Methods

High intensity UV-B and UV-A radiation from plasma-based sources

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Introduction

Ceravision is a privately owned SME specialising in lighting systems based on high-pressure electrodeless discharges. In particular, it concentrates on sources for the generation of UV-A and UV-B radiation. These were developed primarily as light sources for supplementary lighting in greenhouses and grow-rooms. This work has contributed to a more wide ranging interest in lighting for horticulture.

Plants grown outdoors are subjected to varying amounts of both UV-A (315 to 400 nm) and UV-B (280 to 315 nm) depending on geographical location and time of the year. It has been known for a long time that radiation in the range 280 to 550 nm (i.e. UV-A, UV-B and blue light) is important to the growth and development of plants (Schäfer and Nagy 2006). There is solid evidence indicating that UV-A and UV-B radiation perceived through UVR8 and cryptochrome photoreceptors drives photomorphogenic plant responses including gene regulation, flavonoid biosynthesis, leaf and epidermal cell expansion, stomatal density, and increased photosynthetic efficiency (Bornman et al. 2019). Exposure to UV radiation may also induce the synthesis of specific proteins involved in resistance to microbial attack. However, unnatural ratios between irradiance in different bands of the spectrum can result in disturbances to plant growth and even damage, making the spectral quality of radiation an important factor in the use of artificial light in plant cultivation (Bornman et al. 2019).

The term 'high-pressure electrodeless discharges' will most likely not be familiar to those outside the lighting industry and so this article will outline the fundamental principles of conventional high-pressure discharge lamps, i.e. those with electrodes, before giving an overview of electrodeless high-pressure discharge light sources. This article reviews the technology behind

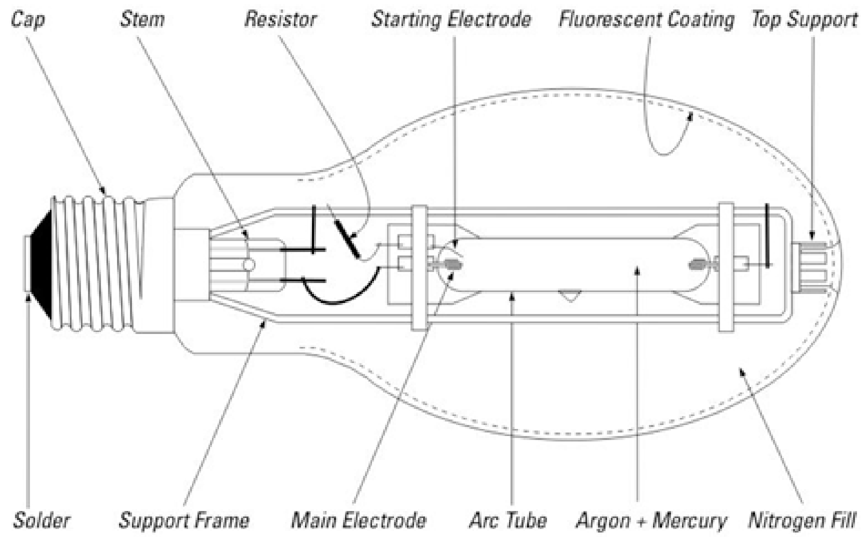

Figure 8.1: Diagram of a typical high-pressure mercury lamp. Image source: http://lamptech.co.uk/. Reproduced by permission.

plasma light sources and the advantages of their use in horticulture compared to other types of discharge lamps. Ceravision's research and development programs on the use of UV radiation in horticulture are briefly presented. The article concludes with a description of the Company's recent initiatives with its research collaborators in the UK and Europe. We have previously drawn the lighting industry's attention to the importance of UV radiation for plants (Stocks and Mucklejohn 2019) and here we aim to draw the attention of the plant science community on our novel UV-lighting technologies.

High-intensity discharge lamps

High-pressure discharge lamps, commonly known as high intensity discharge (HID) lamps, were until recently the mainstay of street and road lighting until they began to be replaced by LED sources. The characteristic golden-white colour appearance of the high-pressure sodium (HPS) lamp is still widespread in road lighting and exterior floodlighting throughout much of Europe. In recent years the HPS lamps' highest-growth application has been for horticultural lighting in greenhouses and grow-rooms. The various parts of a typical HID lamp are shown in a diagram (Figure 8.1) while photographs of many different types of lamps can be found at http://lamptech.co.uk/.

High-pressure discharges are those with operating pressures >100 000 Pa

(>1 atm) whereas low-pressure discharges, such as linear and compact fluorescent lamps, typically have operating pressures <1000 Pa. High-pressure discharges are considered to be in local thermodynamic equilibrium which means the composition of the discharge can be calculated from the thermodynamic properties of the chemical species present. Low-pressure discharges are not in local thermodynamic equilibrium. The first generation of HID lamps was based on mercury discharges, such lamps are no longer permitted to be placed on the market for general lighting purposes in most countries because of their low efficiency. However, these lamps are permitted for specialist applications such as the generation of UV radiation.

Addition of various metal halides to the mercury discharge provided lamps with higher efficiency and better colour rendering properties. The first generations of metal halide lamps had arctubes fabricated from fused silica. The main disadvantages were the relatively poor maintenance of the light output and colour changes through life. Reactions of the metal halides, especially the alkali metal and lanthanide halides, with the fused silica arctube restricted life and performance. The launch of metal halide lamps with ceramic arctubes from the mid-1990s onwards addressed many of the limitations of the earlier generations.

High-pressure sodium (HPS) lamps first became commercially available in the 1960s and have since undergone a series of improvements and adaptations. They are efficient, low cost and highly reliable. They are very effective at producing photosynthetically active radiation (PAR) due to the broadened sodium D-line emissions over the range 500 to 700 nm.

HID lamps are operated with an ignitor to initiate the discharge and a ballast to control the current. The original copper-iron ballasts are increasingly being replaced by electronic control gear (ECG) which also provides the starting mechanism.

Electrodeless high-intensity discharge lamps

Electrodeless HID lamps (also known as high-intensity plasma lamps), as the name suggests are discharge lamps which have no internal electrodes. The lack of electrodes confers a number of benefits when compared with electroded discharges. The constraints on arctube geometry are different. Lamp survival factors are extended because the economic life of regular discharge lamps is generally controlled by the life of the electrodes. Thirdly, there is greater freedom of choice for the chemical composition of the discharge atmosphere, which again in conventional discharge lamps is limited by reactions involving the electrode systems. At high temperature, halogens readily react with tungsten, the metal most commonly used for electrodes, thus metal halide discharge lamps are restricted to using iodides other than for high performance, short life lamps.

Apart from the electrodes, the two types of discharges produce light using the same mechanisms, i.e. from thermally excited atomic and molecular transitions. Commercially available lamps operate in the microwave region (frequency range 300 MHz to 300 GHz) and are driven from a resonant structure integral with the arctube. The use of microwaves implies the need for either a magnetron or solid state microwave oscillator. These devices have the drawback of either lower efficiency than the ballasts for regular discharges or in the case of solid state devices, until very recently, much higher cost. These disadvantages have to be offset by improved performance from the discharge.

For both electrodeless and electroded discharges the discharge volume tends to consist of a cylindrical or approximately cylindrical geometry. This has implications for the light generating mechanism. In the case of electroded lamps the power is dissipated on the axis of the discharge. In the case of an electrodeless discharge, microwaves penetrate the discharge space from the arctube wall to the skin depth of the discharge. This can lead to very different temperature profiles within the discharge that can lead to different emission characteristics. These manifest themselves as differences in the relative amounts of thermal atomic and molecular emissions.

Ceravision's UV420 luminaire

The Ceravision UV420 luminaire (Figure 8.2) was developed to supplement photosynthetically active radiation (PAR) lighting in greenhouses and growrooms. In many commercial installations 1000 W HPS lamps are the light source of choice. This source produces the PAR efficiently but the spectral power distribution (SPD) is heavily weighted towards the red end of the visible spectrum, there is relatively little radiation emitted below 550 nm. Most greenhouse glasses do not transmit UV-B radiation and hence plants grown under such conditions do not benefit from this stimulus. The UV420 luminaire is specifically designed to provide UV-B, UV-A and blue (400 to 500 nm) radiation.

When selecting the metal halides best suited to providing UV-B and UV-A radiation, metals with strong emission lines in the 280 to 550 nm range can be selected from well-established collections of atomic electronic energy levels such as those compiled by NIST (Sansonetti 2003) or held in the Kurucz database (Smith et al. 1995). For example, thallium halides would be selected if intense radiation were required in the region centred on 535 nm and indium halides would be used to generate intense radiation centred on 410 and 455 nm.

To obtain radiation throughout the 280 to 550 nm region, a combination of atomic and molecular radiation is essential if elements outside of Groups 4 to 12 (the Transition Metals) are used. The emission and absorption properties of many diatomic metal halides are not well characterised. A survey of some such molecules contained in the NIST Chemistry WebBook (Linstrom 1997)

Figure 8.2: The Ceravision UV420 luminaire. left: detail, right: in use over industrial hemp.

shows that the molecular constants for many species of interest are subject to large uncertainties or are not listed. The data available do, however, allow calculation of the approximate wavelengths emitted for transitions from the first excited state to the ground state. The intensity of radiation emitted cannot be predicted without the temperature and wavelength variations of the net emission coefficients. These parameters are reported for very few diatomic metal halides and thus experimentation has proved to be the best approach to determine the contributions of various diatomic molecules to the overall optical emission. Gnybida et al. (2014) describe in detail the calculation of the local emission and absorption coefficients for a molecular transition.

Unsaturated arctubes, i.e. those in which the metal halides and mercury are fully evaporated, provide the most resilience to changes in SPD with input power. Thus, component volatility and dose composition are important selection criteria. The SPD can be tailored to application specific requirements by careful selection of the metals, halides and concentrations.

The ratio of output from the UV420 luminaire between 280 to 550 nm compared to 280 to 1100 nm is >0.70. A typical value for this ratio in a 150 W ceramic metal halide (CMH) lamp (saturated dose conditions) with correlated colour temperature 4000 K would be ≈0.35 (Guest et al. 2008).

The output from the UV420 can be modified by changing the glass filters: figure 8.3 shows the relative SPD with filters which give the maximum UV-B (lower panel), intermediate UV-B (middle panel) and low UV-B (upper panel) output, respectively.

Specialist knowledge is essential to select the most appropriate material for the reflector and the glass filters as most materials commonly used in the lighting industry are intended for visible light, and steps are taken to prevent emissions in the UV range. A soda lime glass filter is suitable for absorbing most UV-B radiation from the light source whereas a borosilicate glass with high UV-B transmission is used to provide the maximum UV-B output. A borosilicate glass filter of a different composition is selected to provide intermediate levels of UV-B radiation.

Horticultural trials with Ceravision's UV420 luminaire

Andrew Fuller and his team at the Bridge Farm Group have conducted a series of trials exposing strains of industrial hemp, rosemary and lavender to UV-A and UV-B radiation. UV420 luminaires (Ceravision, Milton Keynes, UK) were used to supplement the lighting provided by high-pressure sodium lamps at selected stages towards the end of the plants' growing cycle, prior to harvest. The plants exposed to UV showed a significant increase in the yield of essential oils, i.e. the terpenes and flavonoids that are responsible for flavour and aroma, compared to the controls which were not exposed to UV radiation. In most crops the payback to the grower depends on the yield of specific components of plant biomass rather than on total biomass yield. This is most obvious when produce is used as raw material for extraction of various compounds including vegetable oil, protein or different essential oils. In an interview with Shane Torpey (MIGRO, a supplier of LED luminaires, https://www.migrolight.com/about/), Andrew Fuller explains the advantages of enhancing the production of essential oils from plants from a producer's viewpoint, while recognizing the need for further research, see 'Using UV to increase CBD in UK Industrial Hemp Facility' in https://www.youtube.com/watch?v=n765oOU_MMo.

The initial trials have shown, as could be expected, complex responses of plants to different UV wavelength ranges and intensity. More work is required to better tune the treatments for different plant cultivars and species and desired target plant responses. However, relatively low-energy UV and blue radiation inputs can deliver a large improvement in the yield of certain terpenes and flavonoids of commercial interest. Management of the radiation spectrum can enable growers' control over the quality of their final product and have great potential for the future'. Studies using different luminaires have also shown that exposure to UV-B radiation can be accompanied by a reduction in the incidence of grey mould, *Botrytis cinerea* (Costa et al. 2013;

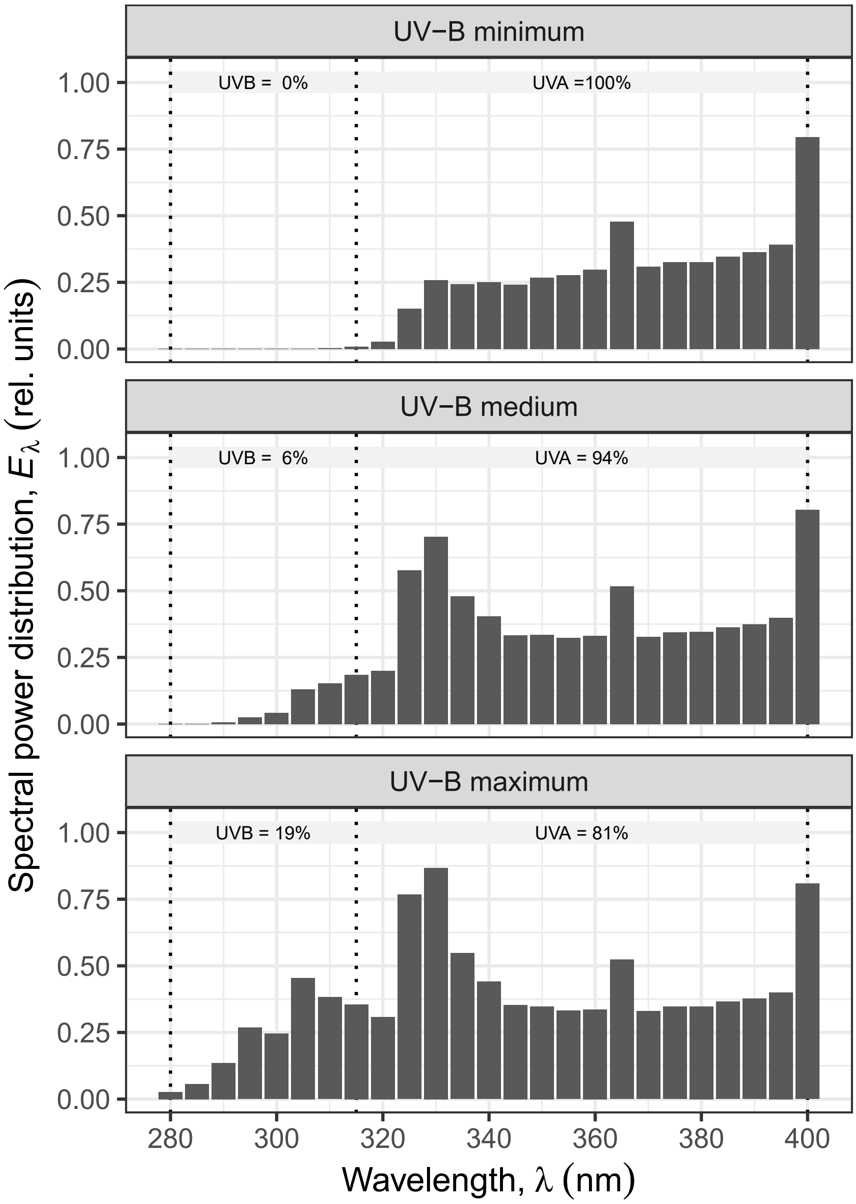

Figure 8.3: Spectral power distribution (SPD) of the UV420 luminaire fitted with three different long-pass filters. The relative units shown are energy based, i.e., the plots only describe the shape of the spectra, while spectral irradiance in absolute units ($\mathrm{W\,m^{-2}\,nm^{-1}}$) will depend on the distance to the lamp, which varies among use cases.

Heuvelink 2006).

When using light sources of any type in the workplace, employers must comply with the applicable national regulations. Within EU countries these regulations would have been derived from the Directive regarding the exposure of workers to risks arising from artificial optical radiation (EU 2006). In particular, exposure of personnel to UV radiation should be strictly controlled with eye and skin protection used.

Estimating irradiance from the sun

To help growers estimate suitable values of exposure to UV-A and UV-B for plants grown indoors it is vital to have realistic values for the irradiances that are encountered by plants in their natural growing environment. A possible target for the research and growing communities might be to replicate the complete solar spectrum at a given location on the Earth's surface. Thus, by knowing the lighting conditions where plants naturally flourish, artificial lighting installations may be designed to closely match the corresponding spectral power distributions and variations through the day and from day to day. On the other hand, knowingly altering such spectrum could serve as a tool for enhancing the commercial yield of valuable products compared to that obtained outdoors.

Several models are available for estimating solar irradiance differing in their reliability and ease of use. For scientific research libRadtran (Emde et al. 2016) and TUV (Madronich and Flocke 1998) two radiation transfer models, are the currently the preferred ones. Simpler and easier to use models maybe preferable for advising growers. The authors have used the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) (Gueymard n.d.) from the National Renewable Energy Laboratory (NREL) in Colorado and the simplified approach described by Bird & Riordan (also from NREL) (Bird and Riordan 1986) to calculate the global spectral solar irradiance at various locations on the Earth's surface. The former model has spectral resolution 0.5 nm for 280 to 400 nm, 1 nm for 400 to 1750 nm and 10 nm for 1750 to 4000 nm.

Lighting calculations

Ceravision has been working with academic institutions, in particular University College London and Laboratoire plasma et conversion d'énergie (LAPLACE) in Toulouse, to develop tools to help growers estimate the number and type of luminaires needed to give a target irradiance for a pre-defined area and to assess the likely environmental impact of their lighting operations.

To quantify the distribution of light from luminaires, manufacturers measure their intensity in a series of different directions. This is done in a standardised way and information is published in an intensity file. The two most widely used file formats are those with extensions `.ies` (IES 2020) and `.ldt` (Keysoft Solutions Ltd. 2020). Knowing the distribution of light from the luminaires, the area being lit and the distribution of luminaires across the area, it is possible to calculate the fraction of the radiation flux leaving the luminaire that hits the reference plane. Dialux (https://www.dialux.com) and Relux (https://www.relux.com) are industry standard software packages, free to download, for lighting design and visualisation that have links to .ies and .ldt files provided by luminaire manufacturers. By knowing the SPD and the total flux from the luminaire, the irradiance ($\mathrm{W\,m^{-2}}$) and the photosynthetically active photon flux density (PPFD) ($\mathrm{\mu mol\,m^{-2}\,s^{-1}}$) in any given wavelength band can then be calculated.

In conjunction with our research partners we have built a database of light sources together with their SPDs, fluxes and luminaires to calculate irradiances, total power demand and power loadings for an installation. Irradiances can be calculated in ranges UV-B, UV-A and PAR. The total electrical power available to a site is often a limiting factor in the design of a commercial greenhouse, as it has to support lighting, heating, cooling and ventilation. A detailed account of this work is in preparation and will be published elsewhere.

Environmental impact and life cycle assessment

When it comes to evaluating the quantifiable effects of products or services on the environment, life cycle assessment (LCA) is probably the most efficient and widely recognized tool. Thanks to a 'cradle to grave' approach, LCA identifies and quantifies, throughout the life of products, the physical flows of matter and energy associated with human activities (extraction of raw materials, manufacturing of the product, distribution, use, collection and disposal at end-of-life). Each of its flows correspond to indicators that illustrate the overall potential impact of the system on our environment. With regard to lighting, 'smart' technologies have made it possible to improve energy efficiency during use phase and thus greatly decrease the impact on the environment.

The traditional functional unit used for assessing light sources, $1 \times 10^6 \mathrm{lm \cdot h}$, is not appropriate for horticultural applications as the lumen is a quantity based on the response of the human eye over the range 380 to 780 nm. Consequently, as a result of a recent collaborations we are proposing a new approach to quantifying the environmental impacts and life cycle assessments for horticultural lighting systems based on functional units expressed as the products of irradiance ($\mathrm{W\,m^{-2}}$) and time (Mucklejohn, S. A., Preston, B., Moutsi, A., Bertin, K., Zissis, G. and Raynham, P , unpublished).

The new assessment approach is based not on the output of the light source, nor on the light source plus the luminaire and electronic control gear, but on the irradiance and uniformity delivered by the lighting installation to a reference plane for a set length of time, e.g. 1000 h. A plane surface has been used for simplicity and repeatability because the actual irradiance impinging on the plant varies as the plant grows and new leaf formation creates shade to older/lower parts of the plant.

This approach reflects the importance of the lighting design as well as the characteristics of the light source, gear and luminaire. It is widely accepted that uniformity is an important factor in lighting for horticulture and various designs can be used to illustrate the compromises between average irradiance and uniformity. Because the SPD over wavelengths from 280 to 1200 nm plays a vital role in the response of plants to radiation, we have defined functional units for several wavelength ranges (unpublished results).

The future

The move away from magnetrons to high-power solid-state microwave generators will continue and will bring higher efficiencies and devices that are more compact. Although very efficient LEDs with long life expectancy are available for wavelengths of 365 nm and longer, currently available LEDs emitting at shorter wavelengths have very low conversion efficiencies and are relatively expensive.

The largest increase in benefits to society from a more widespread use of UV in horticulture is most likely to come from extensive collaboration between plant scientists, commercial growers and suppliers of the infrastructure, including lighting, needed for indoor growing environments. Experiments carried out under carefully controlled, repeatable conditions will be essential to realise the potential of the various opportunities in the application of UV that are now available thanks to technological progress. These advances may subsequently enable a more sustainable approach to global food security as well as healthier food and population.

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