UV-B Induced Secondary Plant Metabolites

Potential benefits for plant and human health

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Epidemiological studies have revealed an association between a high consumption of fruit, vegetables and herbs and a lower risk of both cancer and cardiovascular diseases. This protective effect is mostly due to secondary metabolites present in plant tissues. In contrast to numerous previous UV-B studies, which have focused on the potential impacts of increased levels of solar UV-B radiation reaching the Earth’s surface due to stratospheric ozone depletion, recent investigations revealed that UV-B radiation is an important regulator of plant secondary metabolism. Low, ecologically-relevant UV-B levels trigger distinct changes in the biosynthesis of secondary plant metabolites such as phenolic compounds, carotenoids and glucosinolates. Fundamental understanding of plant UV-B perception and responses opens up new opportunities for crop manipulation. Thus, targeted low dosage UV-B radiation treatments as emerging technology may be used to generate fruit, vegetables and herbs enriched with secondary plant metabolites for either fresh consumption or as a source for functional foods and nutraceuticals.

The new view on secondary plant metabolites

Due to the high and ever increasing incidents of cancer and heart disease in industrialized countries, governments have been making concerted efforts to raise public awareness for the advantages of a healthy diet. Numerous epidemiological studies have already documented reverse trends between the amount of fruit and vegetable consumption and the appearance of chronic diseases such as different types of cancer and cardiovascular disease. The plant compounds that are at least responsible for producing this health-promoting effect are the secondary plant metabolites present in the fruit and vegetable that we consume. However, the overall fruit and vegetable consumption in the industrialized nations of Northern Europe and North America is relatively low, and is also well below internationally recommended amounts, i.e. approx. 650 g fruit and vegetables per day as advocated by many international health bodies (e.g. the World Cancer Research Fund/American Institute for Cancer Research, the Health Education Authority (UK), the German Nutrition Society, and the German Cancer Society). The reason for this low fruit and vegetable consumption may be sub-optimally designed diet campaigns in which the message either did not get across or was misinterpreted. In addition, these promotions could be compounded by consumer complacency, low income and poor educational standards. Therefore, one way of increasing the consumption of health-promoting secondary plant metabolites in the diet would be by increasing metabolite levels in the fruit and vegetables themselves.

UV-B exposure as trigger of the secondary plant metabolism

Upgrading vegetables and fruits in this respect could be done by breeding, genetic engineering, or modification of secondary metabolite biosynthesis by elicitor applications, which provides immediate response. In the latter case we have to identify key enzymes or key genes targeted by these elicitor treatments. We have applied several elicitors for influencing glucosinolate biosynthesis: we used chemical, physical, and biological elicitors. The treatment with UV light, particularly from the UV-B range (280–320 nm), is an example for effective elicitor application.

Secondary plant metabolites mediate many aspects of the interaction of plants with their environment by acting as feeding deterrents against herbivores, pollination attractants, protective compounds against pathogens or various...
Manipulation of UV-B radiation in horticulture

There are two different approaches to manipulate UV-B radiation. In UV-B exclusion studies, solar UV radiation is attenuated using specific wavelength filters (e.g., cladding material in case of protected cropping), whereas in UV-B supplementation studies, plants are exposed to supplementary, artificial UV-B radiation generated by lamps. In the case of UV-B supplementation, the UV-B dose can be easily and accurately controlled by dimming or switching the lamps. Treatments can be stopped whenever required without leaving a residue. Indeed, another advantage of UV-B supplementation is that any "treatment" can be instantaneously terminated (in contrast to the lasting impact of chemical plant growth regulators once taken up by the plant). Current advances in the development of UV-transparent cladding materials, but also UV light emitting diodes (LEDs), provide new opportunities for the precise manipulation of UV-spectra.

UV-A LEDs (predominantly in the 350–385 nm emission wavelength range) are useful in pest and disease control, and in the preservation of agricultural products from decay. In addition, UV-A LEDs have shown positive effects on the growth of tomato but negative effects on cucumber, lettuce and soybean. Li and Kubota (2009) demonstrated that a weak radiation flux from UV-A LEDs increased anthocyanin content by 11% in baby leaf lettuce, while Sumitomo et al. (2012) found that UV-A LEDs had no inhibitory effect on chrysanthemum flowering. Urbanovcicie et al. (2009) showed that a low dose of supplemental UV-A inhibited the free radical scavenging activity and reduced the contents of phenolic compounds in wheat, but increased the vitamin C content. UV-A LEDs have also been the technical basis for devices, such as UV-A induced fluorescence detectors, which are used for assessing different parameters useful for agriculture and/or plant physiology: UV protection by epidermis, polyphenolic content in leaves, ripening stage of fruits and leaves, fruit rotting, and the effect of zinc on photosynthesis. In contrast to the significant use of UV-A LEDs in horticulture, the use of UV-B LEDs is just developing.

Structure-differentiated plant's response to UV-B radiation

Low levels of UV-B radiation can cause distinct changes in the plant's secondary metabolism resulting in the accumulation of a broad range of secondary plant metabolites. Best documented is the UV-B mediated accumulation of flavonoids which have in planta both reactive oxygen species (ROS) scavenging and UV-screening activities. UV-B radiation has frequently been observed to disproportionately enhance the accumulation of the more hydroxylated flavonoids, i.e. quercetin to kaempferol ratios increase. Flavonoids with multiple hydroxyl-groups have particularly good ROS scavenging activity, and for this reason

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Optik&Photonik 2/2014

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Flavonoids and other phenolic compounds

Flavonoids are the main phenolic compounds of plants. They are diverse and naturally occur as flavonoid glycosides. Flavonoid compounds have received considerable attention because of their potential health-promoting properties for human consumers. Key flavonoid biosynthesis genes are regulated by UV-B and flavonoids accumulate in a range of cellular compartments, including cell walls, vacuoles, chloroplasts, nucleus and in trichomes. Flavonols, anthocyanidines and hydroxybenzoic acids increased in black currant fruits (Ribes nigrum) exposed to three low, medium and high UV-B doses of 0.3 to 0.9 kJ m⁻² d⁻¹ UV-B. Furthermore, the hydroxybenzonic acid glycosides disinapoyl-gentiobiose and sinapoyl-feruloyl-gentiobiose were enhanced in a dose-dependent manner under UV-B. For flavonoid glycosides, there are structural characteristics regarding the aglycone, the glycosylated sugars, and the acylated phenolic and organic acids. The effect of UV-B is also modified by UV-B dose the structure of the flavonoids and other phenolics and further environmental factors such as photosynthetically active radiation and temperature (Fig. 2).

Glucosinolates

Although the production of flavonoids and related phenolic compounds in response to UV-B in several plant species has been well documented, effects of ecologically relevant UV-B doses on accumulation of other secondary metabolites such as glucosinolates – the characteristic defence compounds in the order Brassicaceae – received little attention in the past. Glucosinolates are sulphonated thioglucosides sharing a common glucose moiety with a variable aglycone side chain and are, based on this, divided into aliphatic, indoly1, and aromatic glucosinolates. Recent studies have shown that ecologically-relevant low UV-B levels can trigger the induction of glucosinolates in Brassicaceae as demonstrated for Brassica oleracea var. italica (broccoli), Arabidopsis thaliana, and Tropaeolum majus. Low to ambient UV-B doses (0.3 to 1 kJ m⁻² d⁻¹ UV-B) elicited an increase of especially aliphatic methylsulfinylalkyl glucosinolates and the indole 4-methoxy-indol-3-ylmethyl glucosinolate in A. thaliana and broccoli sprouts and an aromatic glucosinolate in nasturtium. Already 2 h after UV-B exposure to 0.3 – 0.6 kJ m⁻² d⁻¹ UV-B, total glucosinolate levels have been increased in broccoli sprouts (Fig. 3). Interestingly, greater doses of up to 0.9 kJ m⁻² d⁻¹ UV-B and multiple exposure times did not elicit a stronger response in glucosinolate accumulation. Due to a lack of studies a comparison is a difficult task. However, Nadeau et al. (2012) showed that 4-methoxy-indol-3-ylmethyl glucosinolate, 4-hydroxy-indol-3-ylmethyl glucosinolate and 4-methylsulfinylbutyl glucosinolate accumulated in broccoli florets in response to exposure to UV-C. Furthermore, it has been shown that the sensitivity of plant organs and response to low levels of UV-B can vary. In nasturtium, unripe green seeds responded to low levels of UV-B with a 6-fold increase in benzy1 glucosinolates and mature leaves only with a 3-fold increase.

Future view – Tailor-made UV-B induction of secondary plant metabolites by UV-B LEDs

Previous studies have indicated that the efficiency for triggering the biosynthesis of secondary plant metabolites by UV light has a local maximum in the UV-B spectral region. Until now, researchers...
have used conventional low-pressure mercury gas-discharge fluorescent lamps as UV-B radiation sources. These lamps utilize a phosphor coating to convert UV-C radiation into a broadband UV-B radiation, which typically exhibits a broad peak between 280 nm and 360 nm. Because of the broad emission spectrum it is not possible to get a differentiated plant response to UV radiation of a certain wavelength. Furthermore, an undesired crosstalk or even harmful stress from UV radiation of different wavelengths on certain secondary plant metabolites or other plant properties is possible. Semiconductort-based UV-B LEDs are an interesting alternative to fluorescent lamps as UV-B light source. The emission spectrum of UV-B LEDs is fairly narrow with full width at half maximum (FWHM) of less than 10 nm and the peak emission wavelength can be tailored to ideally match the effective spectrum for triggering the secondary plant metabolism. UV-B LEDs do not exhibit any additional and unwanted side emission peak that may damage the plants. First experiments with an UV-B LED based module (Fig. 4) showed promising results. The module consists of twelve 310 nm LEDs with an average optical power of 1.0 mW at a current of 50 mA. The LEDs are equipped with a UV-reflector and arranged to uniformly illuminate a target area of 20 cm × 30 cm. An adjustable uniform irradiance of up to 0.1 W m⁻² was obtained at a working distance of 30 cm. Preliminary tests showed that the production of secondary plant metabolites in Arabidopsis leaves and broccoli sprouts is enhanced by UV-B LED irradiation. For example, UV-B exposure with the module for 5 hours increased the total glucosinolate content from 3.0 mg g⁻¹ dry matter of untreated Arabidopsis control plants up to 5.2 mg g⁻¹ dry matter in leaves of treated plants 24 hours after UV-B application. In addition, the UV-radiation induced stress was minimized by adjusting the irradiance.

Overall, these are very promising first results which open up a new field of application for UV-B LEDs. This is particularly attractive, when considering the worldwide trend of changing the artificial illumination in greenhouses and plant-fabrication facilities from conventional gas-discharge lamps to LEDs and the ease of implementing UV-B LEDs in arbitrary spatial conditions.

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