses such as TYLCV and certain clostroviruses like lettuce infectious yellows in lettuce and melons, and the beet pseudo-yellow virus (BPYV) (ANTIGNUS, 2000; BYRNE et al., 1990; COHEN, 1990; FASULO et al., 2003; VAN LENTEREN & NOLDUS, 1990).

2.2.1 Control of *T. vaporariorum*

As a prerequisite for different control measures, methods for monitoring population levels of *T. vaporariorum* have been developed (EKBOM & RUMEI, 1990; MARTIN et al., 1991). According to STANSLY (2004) there are four main methods of managing whiteflies: chemical control, biological control (mainly through inundative releases of Aphenilid parasitoids and predatory Coccinelids and Chrysopids), use of resistant plant varieties (host plant resistance) and cultural control.

2.2.1.1 Chemical control

To date greenhouse whiteflies are difficult to control with insecticides mainly due to development of resistance, the often-prohibitive cost of effective chemical control, the need for thorough coverage, risk of secondary pest outbreaks, side effects on beneficial insects and the regulatory restrictions on the use of insecticides in many countries (DITTRICH et al., 1990; GREER, 2000). Systemic chloronicotinoids such as imidacloprid (Admire® or Confidor®) are effective against whiteflies, particularly when applied to the root system (BI et al., 2002; McDONOUGH et al., 2002; STANSLY, 2004). Certain contact insecticides, especially pyrethroids and organophosphates, some bio-rational pesticides like neem (VON ELLING et al., 2000), insecticidal soaps and horticultural oil, as well as the use of carbamates, chlorinated hydrocarbons and insect growth regulators (FASULO et al., 2003; GREER, 2000) have been reported to successfully control some stages of *T. vaporariorum*.

2.2.1.2 Biological control

Biological control strategies against *T. vaporariorum* include inundative releases of Heteropteran (Anthrodidae and Miridae), Coleopteran (mainly coccinelid larvae) and Neuropteran (Chrysopidae) predators, and parasitic the Aphelinids *Encarsia* and *Eretmocerus* spp. (GERLING, 1990; DOWELL, 1990). The genus *Encarsia* contains about 150 species of parasitoids whose females develop as primary parasitoids in different stages of members of the family Aleyrodidae. *E. formosa* is commercially applied to control *T. vaporariorum* with success in several greenhouse vegetables (McDONOUGH et al., 2002; PARRELLA et al., 1999; VAN LENTEREN 2000). Members of the *Eretmocerus* spp. deposit eggs underneath the whitefly nymph, and the pear-shaped first instar larva penetrates the host from underneath (GERLING, 1990). Successful use of microbial whitefly controls have been reported, mainly by the entomopathogenic fungi *B. bassiana*, *Paecilomyces fumosoroseus* (Wize) Brown & Smith, and *Verticillium lecanii* (Zimm.) Viėgas (Deuteromycotina: Hypomycetes) species (COSTA et al., 2001; FRANSEN, 1990; JAMES & ELZEN, 2001; SKROBEK, 2001). However, introducing biological control organisms into new areas may involve a number of complex problems (ONILLON, 1990). Climatic conditions may either be permissive or prohibitive for the activity of natural enemies (SKROBEK, 2001).

2.2.1.3 Cultural control

There are five main types of cultural control strategies, namely escape in time (e.g. rotations, crop free periods), escape in space (use of screens, floating row covers), behavioural manipulation (crop associations, trap crops, mulches), host suitability (fertilization) and removal (overhead irrigation and rouging) (STANSLY, 2004). The use of physical barriers such as mesh screens and coloured traps aims at preventing the pest from reaching the crop (ANTIGNUS et al., 2001; AJWANG et al. 2002; MICHELLE & BAKER, 2000). Reflective mulches that tend to repel whiteflies, oil coated yellow mulches and yellow sticky cards that act as a trap for whiteflies, floating row covers that exclude whiteflies during the vegetative growth of the crops and trap crops have been reported to reduce whitefly infestations (FASULO et al., 2003). Atmospheres which are lethal to insects as a result of alteration of surrounding air (insecticidal controlled atmospheres) either through the elevation of CO_2 or lowering the oxygen level have been reported to be effective in controlling all life stages of *T. vaporariorum* (HAN & KONIECZNY, 2000). However, treatment time required for achieving complete elimination of the insects also caused phytotoxicity symptoms on poinsettias, *Euphorbia pulcherrima* Willd. ex Klotzsch, thus limiting the application of this method. Another way that has been used to avoid whitefly infestations is the adjustment of planting dates to avoid periods of high insect migration, destruction of crop residues and use of resistant varieties (DE PONTI et al., 1990; XU et al., 1984). Host plant resistance is one of the preferred methods for minimizing damage caused by whiteflies because it does not require the complete elimination of the pest to be effective (FASULO et al., 2003). It protects the crop by making it less suitable for the pest or by making the crop tolerant to the pest e.g. the use of smooth-leaf cotton rather than hairy-leaf cotton.

KASSIS & MICHELAKIS (1993) compared three methods of *T. vaporariorum* control, i.e. physical (chromo-attractive) control using yellow traps, chemical using the systemic insecticide Vydate (oxamyl), and biological control with *E. formosa*. They reported that physical control was the fastest method, chemical control somewhat slower, while biological control was the slowest but the most successful control approach.

2.2.2 Phototactic action spectrum for insects

Of all insects, the vision behaviour of the honeybee *Apis mellifera* L. is the most extensively studied (GOURAS, 1991; MENZEL & BACKHAUS, 1991; GIURFA et al., 1996; GIURFA & VOROBYEV, 1998). Insects communicate with their environment and host plants by light signals that elicit photoreceptors in their compound eyes (GIURFA & MENZEL, 1997). Vision behaviour of insects is linked to the sequence that begins with their orientation to the plant from a distance and ends with their establishment on the plant for feeding and oviposition (ANTIGNUS, 2000). By interfering with links along this pathway, contact between the insect and the plant may be protected. Some species of insects have been shown to be dependent on UV light for orientation during flight and may use UV light reflectance patterns as cues in recognizing host plants and flower species (COOMBE, 1981, 1982; KRING, 1969; KRING & SCHUSTER, 1992; KIRK, 1984).

Vision (colour, shape and size) and olfaction (host odour) are the primary cues used by insects to orient to their plant hosts, and sometimes the two types of cues work complementary. Insects often respond to a particular wavelength band with a different behaviour (KIRK, 1984; MENZEL & BACKHAUS, 1991). Such wavelength selective behaviour may also include aspects of colour vision, i.e. a receptor neural strategy that enables animals to detect and recognize objects of differing spectral reflection or emission properties and irrespective of differences in light intensity (MENZEL & BACKHAUS, 1991). Insects use colour and colour contrasts to distinguish between a host and the surrounding environment (NIGGERBRÜGGE & DE IBARRA, 2003; ANTIGNUS, 2000). Wavelength selective behaviour is highly dependent on intensity within each wavelength band, and involves different behaviours. For instance; honeybees possess a trichromatic colour vision system, with three spectral types of photoreceptors peaking in the UV (λ: 344 nm), blue (λ: 436 nm), and green (λ: 556 nm) regions of the spectrum, respectively. Wavelength selective behaviours have been reported in the feeding (λ: 450 and 600 nm), drumming (λ: 450 nm) and oviposition (around λ: 540 nm) of the cabbage caterpillar *Pieris brassicae* (L.) (Lep.: Pieridae) (MENZEL & BACKHAUS, 1991).

MOUND (1962), (cited by VAN LENTEREN & NOLDUS, 1990), reported that *B. tabaci* did not react to odour of the host plant but did react to two ranges of wavelengths, i.e. blue/ultraviolet (400 nm) and yellow (500 nm). He suggested that short wavelengths (blue/UV) might play a role in the migration behaviour, while yellow radiation induces vegetative behaviour that may be part of the host plant selection. Using an electroretinogram (ERG) technique, MELLOR et al., (1997) measured the spectral efficiency of *T. vaporariorum* at selected wavelengths between 340 nm and 670 nm and reported that primary peak efficiency occurred in the blue-green-yellow region, peak at 520 nm and a secondary peak in the UV region. LLOYD (1921) (cited by ANTIGNUS et al., 1996), reported that *T. vaporariorum* was attracted in greater numbers to yellow sticky traps than to traps of other colours. COOMBE (1981) reported that whiteflies took off more readily and walked faster under light with λ of 400 nm. In flight, they oriented towards 400 nm when simultaneously illuminated with equal quanta of 550 and 400 nm light. He concluded that in nature flying adults would orient towards the sky (400 nm) but would tend to land on green plants, which reflect highest at 550 nm, for feeding and oviposition. AFFELDT et al. (1983) recorded maximum capture of *T. vaporariorum* on traps reflecting radiation with λ between 500-600 nm (yellow) and inhibition of landings under radiation with λ between 400-490 nm. The two types of radiation are complementary, thus eliciting a balance between migratory behaviour induced by UV and a landing reaction controlled by sensitivity to yellow (MOUND, 1962; COOMBE, 1981, MÖLLER, 2002). Furthermore whiteflies do not exhibit any long distance responses but seem to react only to certain colours; hence, colour is the most important factor in long-range host plant selection by whiteflies (VAN LENTEREN & NOLDUS, 1990).

According to MELLOR et al. (1997), *T. vaporariorum* has divided compound eyes with distinct dorsal and ventral regions. The percentage response in the UV, of the dorsal region of the eye, is significantly greater than that of the ventral region of the eye relative to the percentage response in the blue-green-yellow region. Both *T. vaporariorum* and *E. formosa* have a maximal peak of efficiency at 520 nm and a secondary peak in the UV region (MELLOR et al., 1997).

2.2.3 Insect sensitivity to polarised light

Light wave in which vibrations occur in a single plane is referred to as polarised light. Polarisation is the process of transforming unpolarised light in to polarised light. There are four main methods of polarisation: reflection, refraction, transmission or by scattering (ANONYMOUS, 2004 (a)).

Some insects are sensitive to polarised light and use it for navigation (HORVATH et al., 2002, REPPERT et al., 2004). The UV and polarisation sensitive photoreceptors concerned are gathered in an upward pointing narrow area located at the dorsal rim of the eye. According to HORVATH et al. (2002) the degree and angle of polarisation of reflected light depends on how smooth the plant surfaces are and how they are oriented with respect to the incoming light at that direction of view. Thus each receptor gives signal that depends not only on intensity and wavelength but also on the angle and degree of polarisation. If the sensors of a colour vision system are also polarisation sensitive, the system generates 'false colours' that may obscure the real colours defined by the spectral properties of the object. Hence some insects have some twisted photoreceptors whose function is to avoid the polarisation induced false colours. Rough surfaces (e.g. owing to the presence of a waxy layer or other microstructures) reflect light diffusely, which reduces polarisation, while in a given spectral region, darker objects polarize light to a higher degree if the illuminating light is unpolarised and white. Thus, green leaves are less polarised in the green range than in the blue and red ranges (HORVATH et al., 2004).

The compound multifaceted eyes of insects are composed of thousands of simple eyes (ommatidia), each with its own lens, crystalline, and several long visual cells arranged in a star pattern. The light sensitive parts of the visual cells are the microvilli (an array of tube-like membranes where the pigment rhodopsin is located). All the microvilli of the visual cells of an ommatidium point towards the center of the star, forming light detecting waveguide: the rhabdom. The rhodopsin molecules are aligned preferentially parallel to the axes of the microvilli tubes. Thus, in principle, each visual cell would be maximally sensitive to light polarised parallel to its microvilli (ANONYMOUS, 2004 (b)).

Polarisation sensitivity of insects that use it for navigation is generally restricted to the dorsal upward-looking portion of their eyes and is cancelled out if the ommatidia are twisted along their length. Generally, bees are sensitive to three colours i.e. green, blue and UV. Each ommatidium has three visual cells for each colour. Eight of the cells are twisted 180 degrees from bottom to top, but the ninth is much shorter than the rest and only twists by 40 degrees. This last visual cell is the one that is sensitive to UV, thus bees only detect polarisation in the UV (ANONYMOUS, 2004 (b)).

3 RESEARCH OBJECTIVES AND HYPOTHESIS

3.1 Statement of the research problem

Whitefly populations have drastically increased throughout the world since 1970s, attacking previously un-infested plant species and becoming acclimatized to new environments (BROWN, 1994). The cause of this increase is unknown, but it may be due to the extended use of synthetic insecticides and subsequent augmented resistance, while their widespread distribution is attributed to their exceptionally wide host range and short generation time (SKROBEK, 2001). Moreover, the high population densities and short generation times of the greenhouse whitefly *T. vaporariorum* are responsible for rapid development of strains resistant to synthetic insecticides (BECKER et al., 1992).

T. vaporariorum damages crops either directly by sucking the sap from the plants or indirectly by excreting honeydew on which sooty mould grows thereby obscuring leaves (reducing both photosynthesis and plant quality) and acting as vectors for plant pathogenic viruses. Infestations can lead to severe economic losses as a result of crop yield reductions. Mature insects spread very fast among plants and cling on the underside of foliage, making it difficult for contact pesticides to reach them. Immature stages, on the other hand, are not only small and difficult to detect, but also often tolerant and/or resistant to many insecticides (BEVERLY et al., 2002). Chemical control of *T. vaporariorum* has thus become unreliable because of wide spread development of resistance to insecticides (FASULO et al., 2003). According to these authors, the slow development of commercial cultivars, and the level of pest infestation limit the use of resistant plant varieties. Additionally, neither biological nor cultural control measures can achieve the level of efficacy needed by growers in the case of virus transmission by *T. vaporariorum.* Plant disorders and virus transmission are of particular concern because they can occur even at very low whitefly infestation levels.

Due to the ineffectiveness and the increase in the cost of chemical control, the low threshold requirement, development of resistance against pesticides and the complexity of biological control strategies, it is important to develop alternative pest control measures to ensure the cultivation of pesticide-free products, including the development and adoption of environmentally friendly production techniques. The present study was initiated in order to investigate the effects of UV-absorbing plastic films for control of *T. vaporariorum* in the low light intensities prevalent in northern Germany. The potential of using UV-absorbing plastic films to replace conventional, often highly toxic, pesticides in integrated crop production and protection was evaluated. Specifically, the effects of the quantity of UV on *T. vaporariorum* were studied in detail. Such information can contribute to the development of a practical, environmentally safe and sustainable pest management programs for control of *T. vaporariorum*.

3.2 Research objectives

The overall objective of this research was to investigate the potential of integrating UV-absorbing greenhouse covering plastic films into an effective and inexpensive IPM strategy for control of the greenhouse whitefly *T. vaporariorum*. More specifically:

1. to investigate the effect of UV intensity on the invasion and orientation behaviour of *T. vaporariorum*, and
2. to investigate the effect of UV intensity on the colonization and distribution behaviour of *T. vaporariorum*.

3.3 Research hypothesis

T. vaporariorum uses UV for orientation during migration (COOMBE, 1982). The use of UV-absorbing plastic films as greenhouse covers may lower the quantity of UV inside a greenhouse, thereby interfering with the visual cues used by *T. vaporariorum* (ANTIGNUS et al., 1996). Interference with visual cues may lead to:

- reduced invasions of a greenhouse by *T. vaporariorum*, and
- limited distribution of *T. vaporariorum* inside a greenhouse.

Reduced invasion and distribution will lead to low population levels of *T. vaporariorum* inside a greenhouse.

4 MATERIAL AND METHODS

4.1 Location of study

The study was conducted in University of Hannover, Germany. The university is located on latitude 52° N and longitude 10° E. The mean annual values for temperature, rainfall and duration of sunshine are 8.9°C, 564 mm and 1,515 hours, respectively.

4.2 Preparation of Materials

4.2.1 Plastic films

The spectral transmission properties of plastic films were analysed in the laboratory at the Institute of Agricultural Engineering (ITG) (University of Hannover, Germany) using a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrophotometer (Perkin-Elmer Instruments, Norwalk, USA). The spectrophotometer could measure radiation with wavelengths ranging from 250 nm to 2,500 nm. Two plastic films, namely K-Rose (KR) and Thermilux (Tlux), with different light (spectral) transmission characteristics for UV i.e. KR and Tlux were UV-absorbing and UV-transmitting plastic films, respectively, were chosen. Both plastic films were supplied by Hyplast Ltd. (Hoogstaten, Belgium) and were 0.15 mm thick. One sunny (17th July 2004), and one cloudy day (13th July 2004) were selected and used for comparison of differences in temperature, RH, UVA intensity and the intensity of global radiation inside and outside the tunnels. For details of the sensors see below.

Separately, the reflectivity of a fresh green tobacco leaf and a yellow sticky trap were measured using the same equipment.

4.2.2 UV Lamp

The UV lamp used in one of the greenhouse experiments was a 160 W fluorescent-tube-type (Philips CLEO performance R). The lamp was 1.778 m long, had a diameter of 0.041 m and was supplied by Sonepaar Deutschland, Hannover, Germany. The spectral irradiance was measured in a light-tight room, using a LI-1800 portable spectroradiometer (LI-COR, Inc., Lincoln, Nebraska, USA). The quantum flux density was calculated by performing integration between the wavelengths 330 and 850 nm, for five measurements. During the measurement, the UV lamp was placed horizontally 0.40 m above the cosine receptor.

4.2.3 Greenhouse Whiteflies

Greenhouse whiteflies, *T. vaporariorum* were mass reared on tobacco plants (*Nicotiana tabacum* L. (Solanaceae) cv. Xanthi) in insect proof cages (80×60×60 cm) at the Institute of Plant Diseases and Plant Protection (IPP) (University of Hannover, Germany). The top and bottom of the cages were covered with glass and plywood, respectively, while the sides were covered with a fine insect proof screen. The cages were kept in a greenhouse cabinet at 22 ± 2°C and 60 - 80% RH. Tobacco plants in the cages were replaced with new and insect-free ones, produced in a pest and disease free greenhouse at IPP, every two weeks. Whiteflies were collected with a small aspirator and then transferred into a Petri dish (5 cm diameter × 2.5 cm deep) before release in the respective experiments.

4.2.4 Sensors

The intensity of UVA inside the tunnels was measured using a radiometer UV-sensor (Dr. Groebel UV Electronic GmbH, Ettlingen, Germany). The sensor was connected to the display electronics via a 5-lead shielded cable. The sensor's electronics provide a voltage signal proportional to the incident irradiance. The UV-meters could measure radiation with wavelength from 315 to 400 nm up to a maximum intensity of 200 W/m^2.

The intensity of incoming global radiation was measured using solarimeters (Kipp and Zonen, Delft, The Netherlands). The measurement range for the solarimeters was 300 to 3,000 nm. Routine maintenance of the solarimeters included removing dust from the glass, keeping the spirit level in the centre and changing the drying material.

Temperature both inside and outside the tunnels was measured using a psychrometer developed at ITG (ITG, 1988), fitted with two thermocouples. Dry and wet thermocouples were used to measure the dry and wet air temperatures, respectively. A shield was used to protect the thermocouples from direct solar radiation, while a bronze container was used to supply water to the wet bulb. RH was calculated from the difference between the measurements of the wet and dry thermocouples.

All sensors were placed on a flat surface 1 m above the ground.

4.2.5 Collection of climatic data

The climate data from all sensors were automatically recorded every ten minutes by a low power consumption data-logger assembled at ITG (ITG, 2003). The data logger had the following specifications: 16 bit Sigma Delta ADC, 8 bit Micro-controller 12 MHz, 64 KB I^2C memory, on board watch-dog and a real time clock with a maximum of 70 message channel automatic cold junction compensation. Connection between the logger and the periphery was over a I^2C BUS. Data was retrieved using a chip card and transferred to a computer where the chip card was read and the data transformed from electric measurements (millivolts) to the respective physical values (SI units) using a macro written in Microsoft Visual Basic program (VON ELSNER, 2003).

4.3 Effects of UV intensity on the orientation behaviour of *T. vaporariorum*

Eight completely enclosed tunnels (3 m long × 3 m wide × 2.5 m high) were constructed, using Polyvinylchloride (PVC) pipes and timber frames. Four tunnels were placed at right angles to each other in a cross-shaped pattern, thereby creating two cross-shaped structures (Fig. 2). In each cross-shaped structure, two adjacent tunnels were covered with KR and the other two with Tlux. This arrangement provided one tunnel covered with each plastic type in each of the four cardinals (Fig. 1). Entrance to each tunnel was through a main door (1 m wide × 2 m high) on one gable side. At the centre of each cross-shaped structure was a compartment entirely covered by a plastic film with a white surface on the outside (to reflect unwanted heat and light) and a black surface on the inside (to maintain the compartment as dark as possible). This ‘black compartment’ was connected to each of the four tunnels through small doors (1 m wide × 1 m high). Weeds inside and around the tunnels were controlled by mulching and mowing. Four yellow sticky traps, each measuring 25 cm long × 10 cm wide, (Aeroxon GmbH, Waibligen, Germany), were positioned 0.25 m above the ground inside each tunnel at 0.6, 1.2, 1.8 and 2.4 m distance from the black compartment, respectively.

During each experiment, 500 adult *T. vaporariorum* were released from the centre of the black compartment and allowed to fly into a tunnel of their choice where they were recaptured by the yellow sticky traps. The experiments were conducted from 9.00 am to 5.00 pm. A total of ten experiments were performed between June and September 2003. The following climatic parameters were recorded for each experiment: UVA intensity (inside the tunnels), and temperature (inside and outside the tunnels). Due to a shortage of solarimeters, the intensity of global radiation was only recorded outside and inside the Tlux-covered tunnels.

In May 2004, i.e. one year after the construction of the tunnels, two samples were taken from each of the two plastic films on the tunnels and their spectral transmissions were re-analysed.

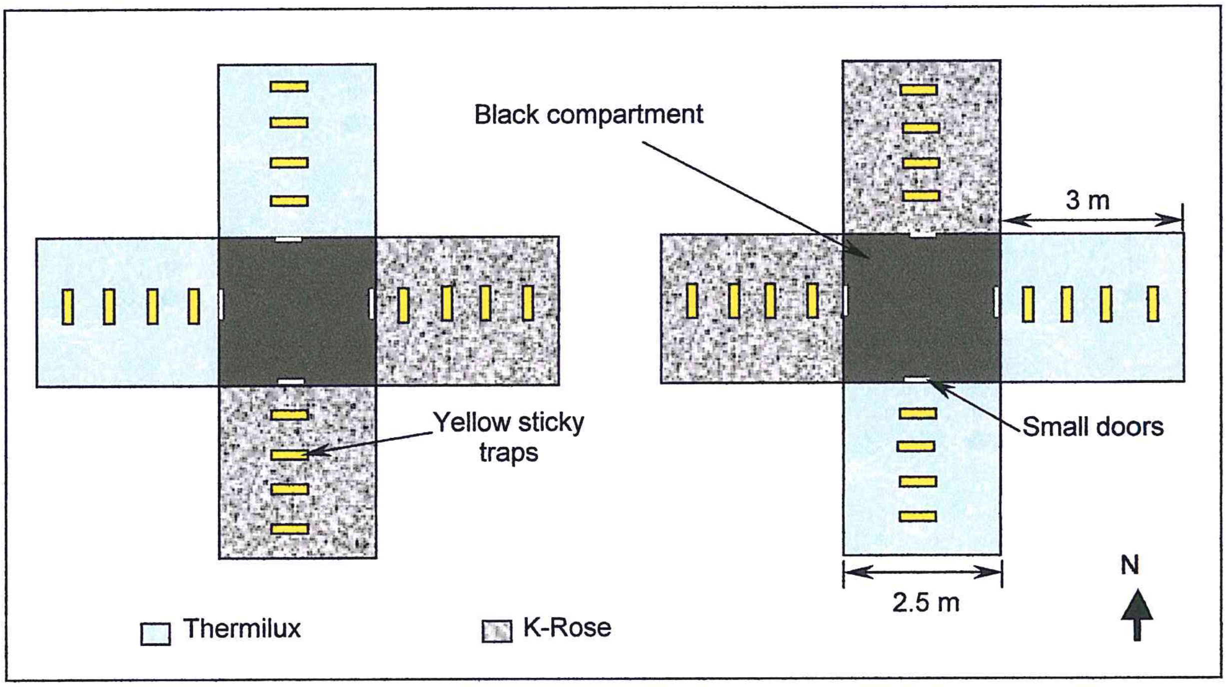

Figure 1: Experimental layout of the plastic tunnels used in the choice experiments.

Figure 2: Photograph of the tunnels used for the choice experiments. The white "projection" in the middle is the roof of the black compartment.

4.4 Effects of an artificial UV source on the orientation of *T. vaporariorum*

Four small tunnels (1.0 m long × 0.5 m wide × 0.5 m high) were constructed and covered with the UV-transmitting plastic film (Tlux). The four tunnels were positioned in four locations (imitating the four arms of a cross) and were connected by small doors (0.15 wide × 0.15 m high) to a light-tight black compartment (made from timber and the black and white plastic film described in section 4.3) at the centre of the apparatus (Fig. 3). Inside each tunnel one yellow sticky card was positioned 0.01 m above the ground at a distance of 0.50 m from the black compartment. The entire apparatus was placed in a greenhouse whose temperature and RH were maintained at 20 ± 2°C and 60-80%, respectively.

Two different types of experiments were performed using this set-up. In all experiments, 200 adult *T. vaporariorum* were released from the black compartment and allowed to fly into a tunnel of their choice where they were recaptured by the yellow sticky traps. Each experiment, conducted between December 2003 and March 2004, was initiated at 5.00 pm and lasted until 7.00 am the following morning. During an experiment all lights inside the greenhouse were switched off. In addition, light from adjacent buildings was blocked by a 2.5 m high plastic film "perimeter wall" created around the apparatus.

In the first set of experiments different UV intensities were generated in the various tunnels by positioning the UV lamp at a height of 0.40 m directly above the extreme edge of one of the tunnels (i.e., in the southern end of the apparatus). In other words, the central part of the lamp (approximately 0.5 m in length, i.e., the width of the tunnel) was positioned directly above the southern edge of the tunnels and the two other portions (one on each end), measuring approximately 0.635 m, protruded from either side of the tunnel (Fig. 4). This ensured that the tunnel below (i.e., the southern) and the one furthest away from the lamp (i.e., the northern) received the highest and lowest UV intensities, respectively, while the two tunnels in the middle (i.e., the eastern and western) were exposed to equal UV intensities. This experiment was repeated four times. For a replication, the lamp was positioned at the same height on the opposite side (north). A total of eight experiments were conducted i.e. four experiments with the lamp on each position.

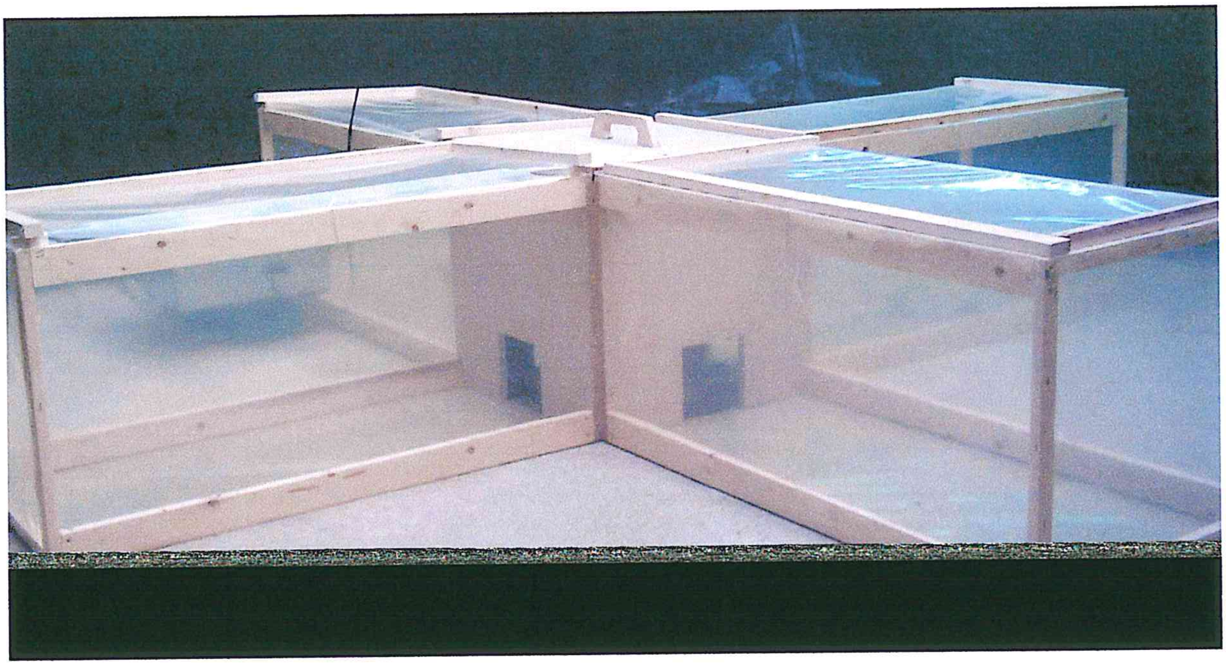

Figure 3: Photograph of the tunnels used for the greenhouse experiments using a UV lamp. All the four tunnels were covered with Thermilux (UV-transmitting) plastic film.

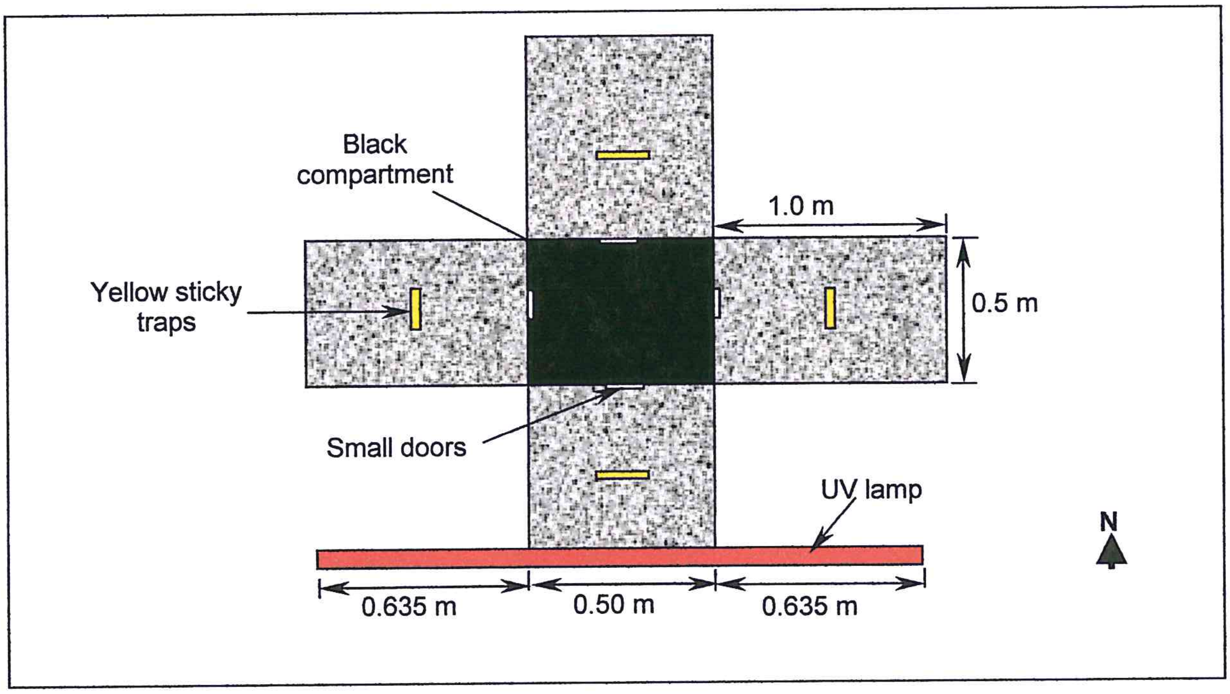

Figure 4: Experimental layout of the choice experiments conducted in the greenhouse with the UV lamp.

The second set of experiments acted as a control and involved the generation of equal UV intensities in all the four tunnels. This was achieved by positioning the same lamp at a height of 0.4 m directly above one of the diagonals of the black compartment. This was done such that slightly less than half of the lamp length (0.707 m) was positioned directly above and along one of the diagonals of the black compartment, thereby allowing two equal lamp portions (one on each end), measuring approximately 0.535 m in length, to protrude between the two tunnel junctions (i.e., southern-western and northern-eastern junctions) (Fig. 5). This experiment was repeated seven times.

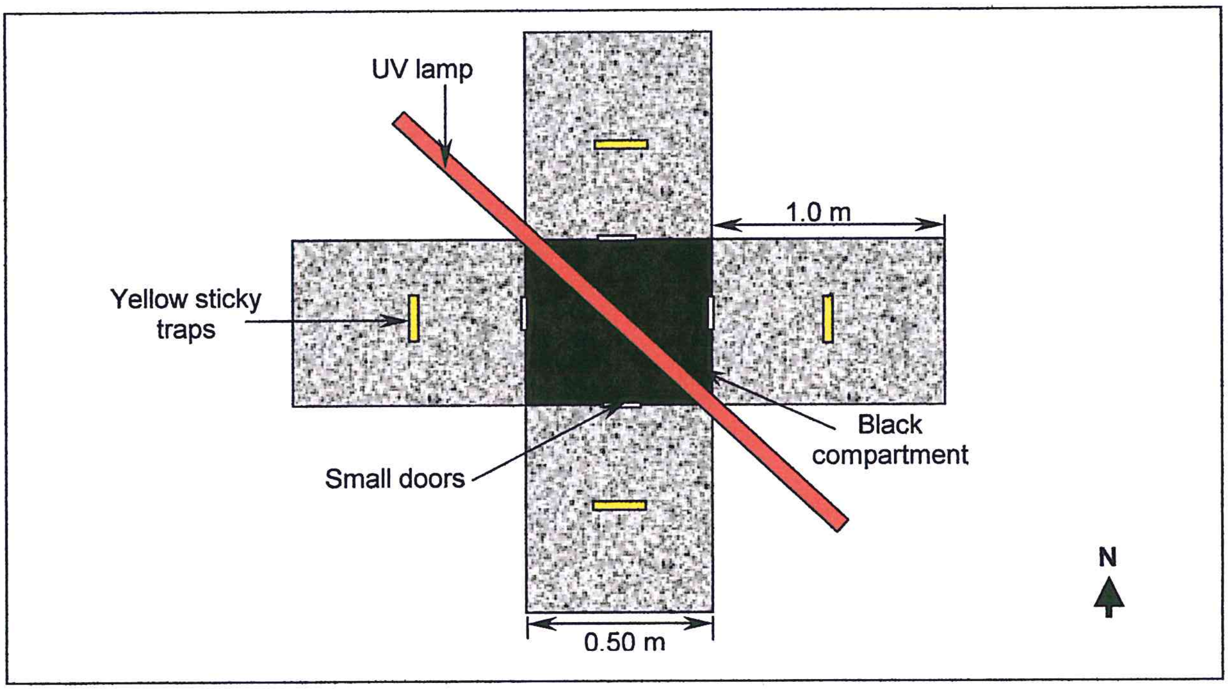

Figure 5: Layout of the choice experiments conducted in the greenhouse with the UV lamp positioned across the black compartment.

4.5 Effect of UV intensity on *T. vaporariorum* penetration in the tunnels

Two tunnels, one covered with Tlux and the other with KR, constructed in an East-West orientation were chosen from the cross-like structure described in section 4.3 (Fig. 6) and modified by blocking the small door connecting each tunnel to the black compartment was with a black polythene film (thus making the western gable of these tunnels darker in comparison to the eastern one). Four yellow sticky cards were positioned inside each tunnel at 0.6, 1.2, 1.8 and 2.4 m from the black end of the tunnel. All cards were placed at a height of 0.25 m above the ground surface. In each experiment, 200 whiteflies were released from the black end of the tunnel and the penetration into the tunnel was monitored by counting the number of whiteflies trapped on the yellow sticky cards. Each experiment involved the use of a new group of insects and yellow sticky traps and lasted for 8 hours (from 9.00 am to 5.00 pm). Five repetitions were conducted between September and October 2003. A similar experiment was conducted in June 2004 (Appendix).

In addition, a separate experiment was conducted to investigate whether the presence of plants inside the tunnels affected whitefly penetration. For this the same experimental layout was used but in addition a young tobacco plant with four fully opened leaves (approximately 3.5 weeks old) was placed under each yellow sticky card, i.e., at a distance of 0.6, 1.2, 1.8 and 2.4 m from the insect release point. Hence each tunnel contained four plants and four yellow sticky traps. At the start of each experiment, 200 *T. vaporariorum* adults were released from the black end of the tunnel and their penetration into the tunnels was monitored by counting the number of whiteflies found on each plant and/or trap. Each experiment lasted four hours (from 8.00 am to 12.00 am). Five repetitions were performed between July and August 2003.

In each experiment, temperature and RH (both inside and outside the tunnels), the intensity of UVA (inside the tunnels) and the intensity of global radiation (both outside and inside the Tlux-covered tunnels) were recorded.

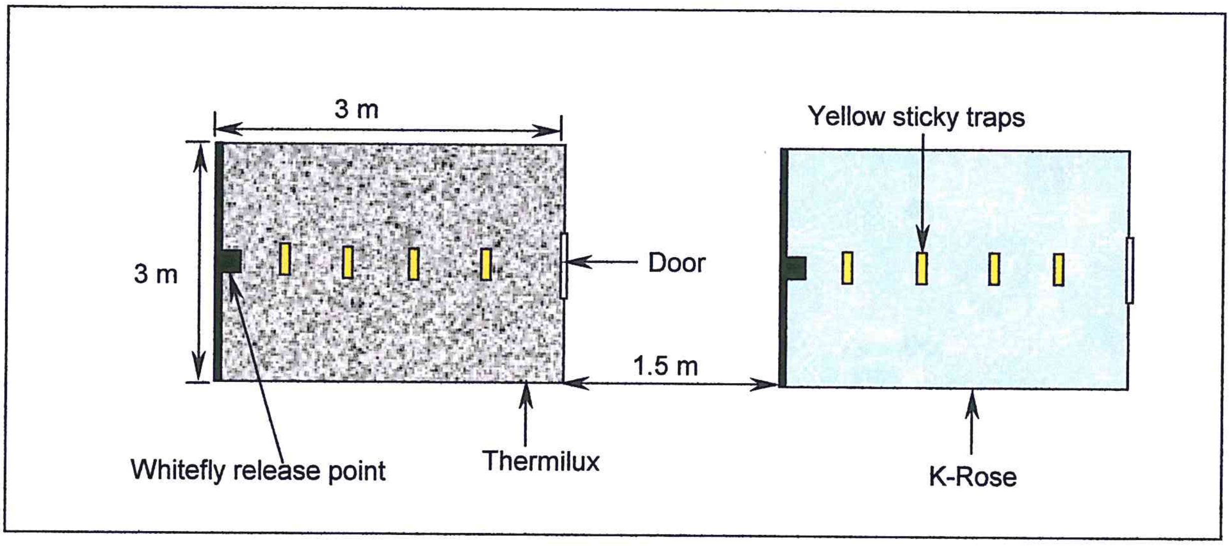

Figure 6: Layout of the penetration no-choice experiments. The black end shows the gable connecting the tunnel to the black compartment.

4.6 Effect of UV intensity on dispersion of *T. vaporariorum* inside Thermilux- and K-Rose- covered tunnels (no-choice experiment)

A no-choice, release and re-capture experiment was conducted in summer 2004. Four tunnels, each measuring 3 m in length and width and 2.5 m in height, were constructed in an east-west orientation (Fig. 7 & 8). Two tunnels were covered with KR and Tlux plastic films, respectively. Each Tlux-covered tunnel was placed opposite to a KR-covered tunnel. Inside the tunnels six yellow sticky traps were placed at a height of 0.25 m above the ground. The traps were arranged in a grid that formed two concentric circles: an internal circle with a diameter of 1.0 m and an external circle with a diameter of 2.0 m. In other words three yellow stick traps were carefully positioned at equal distances from each other (approximately an arc with a length of 1.05 and 2.09 m for the inner and outer circles, respectively). Between every two yellow sticky traps in the same circle, an angle of 120° was maintained. In addition, to avoid obstruction of the yellow sticky traps within different circles, an angle of 60° was maintained between the yellow sticky traps in the internal and those in the external circles, i.e., the traps were positioned alternately on the inner and outer circles with a 60° angle between them. During each experiment 200 whiteflies were released from the centre of the two circles and their dispersion was monitored by counting the number of insects trapped on the yellow sticky traps. The experiment was run for four hours (from 7.30 am to 11.30 am) and was repeated four times.

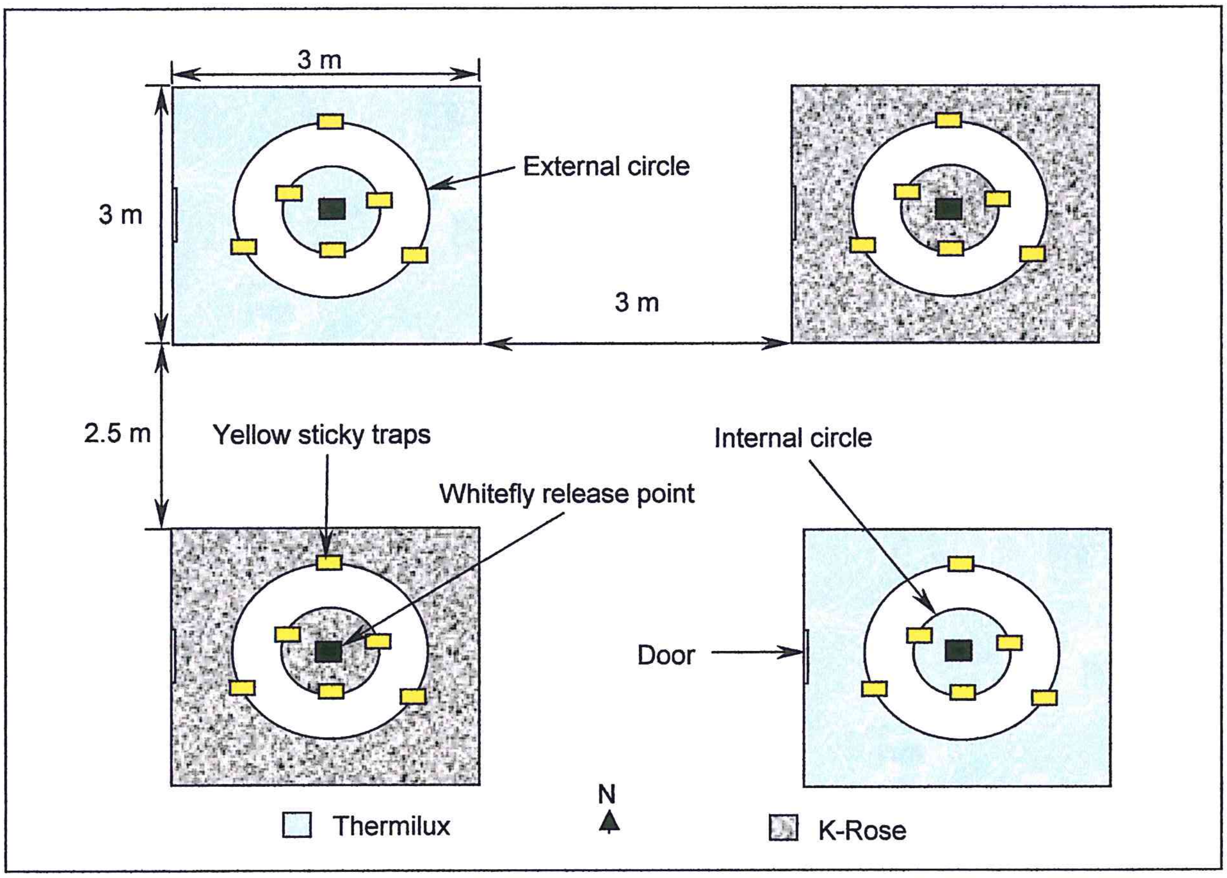

Figure 7: Experimental layout of the no-choice dispersion experiments.

Figure 8: A photograph of the tunnels used for the no-choice dispersion experiments.

4.7 Data analysis

Data of experiments repeated over time were checked for homogeneity of variance using the HOVTEST=LEVENE option of SAS (SAS, 2001) and only pooled when variance homogeneity could be assumed. Means of climatic data for the tunnels covered with different plastic types were compared using ANOVA (Tukey test) in SAS (SAS, 2001).

For the field experiments to determine the effects of UV intensity on the orientation of *T. vaporariorum*, preference responses to a particular treatment (plastic type) were determined by comparing the number of whiteflies recaptured in each tunnel using the PROC MIXED procedure of SAS (LITTEL et al., 2000). Because the cardinal position of the tunnels and the repetitions were randomly fixed, their effects were treated as random factors. The main factors, i.e., tunnel orientation, plastic film type and the interaction effect between orientation and plastic film type were treated as fixed factors in the model. For the analysis of orientation effects within the same plastic film type, differences in least square means were compared using the same procedure. Only fixed effects are discussed in this report.

Data from the experiments on whitefly penetration and dispersion, as well as from the experiment with the artificial UV source, were analysed using Chi-square test of association (PROC FREQ) in SAS. When the null hypothesis was rejected in the experiments using the artificial UV source, simultaneous confidence intervals for multinomial proportions were constructed based on GOODMAN'S (1965) method using R statistical software (CCI, 2004).

All analyses were performed at 5 % confidence level.

5 RESULTS

5.1 Plastic films

Before the start of the experiment, the overall light transmission of the plastic films in the whole spectrum (250 – 2,500 nm) was 87 and 85% for Tlux and KR, respectively. Transmission in the UV and PAR was 78 and 86% for Tlux, and 10 and 89% for KR, respectively (Fig. 9). In the NIR range, the transmission was 88 and 89% for Tlux and KR, respectively. Moreover between 403 and 504 nm wavelengths, KR transmission was slightly higher (88%) than that of Tlux (81%). The same pattern was observed when the transmission of the plastic films was computed relative to that measured on a horizontal surface at 48.3° latitude (CIE, 1989) (Fig. 10). One year later, the transmission profile for KR had remained the same (Fig. 11), while the transmissivity of Tlux for light with wavelength between 300 and 500 nm had increased slightly. For instance at a wavelength of 300 nm, light transmission in Tlux had increased within one year from 70 to 80%; yet beyond 500 nm it remained almost constant (Fig. 12).

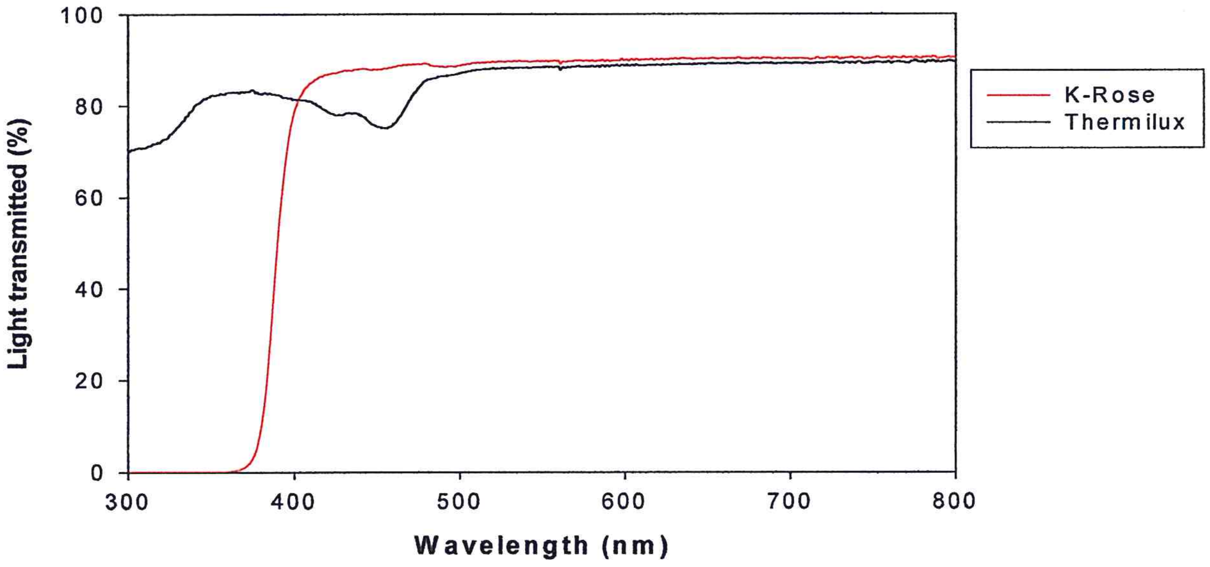

Figure 9: Spectral transmissivity of new Thermilux (UV-transmitting) and K-Rose (UV-absorbing) plastic films measured with a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrophotometer (Perkin-Elmer Instruments, Norwalk, USA).

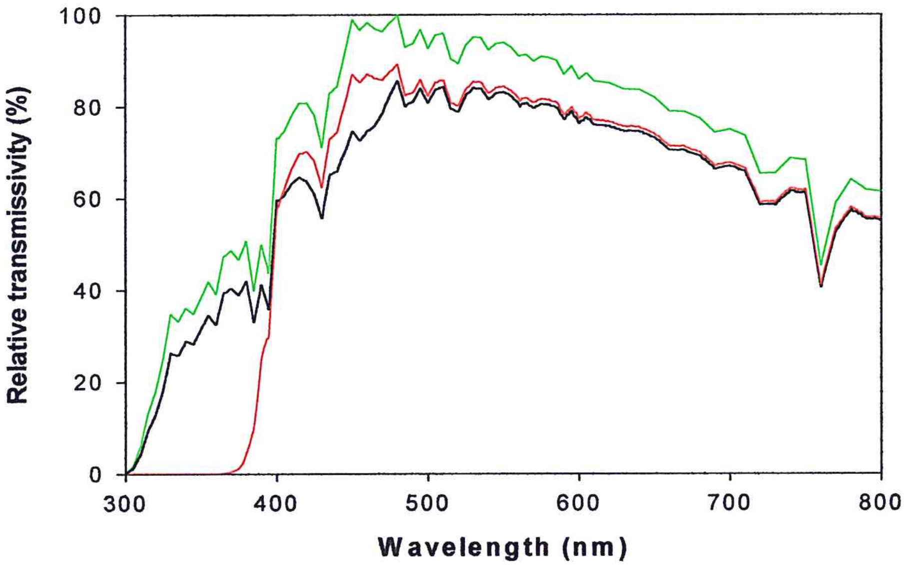

Figure 10: Spectral transmissivity of Thermilux (UV-transmitting) and K-Rose (UV-absorbing) plastic films relative to that measured at latitude 48.2°N.

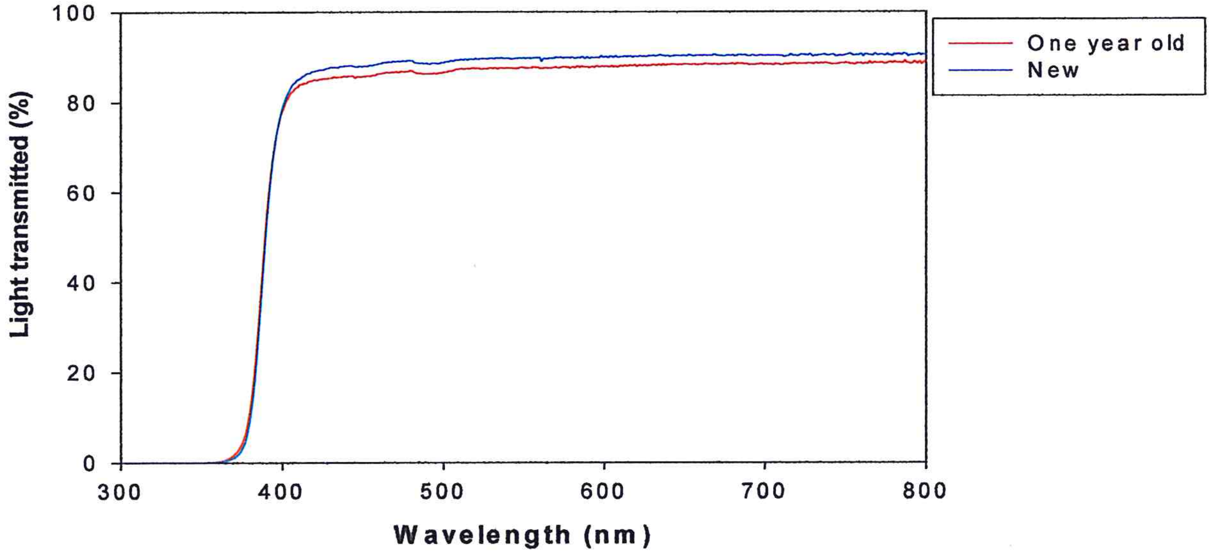

Figure 11: Spectral transmissivity of new and one year-old K-Rose (UV-absorbing) plastic films measured with a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrophotometer (Perkin-Elmer Instruments, Norwalk, USA).

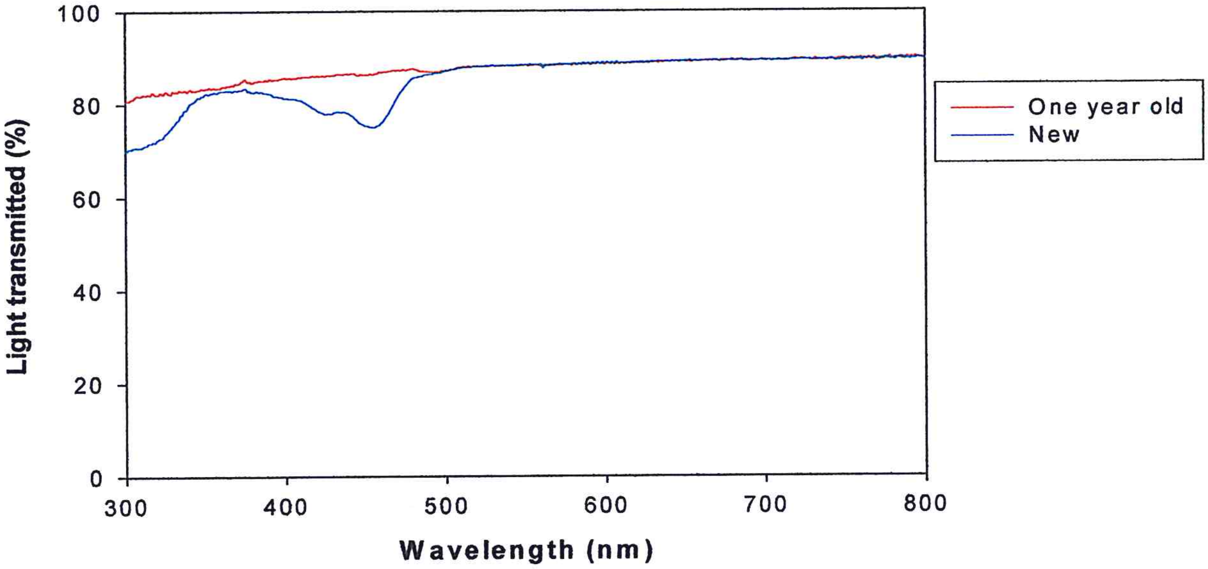

Figure 12: Spectral transmissivity of new and one year-old Thermilux (UV-transmitting) plastic films measured with a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrophotometer (Perkin-Elmer Instruments, Norwalk, USA).

No significant differences in temperature (as mean of 24 hours) were recorded inside Tlux and KR-covered tunnels on both sunny (F = 0.18; df = 1, 288; $P = 0.069$) and cloudy days (F = 0.71; df = 1, 288; $P = 0.397$) (Table 1). The temperature profiles for both plastic types on sunny and cloudy days looked rather similar (Figs. 13 & 14). Similarly, there were no significant differences in RH recorded inside both tunnel types on sunny (F = 0.81; df = 1, 288; $P = 0.36$) and cloudy days (F = 0.19; df = 1, 288; $P = 0.65$) (Table 1). The RH profiles for Tlux and KR looked very similar and were always above the RH profile recorded outside the tunnels (Figs. 15 & 16). However, significant differences were detected in the mean UVA intensities recorded inside Tlux- and KR-covered tunnels recorded over a 16 hrs period (from 6.00 to 22.00 hrs) on both the selected sunny (F = 120.54; df = 1, 192; $P < 0.0001$) and cloudy day (F = 172.19; df = 1, 192; $P < 0.0001$) (Table 2). Moreover, the global radiation intensity recorded inside KR- and Tlux-covered tunnels did not differ significantly on either the selected cloudy (F = 0.53;

df = 1, 192; *P* = 0.467) or sunny day (F = 0.15; df = 1, 192; *P* = 0.697). The UVA intensity profiles for both plastic types recorded on the selected sunny and cloudy days are shown in Figs. 17 & 18, while global radiation intensity profiles on the same days is shown in Figs. 19 & 20, respectively. Furthermore temperature, RH and UVA recorded inside the tunnels on the selected sunny day were considerably different from those recorded outside the tunnels.

Table 1: Mean (± SE) values for temperature and relative humidity (RH) recorded inside Thermilux (Tlux) and K-Rose (KR) covered tunnels on a sunny (i.e., 13.07.2004) and cloudy (i.e., 17.07.2004) day at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

Plastic film type	**Temperature (°C)**		**RH (%)**	
	Sunny day	**Cloudy day**	**Sunny day**	**Cloudy day**
Tlux	24.96 ± 0.82 a	15.14 ± 0.33 a	89.90 ± 1.09 a	95.37 ± 0.47 a
KR	24.48 ± 0.82 a	14.73 ± 0.35 a	91.19 ± 0.91 a	95.08 ± 0.43 a

Note: Means (± SE) in the same column followed by the same letter are not significantly different at $\alpha = 0.05$, Tukey test. Means were calculated over repeated measurements recorded over a period of 24 hrs.

Table 2: Mean (± SE) values for the intensity of UVA and global radiation recorded inside Thermilux (Tlux) and K-Rose (KR) covered tunnels on a sunny (i.e., 13.07.2004) and cloudy (i.e., 17.07.2004) day at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

Plastic film type	**UVA (W/m^2)**		**Global radiation (W/m^2)**	
	Sunny day	**Cloudy day**	**Sunny day**	**Cloudy day**
Tlux	3.40 ± 0.30 a	1.91 ± 0.14 a	228.92 ± 21.22 a	97.15 ± 8.09 a
KR	0.13 ± 0.01 b	0.027 ± 0.005 b	241.06 ± 22.73 a	105.84 ± 8.74 a

Note: Means (± SE) in the same column followed by the same letter are not significantly different at $\alpha = 0.05$, Tukey test. Means were calculated over repeated measurements recorded over a period of 16 hours.

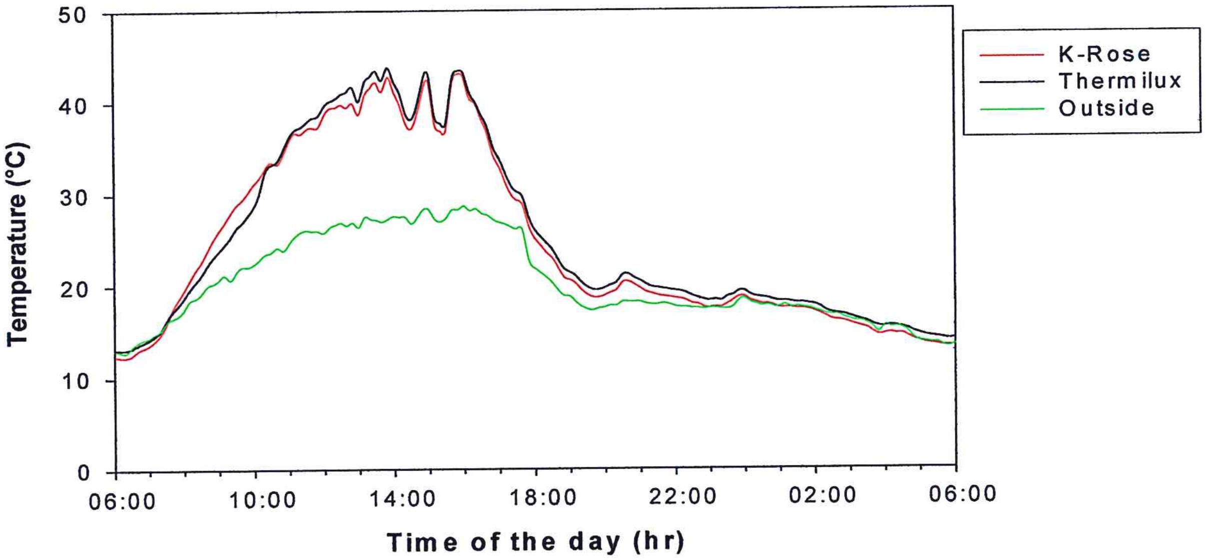

Figure 13: Temperature (°C) profile on the 17th of July 2004, the selected sunny day, inside and outside Thermilux-& K-Rose covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

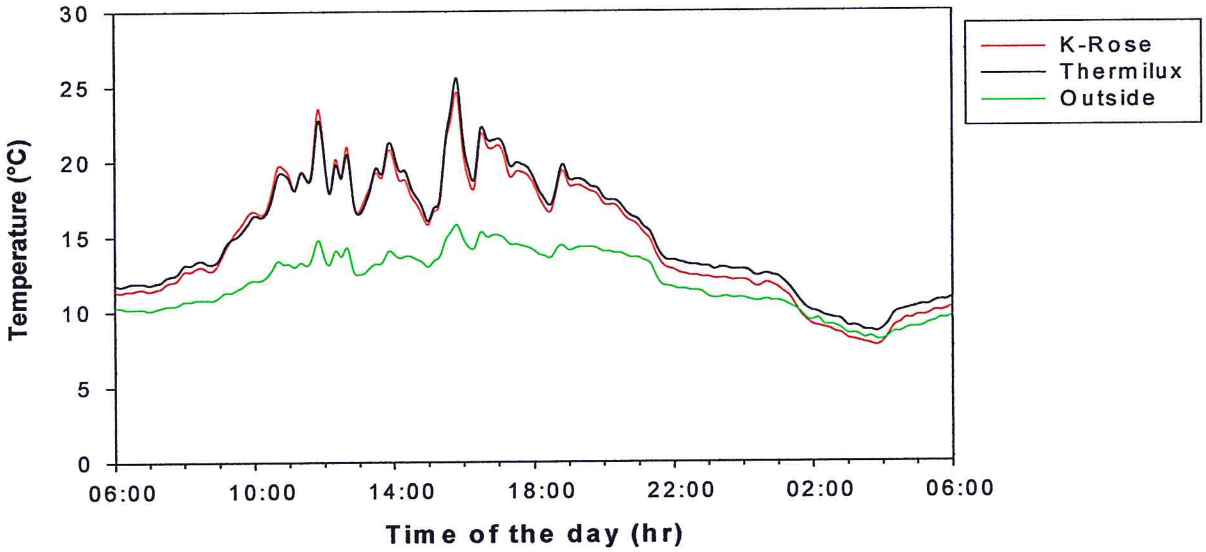

Figure 14: Temperature (°C) profile on the 13th of July 2004, the selected cloudy day, inside and outside Thermilux-& K-Rose-covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

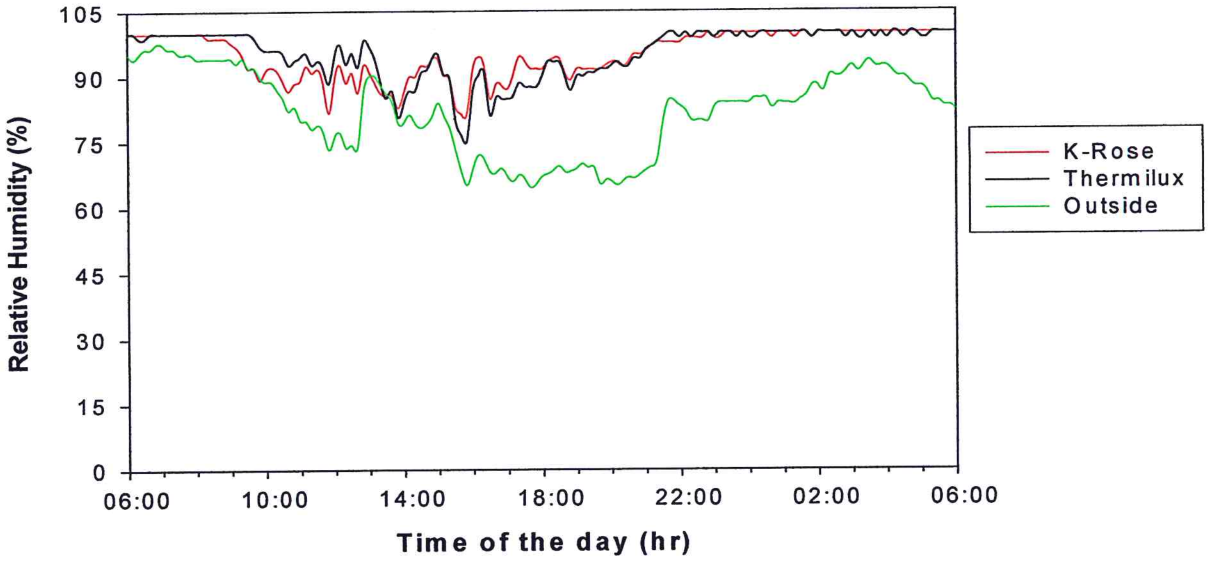

Figure 15: RH (%) profile on the 13th of July 2004, the selected cloudy day, inside and outside Thermilux-& K-Rose-covered tunnels at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

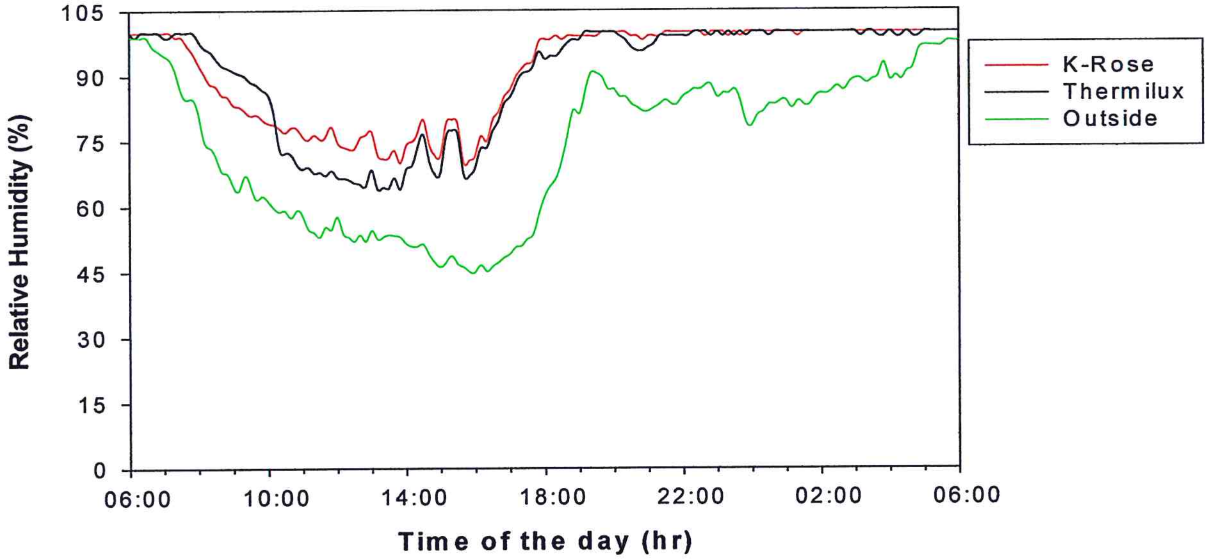

Figure 16: RH (%) profile on the 17th of July 2004, the selected sunny day, inside and outside Thermilux-& K-Rose-covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

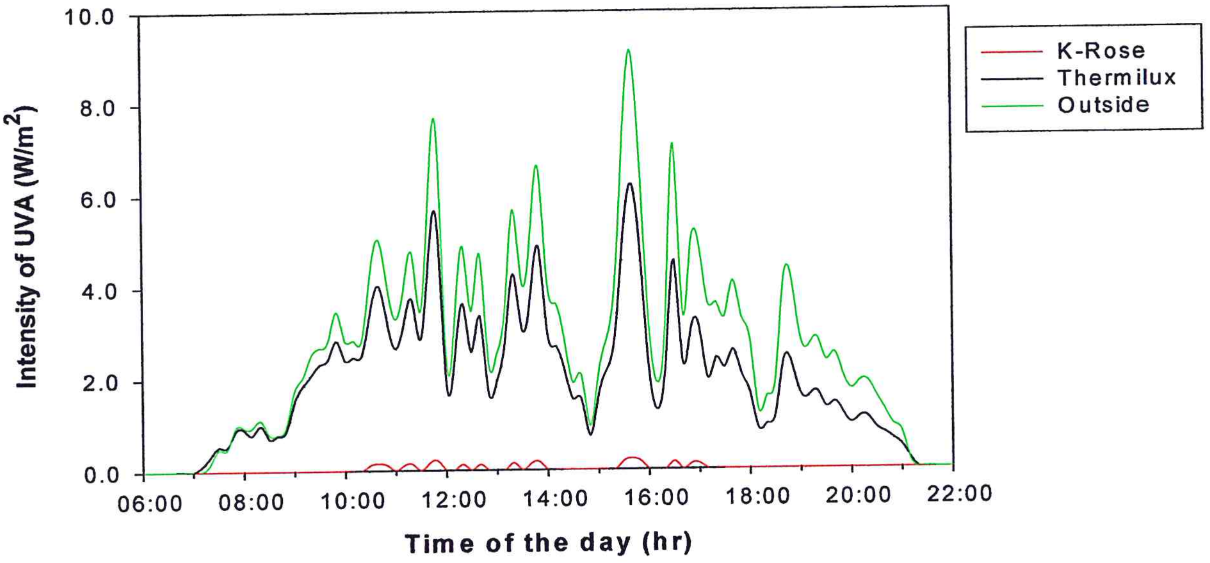

Figure 17: Profile of UVA intensity (W/m^2) on the 13th of July 2004, the selected cloudy day, inside and outside Thermilux-& K-Rose-covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

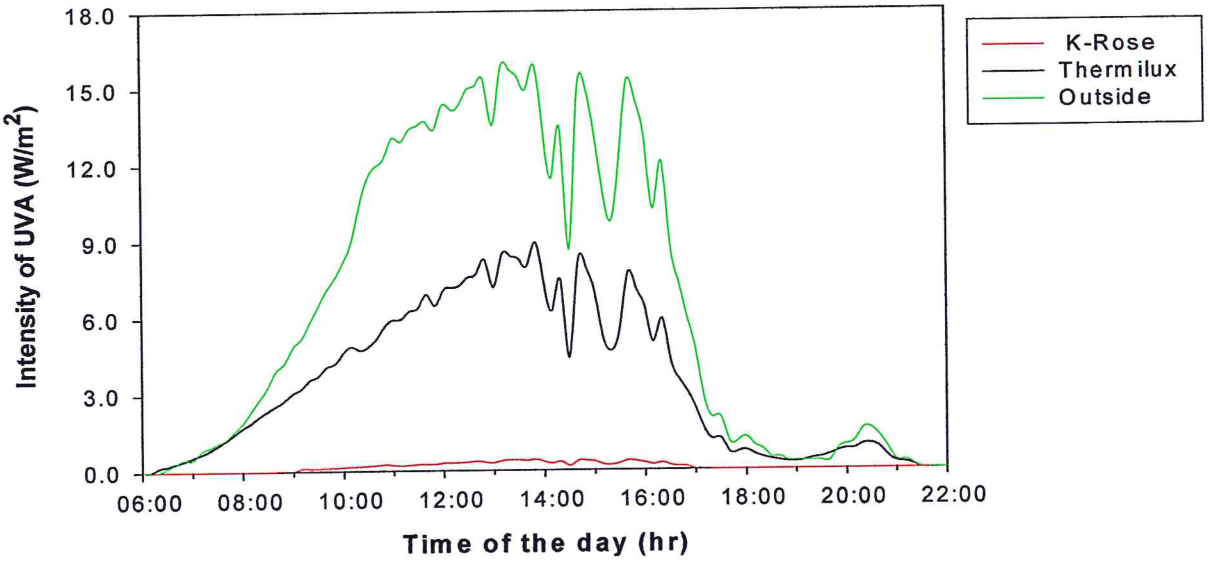

Figure 18: Profile of UVA intensity (W/m^2) on the 17th of July 2004, the selected sunny day, inside and outside Thermilux-& K-Rose-covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

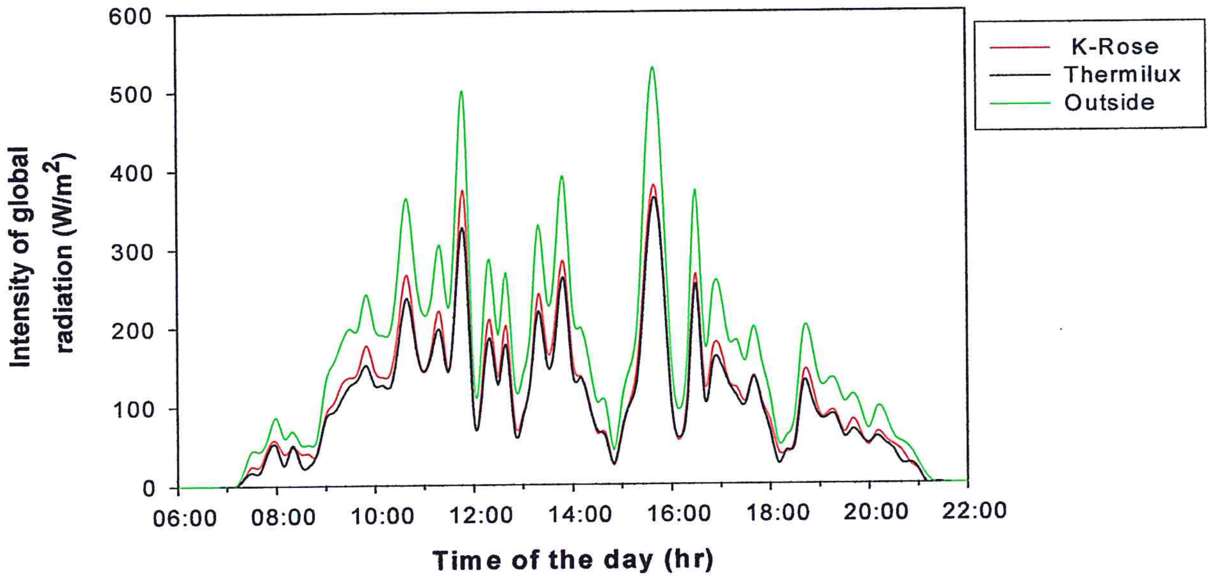

Figure 19: Profile of global radiation (W/m^2) on the 13th of July 2004, the selected cloudy day, inside and outside Thermilux-& K-Rose covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

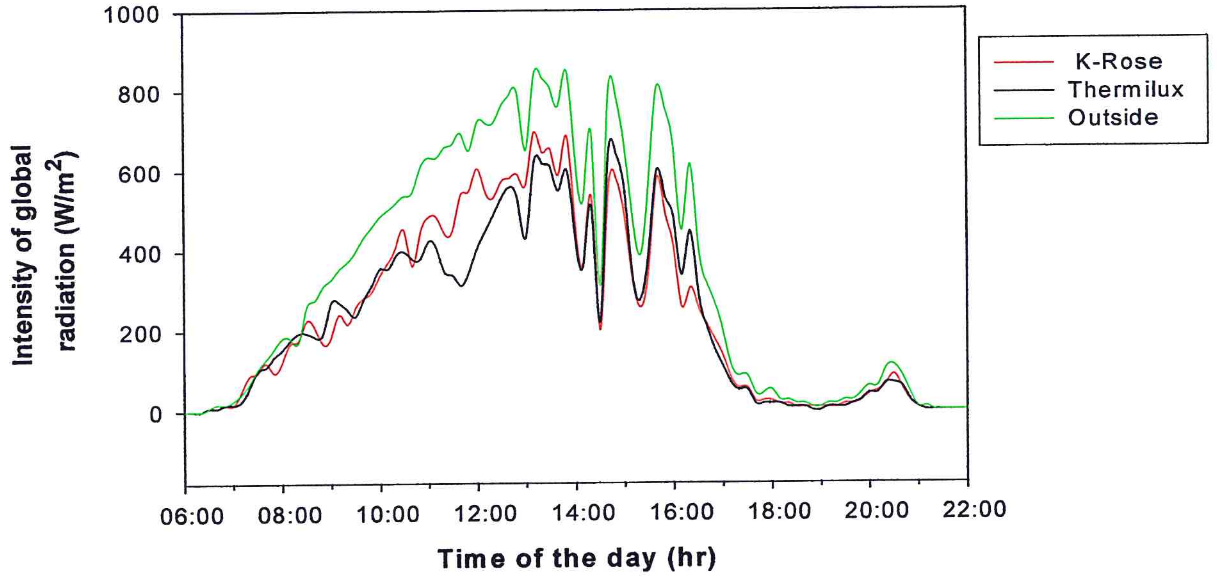

Figure 20: Profile of global radiation (W/m^2) on the 17th of July 2004, the selected sunny day, inside and outside Thermilux-& K-Rose covered tunnels, at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

The two plastic films showed different hydrophobic behaviours, with Tlux a more drop-wise condensation while KR exhibited a film-wise condensation type (Fig. 21).

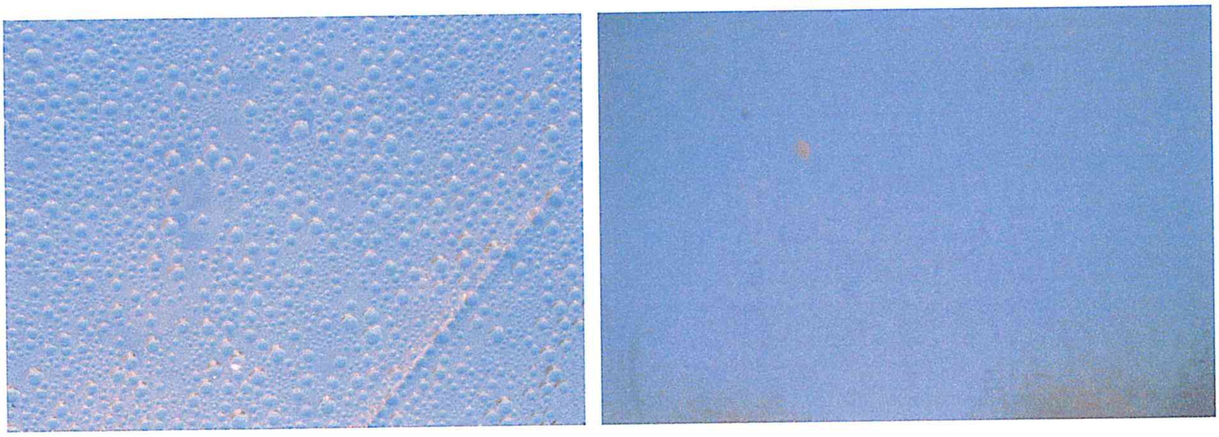

Figure 21: Photographs showing drop-wise (left) and film-wise (right) condensation observed in Thermilux- (UV-transmitting) and K-Rose- (UV-absorbing) covered tunnels, respectively.

5.2 Effect of UV intensity on the orientation of *T. vaporariorum*

Variance homogeneity was assumed, as the time of experimentation had no significant effect (F = 0.97; df = 9, 70; $P = 0.4687$). Consequently data of repetitions over time were pooled and analysed together. Both the type of plastic films (F = 204.28; df = 1, 54; $P < 0.0001$) and the cardinal position of the tunnels (F = 3.14; df = 3, 54; $P = 0.0325$) significantly affected the number of recaptured whiteflies while the interaction between type of plastic films and orientation had no effect on the orientation of *T. vaporariorum* (F = 1.89; df = 3, 54; $P = 0.1428$) (Table 3). In a choice situation more than 90% of the whiteflies were recaptured in the Tlux-covered tunnels. For both materials, the eastern tunnel attracted the highest number of whiteflies while in the northern tunnel the lowest number of *T. vaporariorum* were recaptured (Fig. 22).

When the effects of cardinal positions of the tunnels were analysed separately for each material, orientation did not have a significant effect for KR- (F = 3.04; df = 3, 18; $P = 0.0556$) and Tlux-covered tunnels (F = 2.34; df = 3, 18; $P = 0.1077$), respectively. In Tlux-covered tunnels, the mean number of *T. vaporariorum* recaptured in the eastern tunnel was significantly higher than that in the northern (t = 2.11; $P = 0.0489$) and southern (t = 2.44; $P = 0.0252$) tunnels. Yet, no significant differences in numbers of recaptured whiteflies were found between the northern and southern (t = 0.33; $P = 0.7467$), western and northern (t = 0.59; $P = 0.5618$) and between the western and southern (t = 0.92; $P = 0.3702$) tunnels.

In the KR-covered tunnels, the mean number of *T. vaporariorum* recaptured in the eastern was significantly higher than that in the northern (t = 2.41; $P = 0.0268$) and western (t = 2.57; $P = 0.0194$) tunnels. There was no significant difference between the mean number of whiteflies recaptured in the eastern and southern tunnels (t = 1.98; $P = 0.0631$), northern and southern (t = 1.78; $P = 0.0924$), northern and western (t = 0.48; $P = 0.6348$), and between the southern and western tunnels (t = 1.93; $P = 0.0692$).

During the experiments, there was no significant difference in the temperature and RH recorded inside the tunnels covered by the two plastic types (Table 4). However, temperature and RH recorded inside the tunnels differed significantly from that recorded outside the tunnels (for temperature F = 8.84; df = 2, 27; $P = 0.0011$ and for RH F = 11.57; df = 2, 27;

P = 0.0002). Moreover, the intensity of UVA recorded at the time of experimentation inside the Tlux-covered tunnels was significantly higher than that recorded in the KR-covered tunnels (F = 56.60; df = 1, 18; $P < 0.0001$).

Table 3: Interaction of the fixed effects in choice experiments in Thermilux-(UV transmitting) and K-Rose (UV-absorbing)-covered tunnels performed using mixed model (LITTLE et al., 2000).

Effect	Degrees of freedom	F-values	P-values
Orientation	3, 54	3.14	0.0325*
Material	1, 54	204.28	< 0.0001*
Material*Orientation	3, 54	1.89	0.1428

Note: *P* values in the same row followed by an asterisk (*) indicates significant interactions effect at α = 0.05, Mixed model test.

Table 4: Mean (± SE) temperature, RH and UVA intensity recorded inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during the choice experiments at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

Material	Temperature (°C)	RH (%)	UVA (W/m^2)
Thermilux	34.92 ± 2.47 a	78.80 ± 2.58 a	4.65 ± 0.61 a
K-Rose	33.91 ± 2.45 a	86.15 ± 2.30 a	0.12 ± 0.02 b
Out[1]	22.99 ± 1.67 b	65.86 ± 3.92 b	nr[2]

Note: Means in the same column followed by the same letter do not differ significantly at α=0.05 (Tukey test).

[1] outside the tunnels

[2] parameter was not recorded

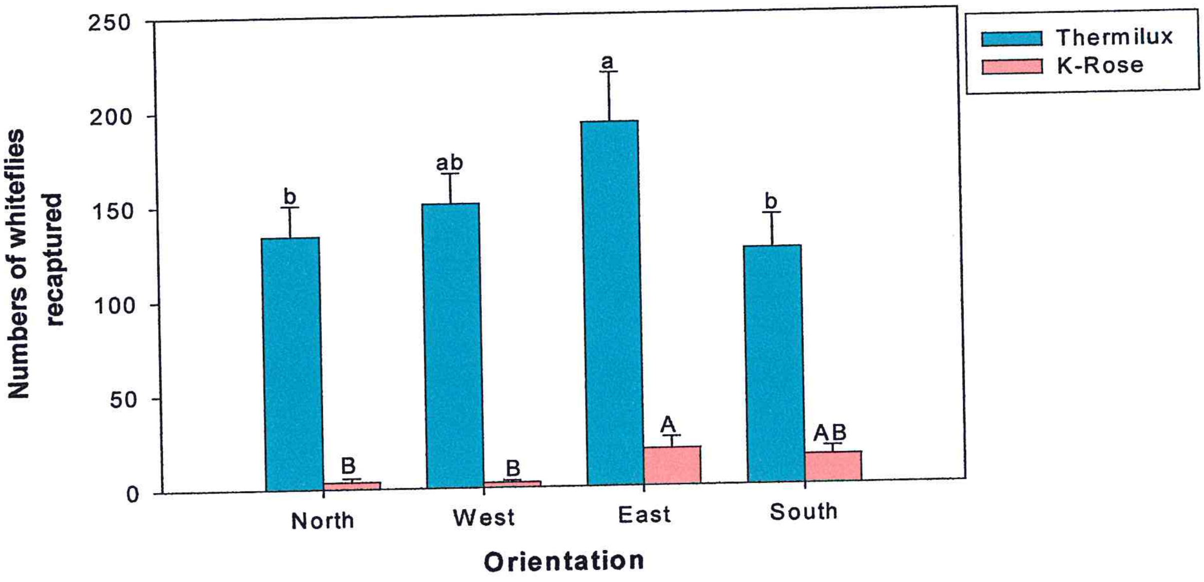

Figure 22: Numbers (mean number ± SE) of whiteflies trapped inside Thermilux- (UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels in choice experiments. Different upper and lower case letters above bars indicate significant ($P = 0.05$) differences in orientations for K-Rose and Thermilux plastic films, respectively.

5.3 Effect of an artificial UV-source on the orientation of *T. vaporariorum*

The UV lamp was emitting 89 and 11% in the UV and PAR wavelengths, respectively (Fig. 23). The highest emission (0.37 W/m^2/nm)) was recorded at 355 nm. Additionally, the lamp showed no emission in the NIR region. The total emission calculated from the recorded values was 0.88 W/m^2.

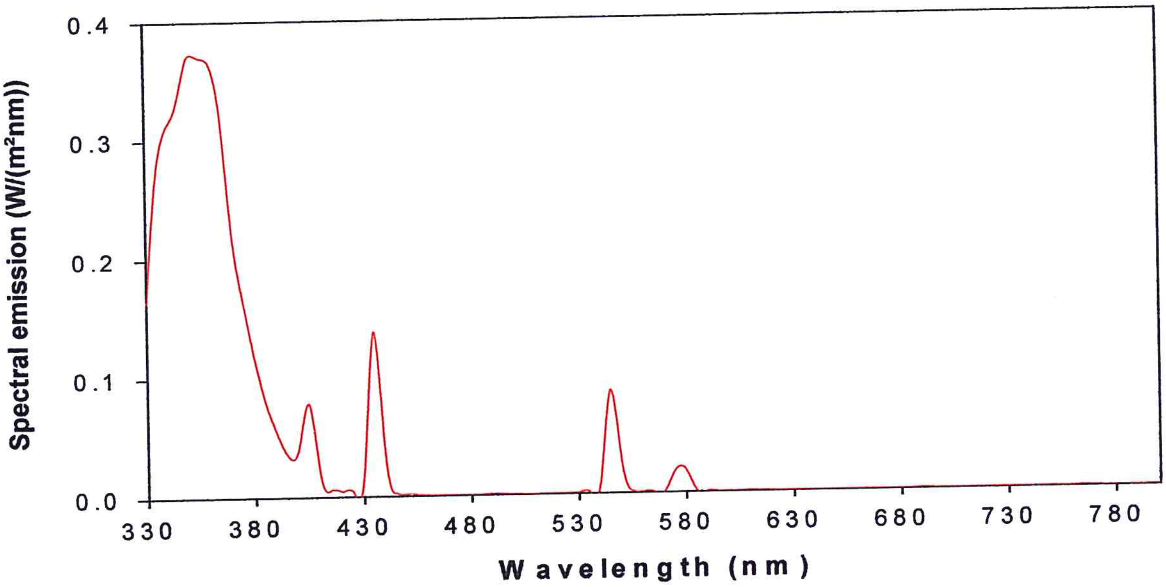

Figure 23: Spectral emission of the UV-lamp (Philips 160 W CLEO performance R) measured inside a light-tight room with a portable LI-1800 spectroradiometer (LI-COR, Inc. Lincoln, USA).

Experiments repeated over time were not significantly different from each other ($F = 1.38$; $df = 6, 21$; $P = 0.2699$) hence variance homogeneity could be assumed. Consequently data of repetitions over time were pooled and analysed together. When the UV lamp was positioned directly above the tunnels, assuring an equal distribution of UV intensity in all the tunnels, whiteflies were evenly distributed in all the tunnels. There were no significant differences in the number of whiteflies recaptured in the four different tunnels ($\chi^2 = 6.2606$; $P = 0.0996$) (Fig. 24). The tunnel in the west, north, east and south attracted 27.38, 25.85, 24.31 and 22.46% of the recaptured *T. vaporariorum*, respectively.

When the lamp was placed on the southern end of the cross-like apparatus, time did not have a significant effect (F = 1.38; df = 7, 24; $P = 0.2578$), hence data of repetitions over time were pooled and analysed together (variance homogeneity could be assumed). The number of whiteflies recaptured in the four tunnels differed significantly ($\chi^2 = 596.54$; $P < 0.0001$) (Fig. 25). The tunnel with the highest UV intensity (i.e. the southern one) attracted the significantly highest number of whiteflies (approximately 70%), the tunnel with the lowest UV intensity (i.e., the northern one) had the least (4.03%), while the tunnels on the east and west had similar proportions (10.83% and 11.68%, respectively) (Fig. 25).

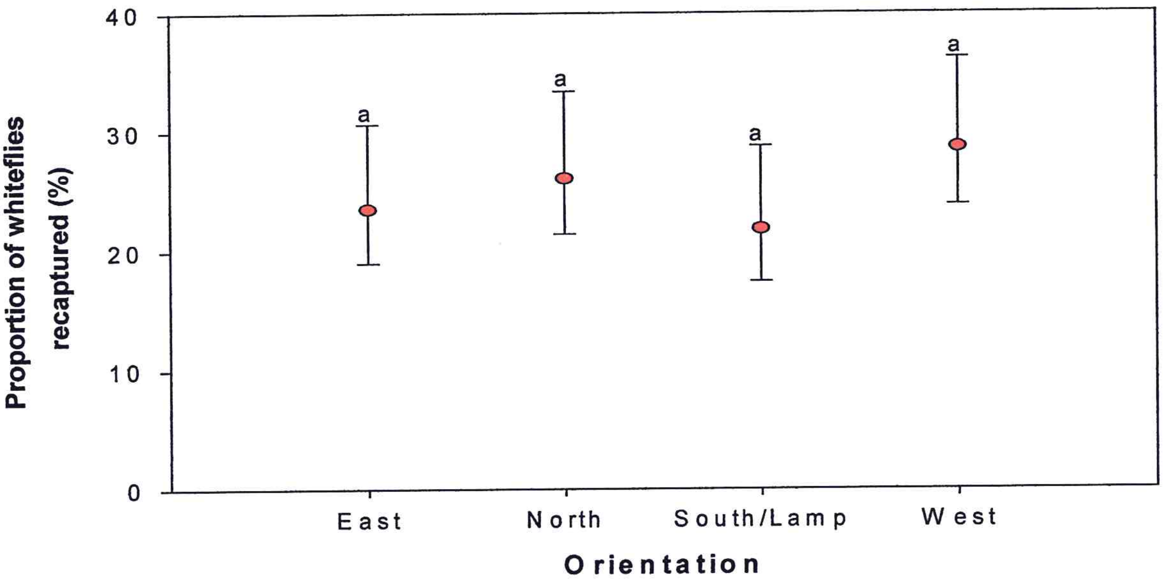

Figure 24: Proportion of recaptured *T. vaporariorum* (in mean % ± 95% confidence intervals) in plastic tunnels exposed to equal UV intensities (i.e. the UV lamp placed overhead the four tunnels). Means followed by the same letter are not significantly different (χ^2–test, $P < 0.05$).

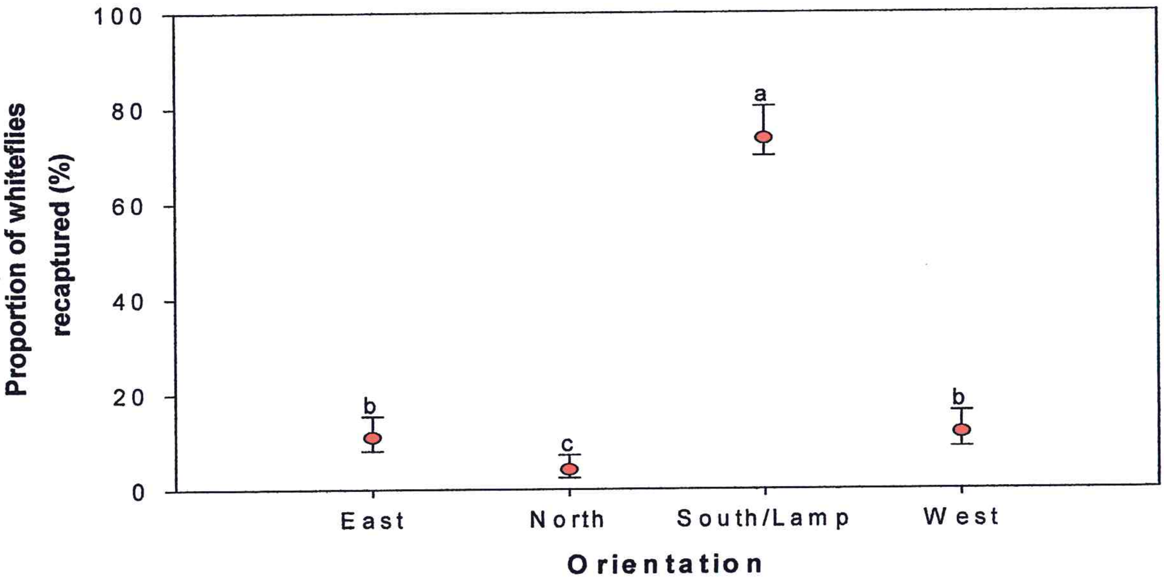

Figure 25: Proportion of recaptured *T. vaporariorum* (in mean % ± 95% confidence intervals) in plastic tunnels exposed to different UV intensities (i.e. the UV lamp placed over one end of the four tunnels). Means followed by the same letter are not significantly different (χ^2–test, $P < 0.05$).

5.4 Effect of UV-intensity on the penetration of *T. vaporariorum* into the tunnels

In the no-plants no-choice penetration experiments, variance homogeneity could be assumed, as the time of experimentation had no significant effect (F = 0.30; df = 3, 28; $P = 0.8251$). Consequently data of repetitions over time were pooled and analysed together. Mean temperature recorded inside Tlux-and KR-covered tunnels was 24.30 and 23.95°C, respectively, and 14.85°C outside the tunnels. Additionally mean RH recorded inside the tunnels during the experiments was 88.85 and 89.25% inside Tlux-and KR-covered tunnels, and 71.68% outside the tunnels, respectively. The temperature and RH recorded inside the tunnels differed significantly from those recorded outside the tunnels (temperature F = 11.51; df = 2, 9; $P = 0.0033$ and RH F = 8.81; df = 2, 9; $P = 0.0076$) (Table 5). Mean UVA recorded inside KR- and Tlux-covered tunnels differed significantly (F = 73.97; df = 1, 6; $P < 0.0001$), while the mean intensity of global radiation inside and outside Tlux-covered tunnels was not significantly different (F = 2.21; df = 1, 6; $P < 0.1878$) (Table 5).

Whitefly distribution differed significantly between both materials at all distances recorded ($\chi^2 = 34.17$; $P < 0.0001$) (Fig. 26). Independent of the plastic material trap catches varied significantly with position with the significantly highest proportion recorded in the trap nearest to the release point (Tlux $\chi^2 = 755.84$; $P < 0.0001$), and KR ($\chi^2 = 1268.73$; $P < 0.0001$). The proportion of whiteflies recorded on the first yellow sticky trap (positioned 0.6 m from the insect release point) differed significantly between the two plastic film types ($\chi^2 = 21.06$; $P < 0.0001$), with almost 10% more whiteflies recorded in KR compared to Tlux tunnels. Moreover, the proportion of whiteflies recorded on the yellow sticky trap furthest away from the insect release point (i.e., at a distance of 2.4 m) in the Tlux tunnel (5.89%) was significantly higher (and more than ten times higher) than that recorded in the KR tunnel (0.52%) ($\chi^2 = 21.06$; $P < 0.0001$). However, there was no significant difference in the proportion of whiteflies recorded on the yellow sticky trap positioned at 1.2 m ($\chi^2 = 2.41$; $P < 0.15$) and 1.8 m ($\chi^2 = 0.47$; $P = 0.49$) from the insect release point.

Table 5: Mean (± SE) temperature, RH, intensity of UVA and global radiation intensity recorded inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during the no-choice experiments without plants at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

Location of sensor	**Temperature (°C)**	**RH (%)**	**UVA (W/m^2)**	**Global radiation (W/m^2)**
Thermilux	24.30 ± 1.82 a	85.85 ± 1.93 a	3.45 ± 0.40 a	215.70 ± 19.13 a
K-Rose	23.95 ± 1.76 a	89.25 ± 1.04 a	0.54 ± 0.01 b	nr[2]
Out[1]	14.83 ± 1.04 b	71.68 ± 4.97 b	nr	265.79 ± 27.73 a

Note: Means in the same column followed by the same letter do not differ significantly at α=0.05 (Tukey test).

[1] outside the tunnels

[2] parameter was not recorded

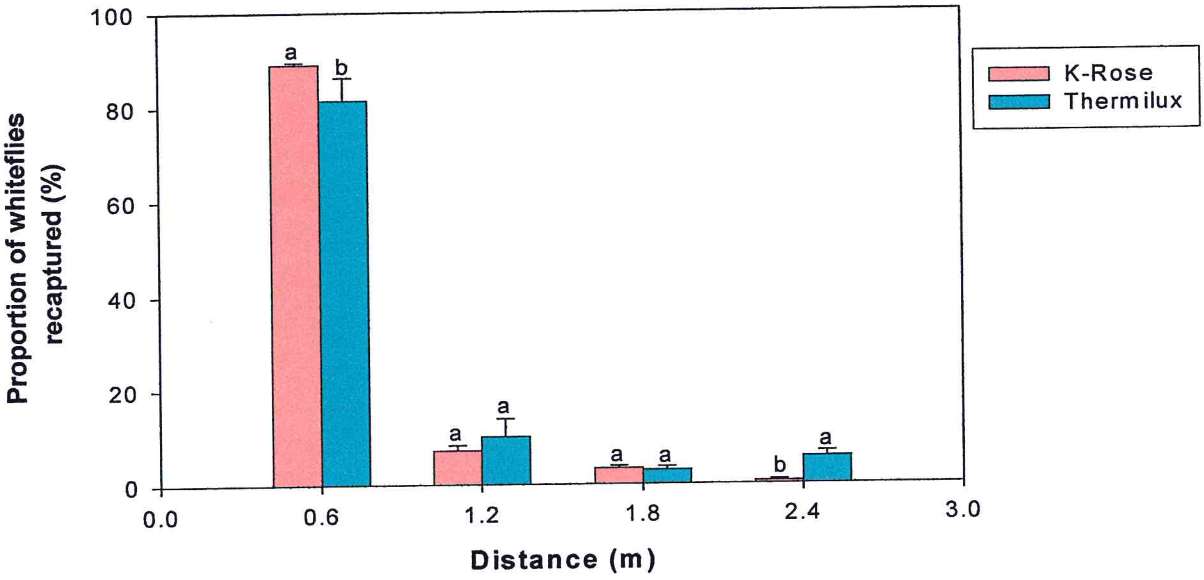

Figure 26: Proportion of recaptured *T. vaporariorum* (in mean % ± SE) on yellow sticky traps inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during no choice experiments without plants. Traps were positioned at increasing distance from the insect release point. Means for the same distance followed by the same letter are not significantly different at α = 0.05 (χ^2–test).

In no-choice experiments when both plants and yellow sticky traps were used to monitor whitefly penetration, variance homogeneity could be assumed, as the time of experimentation had no significant effect (F = 0.49; df = 4, 75; $P = 0.75$). Consequently data of repetitions over time were pooled and analysed together. The total proportion of whiteflies recaptured inside tunnels did not differ significantly between Tlux and KR tunnels ($\chi^2 = 2.67$; $P = 0.11$).

In Tlux-covered tunnels, the total proportion of whiteflies recorded on plants (23.63%) and traps (76.38%) differed significantly ($\chi^2 = 222.61$; $P < 0.0001$) (Fig. 27). Moreover, inside Tlux-covered tunnels the recapture rate differed with the position of the traps ($\chi^2 = 1108.13$; $P < 0.0001$). The highest recapture rate was recorded at position one, then decreased for two and three, and interestingly at position four there was a slight increase.

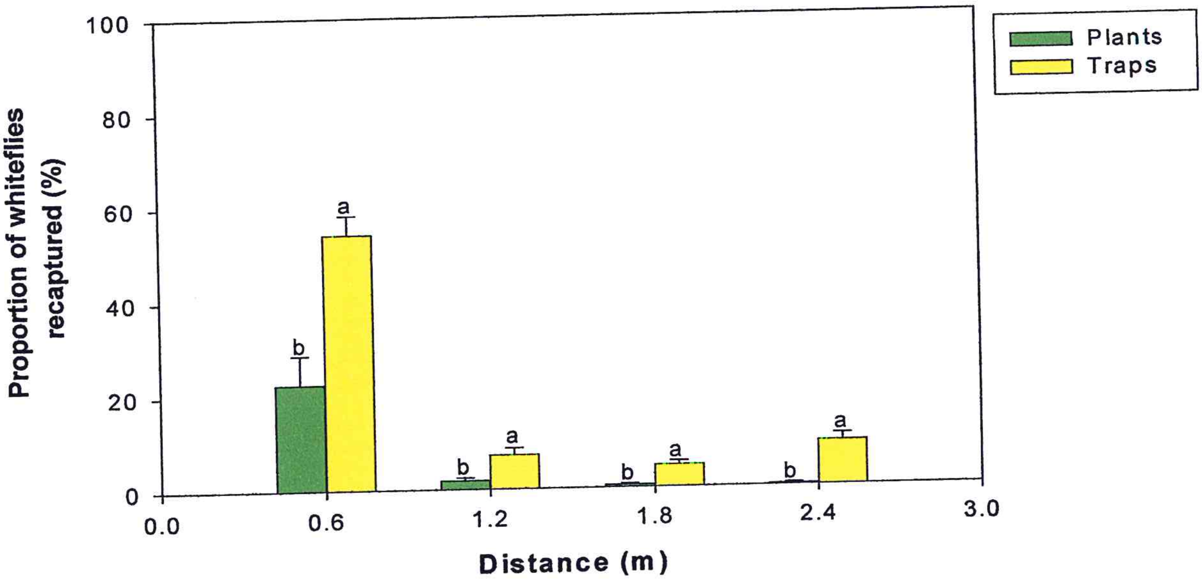

Figure 27: Proportion of recaptured *T. vaporariorum* (in mean % ± SE) on both plants and yellow sticky traps inside the Thermilux-(UV-transmitting) covered tunnels during no choice experiments with plants. Traps and tobacco plants were positioned at increasing distance from the insect release point. Means for the same distance followed by the same letter are not significantly different at $\alpha = 0.05$ (χ^2–test).

In KR-covered tunnels, the total proportion of whiteflies recorded on plants (21.48%) and traps (78.52%) differed significantly ($\chi^2 = 281.79$; $P < 0.0001$) (Fig. 28). Like in Tlux always significantly higher proportions of recaptured *T. vaporariorum* were recorded on the traps compared to the plants. No whiteflies were observed on plants positioned at 1.8 and 2.4 m from the insect release point while on the corresponding traps few whiteflies were recorded (Fig. 28). The highest recapture rate was recorded on the yellow trap at position one, then decreased for two, three and four. In addition, results from reflectivity measurements revealed that yellow sticky traps reflected considerably more UV than a fresh tobacco leaf when measured with the UV/VIS/NIR spectrophotometer (Fig. 29).

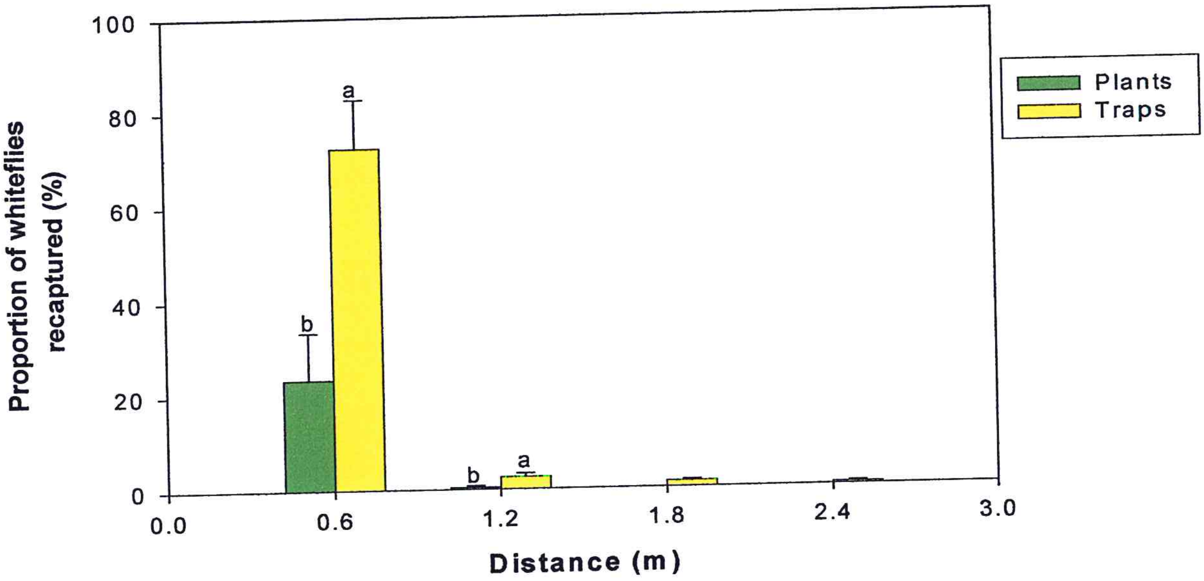

Figure 28: Proportion of recaptured *T. vaporariorum* (in mean % ± SE) on both plants and yellow sticky traps inside the K-Rose-(UV-absorbing) covered tunnels during no-choice experiments with plants. Traps and tobacco plants were positioned at increasing distance from the insect release point. Means for the same distance followed by the same letter are not significantly different at $\alpha = 0.05$ (χ^2–test).

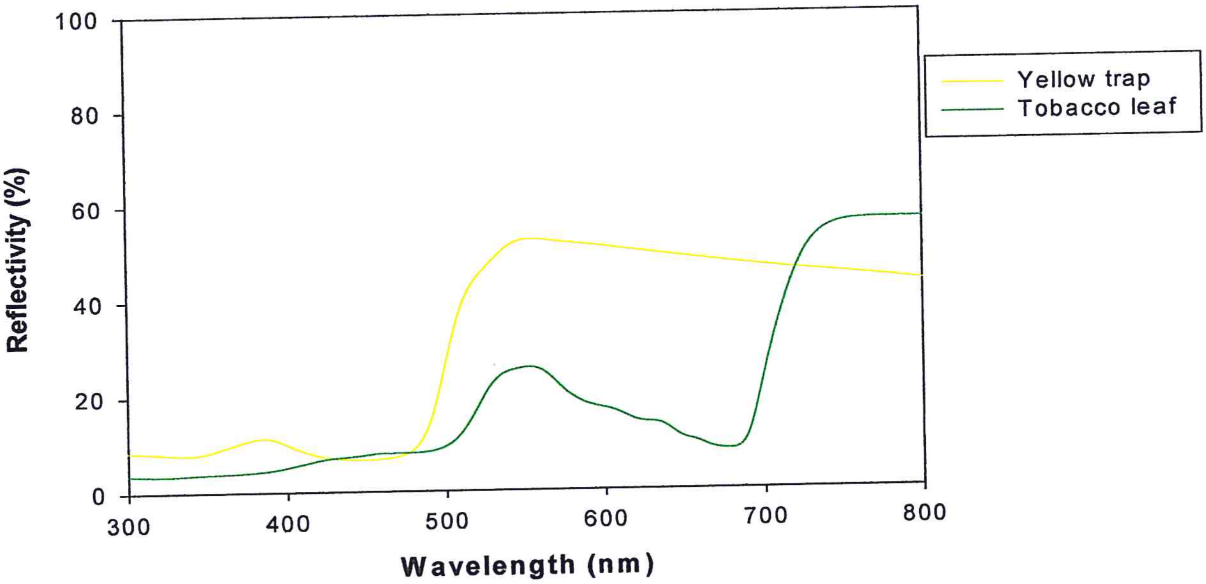

Figure 29: Reflectivity of a yellow sticky trap and a fresh tobacco (*Nicotiana tabacum cv Xanthi*) leaf measured with a Perkin-Elmer Lambda 900 UV/VIS/NIR spectrophotometer (Perkin-Elmer Instruments, Norwalk, USA).

5.5 Effect of UV-intensity on the dispersion of *T. vaporariorum* inside Thermilux- and K-Rose- covered tunnels (no-choice experiment)

Variance homogeneity could be assumed, as the time of experimentation had no significant effect (F = 1.60; df = 3, 28; $P = 0.21$). Consequently data of repetitions over time were pooled and analysed together. In both Tlux- and KR-covered tunnels significantly higher proportions of whiteflies were recorded on traps in the internal compared to the external circles (Tlux: $\chi^2 = 94.42$; $P < 0.0001$ and KR: $\chi^2 = 341.53$; $P < 0.0001$), and the total proportion of whiteflies recaptured did not differ between Tlux and KR-covered tunnels ($\chi^2 = 0.99$; $P < 0.31$) (Fig. 30). With 53.4 compared to 46.6% a significantly higher proportion of recaptured whiteflies was recorded on traps inside KR- than in Tlux-covered tunnels, respectively, in the internal circle (diameter = 1.0 m) ($\chi^2 = 8.69$; $P = 0.0032$). However, on traps in the external circle (diameter = 2.0 m) a significantly higher proportion was detected on traps in Tlux-covered tunnels (60.7%) than in KR-covered tunnels (39.3%) ($\chi^2 = 38.47$; $P < 0.0001$).

RH, temperature and global radiation recorded outside and inside the tunnels did not differ significantly (Table 6). However, mean intensity of UVA recorded differed significantly between the inside and the outside of the tunnels. Mean temperature during the experiments was 19.92 and 20.37°C inside the Tlux-and KR-covered tunnels respectively, and 16.55°C outside the tunnels.

Table 6: Mean (± SE) temperature, RH, intensity of UVA and global radiation intensity recorded inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during the no-choice dispersion experiments at the Institute of Horticultural and Agricultural Engineering in Hannover (52° N), Germany.

Location of sensor	**Temperature (°C)**	**RH (%)**	**UVA (W/m^2)**	**Global radiation (W/m^2)**
Thermilux	19.92 ± 1.09 a	95.29 ± 1.96 a	2.07 ± 0.56 ab	147.70 ± 51.55 a
K-Rose	20.37 ± 1.37 a	92.39 ± 2.75 a	0.04 ± 0.01 b	150.17 ± 50.09 a
Out	16.55 ± 0.35 a	80.83 ± 6.61 a	4.05 ± 1.34 a	206.54 ± 67.15 a

Note: Means in the same column followed by the same letter do not differ significantly at α=0.05 (Tukey test).

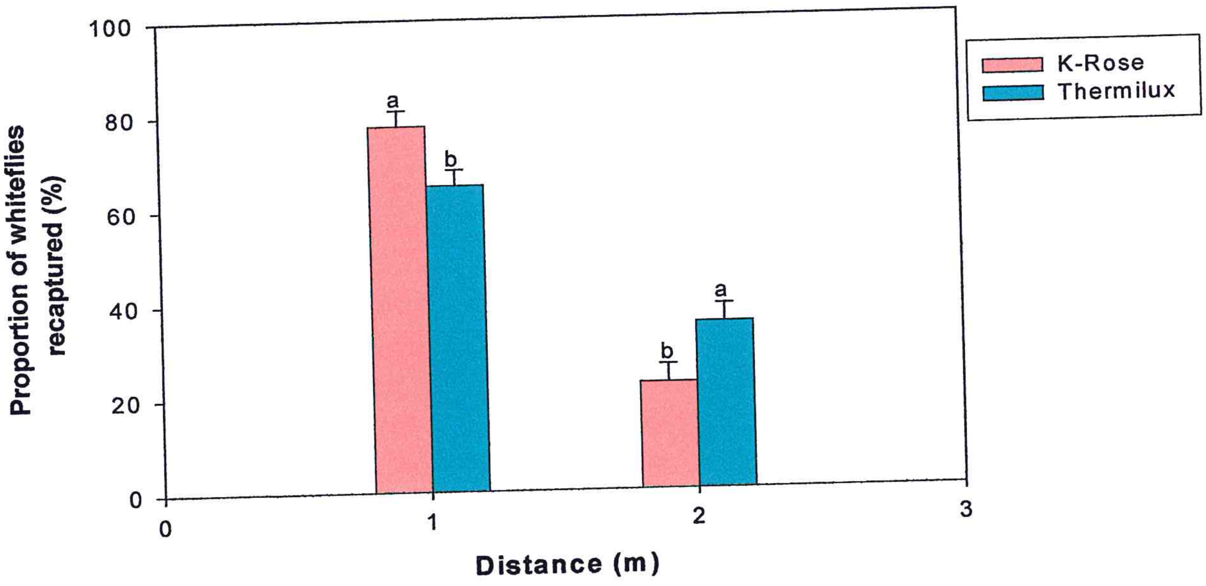

Figure 30: Proportion of recaptured *T. vaporariorum* (in mean % ± SE) on yellow sticky traps inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during no-choice dispersion experiments. Means for the same distance followed by the same letter are not significantly different at $\alpha = 0.05$ (χ^2–test).

6 DISCUSSION

The plastic films used in this study had similar transmission characteristics for PAR and NIR, but differed significantly in terms of UV-transmission. This resulted in significant differences in the quality and quantity of light (specifically the intensity of UVA) inside tunnels covered with the different plastic films but did not significantly affect other climatic parameters like temperature, RH and the intensity of global radiation. Although the transmitted energy (different wavelengths) was absorbed by the surfaces inside the tunnels, thereby heating them up, it resulted in very small differences in temperature. The heat load depends only on the overall energy transmittance and not on the different spectral characteristics of the films (VON ELSNER & XIE, 2003). While the two plastic films had different hydrophobic behaviours, with Tlux and KR exhibiting drop-wise and film-wise condensations, respectively, the RH level and intensity of global radiation inside the tunnels was not significantly affected. In large greenhouses, drop-wise condensation reduces the amount of light transmitted through the cover material (GBIORCZYK, 2003). Tlux-covered tunnels were slightly cooler and had slightly higher RH than the KR-covered ones, probably due to the longer duration required for the water droplets to accumulate and fall down as compared to that required for a water film to drip down (GBIORCZYK, 2003). The tunnels were not ventilated, and consequently on some days very high temperatures were recorded inside them. This affected the numbers of whiteflies recaptured but not the distribution pattern of *T. vaporariorum*. The spectral transmissivity of the films remained quite stable even though there was a slight change in spectral transmissivity of Tlux one year after tunnel construction. This might have been caused by the activation of UV additives incorporated in the films during manufacture to protect them from photo-degradation (B. VON ELSNER, ITG, personal communication).

The results obtained from this study show that modifying the greenhouse light environment by the use of UV-absorbing plastic films leads to both reduced infestations and colonization of the greenhouse crops by *T. vaporariorum*. This can be attributed to the elimination of UV light in specific wavelengths inside KR-covered tunnels as shown in Figs. 9, 10, 17 & 18 and tables 2, 4, 5 & 6. There was a significant difference in immigration rate of *T. vaporariorum* when given a choice of tunnels covered with UV-absorbing or UV-transmitting plastic films. *T. vaporariorum* showed a consistent and distinct preference for the tunnels rich in UV. As climatic parameters did not differ inside the tunnels of the two materials, the observed differences in colonisation pattern must have been caused by the varying intensities of UV. Additionally, light reflected from yellow surfaces is to a certain degree polarised. Since insects detect polarised light in the UV (ANONYMOUS, 2004 b), the observed differences in whitefly colonisation might have been a reaction to polarised light (KRING, 1969). Previous research reported a reduction in the infestation of vegetables crops grown under UV-absorbing plastic films by *B. tabaci*, *F. occidentalis* and *A. gossypii* (ANTIGNUS et al., 1996; COSTA et al., 2002). The exact mechanisms here fore are unknown but it is presumed that reduced pest infestation levels results from interference with visual cues and/or behavioural responses to UV light (ANTIGNUS et al., 1996).

This wavelength-dependent behaviour of insects is driven by several different spectral classes of receptors and has been described in detail in several insect species (MENZEL & BACKHAUS, 1991). MOUND (1962) reported that *B. tabaci* is attracted to blue/UV and yellow sections of the spectrum, hence postulated that UV results in a strong stimulus for whiteflies to fly towards the sky (migratory behaviour), while yellow radiation induces a landing reaction (a component of host selection mechanism). Inside the KR-covered tunnels, UV light, which is according to MOUND (1962) the signal for migratory behaviour, is missing. Thus in choice experiments, whiteflies did not immigrate into these tunnels but rather chose the UV rich tunnels where the migration signal was present, hence confirming MOUNDS' (1962) hypothesis. It is possible that the small differences in the number of whiteflies recorded in tunnels covered with the same material were due to the cardinal position of the tunnel, i.e., an effect of orientation. The tunnels on the east and south received slightly more intense illumination from the sun in the early morning hours, thus attracting slightly more whiteflies than the other tunnels. On the other hand, in relation to the other tunnels the ones in the west received more illumination in the evening, but did not attract more whiteflies. *T. vaporariorum* flight activity peaks during the late morning and early afternoon hours (COHEN & MELAMED-MADJAR, 1978). In contrast to *T. vaporariorum*, in previous studies the absence of UV did not affect the visual ability and foraging efficiency of certain beneficial insects such as the bumblebee *Bombus terrestris,* Linnaeus (Hymenoptera: Apidae) which are often used to facilitate pollination of greenhouse crops (DYERS & CHITTKA, 2004). These authors tested individual bumblebees in an indoor flight arena to evaluate whether or not search time to find flowers (plastic model flowers with spectral properties similar to tomato flowers) was influenced by the inclusion or exclusion of UV. They observed that bumblebees perceived the inclusion and or exclusion of UV from an illuminating source, but rapidly learnt to find model flowers with an equal efficiency in either illumination environments.

The results from the greenhouse experiments using an artificial UV source are consistent with the observations from the choice experiments conducted in the field. When the UV lamp was positioned on one extreme end, resulting in different UV intensities inside the tunnels, the tunnel with the highest UV intensity attracted over 17 times more whiteflies than the UV-deficient tunnel. In the greenhouse experiments, the two signals, UV for migration and yellow (on the sticky traps) for landing, were present inside all tunnels. Therefore only differences in UV intensity could have caused the differences in whitefly distribution. However, in the greenhouse with the artificial UV source the intensity of UV influenced the main parameters of the colour (from a biological perspective) namely; hue (the dominant wavelength remitted by the surface), colour saturation (purity of the hue), and brightness (light intensity), hence the yellow sticky traps in the tunnel with the highest UV intensity appeared more attractive to the insects. When the lamp was positioned at equal distances from the tunnels (i.e. overhead), there was no difference in these parameters and consequently, no differences in whitefly attraction were recorded, corroborating earlier findings on colour vision in *T. vaporariorum* (MOUND, 1962; AFFEDLT et al., 1983). In addition, ANTIGNUS et al. (1996) studied whitefly behaviour under monochromatic UV light (254-366 nm) filtered through UV-absorbing and UV-transmitting plastic films and reported similar findings. Similar behavioural responses were observed by KRING (1969) studying the behaviour of the black bean aphid, *Aphis fabae* Scopoli, using a blacklight lamp with spectral emission similar to those of the lamp used in this study. However, in the honeybees, *A. mellifera*, colour vision is documented for the orientation towards visual targets in the immediate surrounding of potential and actual food sources and the entrance to the hive (BACKHAUS et al., 1987).

COSTA et al. (2002) reported insignificant differences between *T. vaporariorum* populations recorded under tunnels covered with either UV-absorbing or UV-transmitted plastic films. This discrepancy may have been caused by differences in experimental design. Completely enclosed tunnels were used in this study while COSTA et al. (2002) used tunnels with open sides. Although tunnels with open sides are well ventilated, UV light penetrates through the ventilation openings, thereby raising the UV intensity, resulting in insignificant differences in UV intensity inside tunnels covered with different plastic film types (TANTAU, ITG, personal communication). Moreover, as increasing wind speed inhibits *B. tabaci* from takingoff (ISAACS et al., 1999) it is possible that wind-induced drift affected whitefly flight behaviour. For instance these authors observed that a 20 cm/s wind speed significantly affected the visual stimulation of *B. tabaci* during takeoff.

In the no-choice experiments (both with and without plants), whitefly penetration and dispersion was higher in Tlux-covered tunnels. In these tunnels, both the migratory (UV) and landing (yellow) signals were present, while in the UV-absorbing tunnels only the landing signal was present. Inside the KR-covered tunnels, most whiteflies could only 'land' and not migrate. Hence the yellow sticky traps closest to the whitefly release point recorded a higher number of whiteflies as compared to traps at the same position inside the Tlux-covered tunnels. Yet inside the Tlux tunnels, some whiteflies chose to migrate while others preferred to land, resulting in comparatively lower and higher numbers of *T. vaporariorum* recorded on the first yellow sticky trap and the furthest away from the release point, respectively, as in the KR-covered tunnels. The same observation was made in the dispersion experiments in which fewer whiteflies were found on the yellow sticky traps on the external circle inside the KR-covered tunnels. ANTIGNUS et al. (2001) reported similar results and postulated that inside the UV-rich tunnels whiteflies move in a centrifugal manner away from the central release point towards the walls of the tunnel, as a result of the presence of the two 'contrasting' signals, thereby resulting in higher number of whiteflies on the external circle. In no choice experiments similar to the ones conducted in this study, COSTA & ROBB (1999) reported insignificant differences in the penetration ability of whiteflies inside UV-transmitting and UV-absorbing tunnels, and concluded that their was no obvious negative effect of UV-blocking plastic films on the ability of whiteflies to fly. A possible reason for these contradicting results might be differences in temperature. The small tunnels used by COSTA & ROBB'S (1999), 0.45 m^3 in volume compared to 22.5 m^3 in our study, possibly resulted in higher temperatures inside the tunnels thereby limiting whiteflies ability to fly, as observed in this study. Moreover, it is possible that the small size of the tunnels affected whitefly flight behaviour, due to lack of sufficient space for upward flight, an important aspect in their migratory behaviour ((ANTIGNUS et al., 2001; VAN LENTEREN & NOLDUS, 1990).

When plants were introduced, the general distribution of *T. vaporariorum* among plants and yellow sticky traps under both plastic types was similar. Similar to the studies without plants, whitefly penetration in KR-covered tunnels was limited. The fact that fewer whiteflies were found on plants inside KR-tunnels as compared to Tlux-covered tunnels might be an indication that the cover material influenced the appearance of the plants in the eyes of the insects. Vision behaviour of insect pests is closely linked to the sequence that begins with their orientation to the plant from a distance and ends with their establishment on plants for feeding and oviposition (ANTIGNUS, 2000), and it forms the central link in host plant selection and final landing (both appropriate and inappropriate) (FINCH & COLLIER, 2000). According to MENZEL & BACKHAUS (1991), a prerequisite of colour vision is the ability to discriminate between equally bright stimuli with respect to differences only in chromaticness (colourfulness). Thus the large numbers of whiteflies recorded on yellow sticky traps as compared to those on plants (under both types of plastic films) can be possibly attributed to differences in chromaticness between yellow sticky traps and the young tobacco plants. Furthermore, we recorded a stronger UV reflection from yellow sticky traps than from a green tobacco leaf, indicating that the former was more colourful than the latter. According to MOUND (1962), *B. tabaci* is attracted either to yellow or to UV but not to both at the same time. Thus from a distance, the reflected UV light elicited a migratory stimuli (COOMBE 1982) but the landing stimuli dominated. When the insects approached the source of the reflected light (yellow trap), a cessation of wing movement and a 'fall reflex' occurred as they flew over the yellow surface (MOERICKE et al., 1966) forcing them to land. Moreover the polarisation (as a result of reflection) of light on colours of surfaces influences their perception and may lead to the perception of false colours by insects (HORVATH et al., 2002). Besides, landing may have been provoked by the yellow sticky cards 'looming up' along the path of the flying insects (KENNEDY et al., 1961), as they were placed above the plants. According to FINCH & COLLIER (2000), during host plant finding, the searching insects land indiscriminately on host plants (appropriate landings) and non host plants (in appropriate landings), principally guided by visual stimuli. In addition, the growth stage of the plants can influence their attractiveness to the pests relative to yellow sticky cards (COSTA et al., 2002).

Results from this study have demonstrated the ability of UV-absorbing plastic films to reduce insect pest populations in greenhouses. The fact that similar results were also obtained in areas with higher intensities of UV (such as Israel and California) compared to Europe, and insignificant effect of time on the experiments (since different UV intensities recorded in different experiments did not affect whitefly distribution pattern) indicates that these UV-absorbing plastic films may provide this protection in greenhouses in any part of the world. The use of completely enclosed tunnels enabled the complete elimination of UV light in the

KR-covered tunnels and prevented wind from influencing whitefly flight (whitefly drift) inside the tunnels. Such completely enclosed tunnels are not practical but greenhouse designs may be improved to minimise UV intensities penetrating through the ventilation openings, for instance by extending the roof of the ventilation openings such that solar radiation does not directly enter the greenhouse without limiting air movement. The other option would be to position "trap" plants near the ventilation openings on which the insects can be chemically controlled without necessarily spraying the whole greenhouse. Otherwise these plastic films may be used in combination with screens to physically exclude the pests. A combination of UV-absorbing plastic covers and UV-absorbing insect screens (bionets) may provide adequate protection from insects.

Although the effect of UV on the survival and reproductive behaviour of whiteflies were not studied (and no information was found on literature) there is a possibility that these UV-absorbing plastic films might affect the development of insects. However, the possibility that *T. vaporariorum* develops 'resistance' to low UV environments by adapting its visual systems to conditions with less UV as in the case of bumblebees (DYERS & CHITTKA, 2004), and possible negative effects of lack of UV on certain greenhouse crops and certain beneficial organisms (e.g. *E. formosa*) can not be ruled out.

7 CONCLUSIONS AND RECOMMENDATIONS

Aphids, whiteflies and thrips are among the most important insect pests worldwide, and they are also vectors of many economically important viral diseases. Results of this study demonstrate that UV-absorbing plastic films have the ability of protecting greenhouse crops from infestation by *T. vaporariorum*, the most important whitefly species in European greenhouses. Slowing down pest immigration into the greenhouse leads to a low initial pest population density, which is the key to successful and effective control (XU et al., 1984). Furthermore starting with low initial whitefly population results in higher efficiency of parasitoids (KASSIS & MICHELAKIS, 1993). In addition to protecting crops from infestation by insect pests, other benefits that may be expected from the use of UV-absorbing plastic films include an increased performance of entomopathogenic fungi (COSTA et al., 2001) and baculoviruses (GOULSON et al., 2003), the management of certain fungal diseases (ELAD, 1997; REUVENI & RAVIV, 1992, 1997), and protecting crops from insect-transmitted viral diseases (ANTIGNUS, 2000). Moreover, the use of these UV-absorbing plastic films does not affect the foraging efficiency of beneficial organisms such as the bumblebee, *B. terrestris*, an important pollinator of greenhouse crops (DYERS & CHITTKA, 2004), and the greenhouse temperature.

The exact mechanism of insect reduction in greenhouses covered with UV-absorbing plastic films is unknown. However, it is presumed that reduced pest infestation levels result from interference with visual cues and/or behavioural responses of insect pests to UV light (ANTIGNUS, 2000). Interfering in the host selection process of the insect pests enables crop protection in two ways:

- Reducing immigration rates from the field into the greenhouse and
- Slowing down the dispersion and distribution of the pests once inside the greenhouse.

Theses results in reduced infestations, and hence would allow reducing or even avoiding application of insecticides. Possibly such an approach can also be combined with mass releases of natural enemies, though effects of UV-absorbing plastic films on beneficials like *E. formosa* would first need to be tested. The orientation of the greenhouses appears to be an important factor in determining the level of protection from these UV-absorbing plastic films.

The possibility of developing a UV lamp to trap *T. vaporariorum* in greenhouses should be further studied.

The incorporation of UV-absorbing plastic films in integrated pest management programs is therefore recommended in both regions with high (tropical) and low (temperate) UV intensities.

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9 APPENDIX

Effect of UV intensity on the penetration of greenhouse whitefly

A no-choice, release and re-capture experiment was conducted in June 2004. Four tunnels, each measuring 3 m in length and width and 2.5 m in height, were constructed in an east-west orientation (Fig. 5). Two tunnels were covered with KR and Tlux plastic films, respectively. Each Tlux-covered tunnel was placed opposite to a KR-covered tunnel. Inside the tunnels were positioned at 1.2, 1.8 and 2.4 m from the tunnel entrance. The yellow sticky traps were placed at a height of 0.25 m above the ground. At the beginning of each experiment, 200 whiteflies shall be released from the tunnel entrance and the door closed. Counting the number of insects trapped on the yellow sticky traps monitored whitefly penetration. The experiment was run for four hours (from 7.30 am to 11.30 am) and was repeated four times.

Results

There was a significant interaction between material and distance ($\chi^2 = 40.82$; df = 1, 2; $P > 0.0001$). Thus comparison between the two materials was done at each distance. The number of whiteflies recaptured on the first and last yellow sticky card (positioned 1.2 and 2.4 m) inside Tlux and KR-covered tunnels differed significantly ($\chi^2 = 22.31$; df = 1; $P > 0.0001$ and $\chi^2 = 25.95$; df = 1; $P > 0.0001$, for the first and last yellow sticky cards, respectively). On the first yellow sticky trap, more whiteflies were recorded inside KR as compared to Tlux, while the converse was true for the third yellow sticky trap. There was no significant difference in the number of whiteflies recorded on the second yellow sticky card (positioned 1.8 m) ($\chi^2 = 0.05$; df = 1; $P > 0.81$).Whitefly penetration inside the KR-covered tunnels was limited as only 4.8% of the total number of whiteflies were recorded on the last yellow sticky trap as compared to 12.3% recorded inside Tlux-covered tunnels.

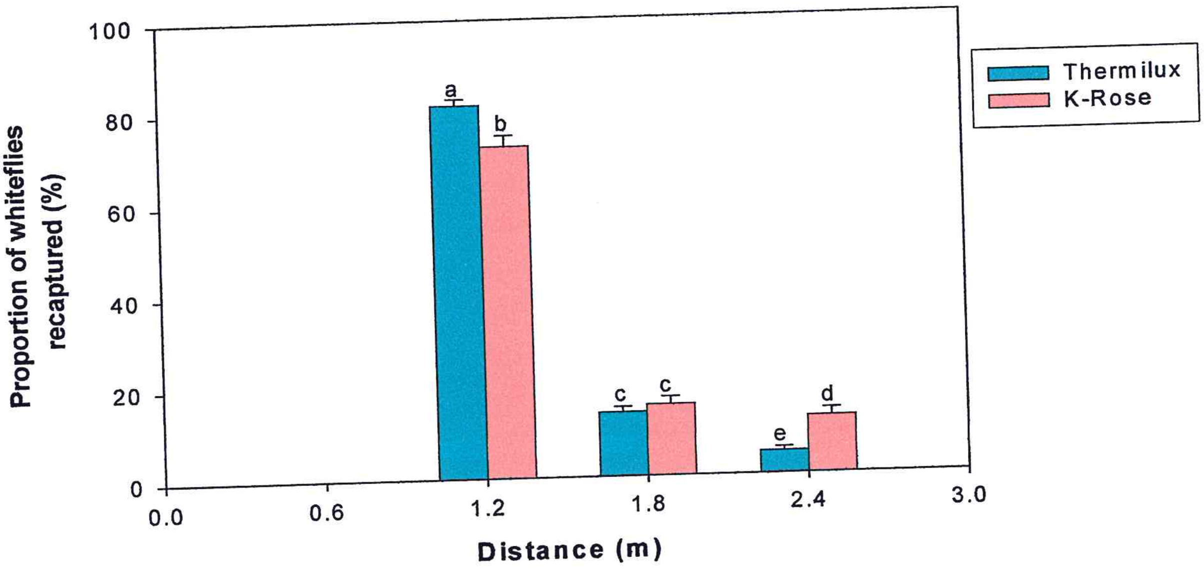

Figure 31: Proportion of recaptured *T. vaporariorum* (in mean % ± SE) on yellow sticky traps inside the Thermilux-(UV-transmitting) and K-Rose-(UV-absorbing) covered tunnels during no choice experiments without plants in June 2004. Traps were positioned at increasing distance from the insect release point. Means for the same distance followed by the same letter are not significantly different at $\alpha = 0.05$ (χ^2 - test).

VITA

Urbanus N. Mutwiwa was born on 24th May 1972 in Machakos, Kenya. He attended Tusunini primary school (1978-1986) and Pope Paul VI Junior Seminary (1987-1990), before joining Jomo Kenyatta University of Agriculture and Technology, JKUAT, Nairobi, Kenya (1991-1996), where he was awarded BSc. in Agricultural Engineering degree. He briefly worked for Booth Irrigation Ltd, Nairobi, Kenya, as an Irrigation Engineer (1997-1998) and later as a coffee estate manager for Sasini Tea and Coffee Limited in the same location. He joined the University of Hannover in August 2002 to pursue a MSc. degree in International Horticulture (Major in Horticultural and Agricultural Engineering). He submitted a thesis entitled "Effects of UV-absorbing plastic films on the behaviour of the greenhouse whitefly" in September 2004. During his stay in Germany, he gained hands-on international business exposure by working for Tchibo FrischRöst Kaffee GmbH, Hamburg, Germany, as an intern (March 2003) and participating in an intensive course in horticultural chains (CHAINS-it 2004), administered by Wageningen University in the University of Angers, France.

DECLARATION

I, the undersigned, declare that this thesis, entitled **“Effects of UV-absorbing plastic films on the behaviour of the greenhouse whitefly”** is an original piece of work conducted by myself and has never been submitted elsewhere.

Hannover, 17th September 2004

Urbanus Ndungwa Mutwiwa