Process Challenges in Applying Low Doses of Ultraviolet Light to Fresh Produce for Eliciting Beneficial Hormetic Responses

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Abstract

A considerable body of evidence has been steadily accumulating pointing to the benefits of post-harvest exposure of fresh produce to low doses of shortwave ultraviolet light (UV). This type of treatment was originally proposed as a method of reducing postharvest losses through fungal attack and premature senescence. UV has been shown to elicit a range of chemical responses in fresh produce ranging from antifungal enzymes to phytoalexins. Moreover, there is evidence to show that some of the induced compounds have beneficial effects on human health. By contrast to the extensive biochemical studies conducted, little attention has focussed on how such treatment may be realised in practice. In this work, therefore, consideration is given to how treatment of produce on a large scale with UV might be designed to offer maximum benefits.

Keywords: Low UV Doses; Hormesis; Commercialization

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1. Introduction

The term ‘hormesis’ is derived from Greek and has variously been cited as meaning ‘to urge on, to impel, and to excite.’ Luckey (1980) provided a more functional definition for hormesis as signifying ‘the stimulation by low doses of any potentially harmful agent.’ Calabrese (2005), who has written widely on the phenomenon of hormesis, attributes the first use of the term in this context to Southam and Ehrlich (1943). It is now known that beneficial hormetic effects can be induced across all taxons of living organisms - bacteria, fungi, protists, plants and animals. Humans are not excluded and, at the other end of the evolutionary scale, nor are viruses. The agents capable of bringing about these stimulatory effects may be either chemical or physical ones. Included amongst the latter are various portions of the electromagnetic spectrum, and Luckey (1980) conducted an extensive survey of hormetic effects induced by both ionising radiation and ultraviolet light (UV).

In the period since the appearance of Luckey’s survey much experimental work has been conducted on the application of low doses of short wavelength UV to agricultural and horticultural commodities and this has recently been summarised (Shama, 2005; Shama and Alderson, 2005). Also relevant is the review of Terry and Joyce (2004) who, whilst acknowledging the term hormesis, described the relevant phenomena in horticultural produce as manifestations of ‘natural disease resistance’. More recently Ben-Yehoshua and Mercier (2005) made reference to ‘abiotic physical elicitors[s] of resistance mechanisms’. Both terms are useful in their own right, however in this article the term hormesis will be taken specifically as meaning beneficial effects arising from the application of low doses of UV. The present work

concerns itself with the issues that would have to be overcome if the concept were to be applied on a commercial basis – what might be referred to in engineering terms as 'scale-up'.

Before going on to consider the process aspects of applying low UV doses to fresh produce, it will prove useful to briefly recapitulate the previously reported benefits of such treatments. It should be noted that the following citations are not intended as an exhaustive survey, but rather to convey the scope of previous work. Short wavelength UV has been shown to reduce storage rots in a number of vegetable crops including onions (Lu et al., 1997), potatoes (Ranganna et al., 1997), sweet potatoes (Stevens et al., 1999) and carrots (Mercier et al., 2000) and also fruit, including tomatoes (Liu et al., 1993), peaches (Stevens et al., 1998), apples (de Capdeville, 2002) mangoes (Gonzalez-Aquilar, 2001), bell peppers (Mercier et al., 2001), grapes (Nigro et al., 1998) cherries and strawberries (Marquenie et al., 2002), grapefruit (D'hallewin et al., 2000), kumquats (Rodov et al., 1992), mandarins (Kinay et al., 2005) and oranges (D'hallewin et al., 1999). Nor are the effects restricted to whole produce; Erkan et al. (2001) demonstrated positive effects by treating slices of zucchini squash (*Cucurbita pepo)* as did Lamikanra et al. (2002) for sliced cantaloupe melons.

Hormetic effects manifest themselves in treated plant tissue through the action of a variety of induced chemical species. In certain cases these have been identified. They include phytoalexins such as scoparone in kumquats (Rodov et al., 1992) and oranges (D'hallewin et al., 1999), 6-methoxymellein in carrots (Mercier et al., 2000) and resveratrol in grapes (Cantos et al., 2002). Also induced are enzymes such as

chitinases and glucanases in peaches (El Ghaouth et al., 2003) and oranges (Porat et al., 2001) and phenylalanine ammonia lyases in peaches (El Ghaouth et al., 2003) and tomatoes (Barka, 2001). It has also been claimed that treatment with hormetic doses of UV results in an enhancement in the levels of anthocyanins in strawberries (Baka et al., 1999) and apples (Dong et al., 1995).

Low dose UV treatment has also been proposed as a method of delaying senescence and ripening in peaches and apples (Lu et al., 1991) and tomatoes (Liu et al., 1993). Whilst a more unusual application is in the production of so-called 'functional foods'. Reserveratrol, for example, displays a number of cardioprotective properties (Bradamante et al., 2004) and Cantos et al. (2002) succeeded in increasing the resveratrol content of grapes by applying hormetic doses of UV.

2. The UV Spectrum

UV radiation constitutes that part of the electromagnetic spectrum lying between visible light and X-rays. This is formally taken as including all wavelengths from approximately 10 to 400 nm. Moreover, all but the shortest UV wavelengths are non-ionising. The UV spectrum has been further subdivided partly on the basis of the characteristics of the radiation, and partly by those who employ UV either in industry, medicine or academia. The shortest UV wavelengths are typically referred to as 'vacuum UV' because they are strongly absorbed by air. The other important divisions are UV-A – 315 to 400 nm, UV-B – 280 to 315 nm, and UV-C – 100 to 280 nm. The latter has also been referred to as 'germicidal UV'. The shortest wavelengths

of the UV spectrum are also the most energetic ones and all previously reported hormetic effects have been brought about by wavelengths from within the UV-C region.

Consideration of the effects of irradiating fresh produce with UV-C is complicated by the fact that this portion of the UV spectrum is directly lethal to micro-organisms – hence the term 'germicidal'. The extent to which low - or hormetic – UV-C doses will result in the direct inactivation of surface-associated micro-organisms is difficult to comment upon in general terms. Gardner and Shama (2000) have shown that surface 'topography' plays a major role in determining survival following exposure to UV-C. In other words, micro-organisms present on a surface that may be considered smooth at scales comparable to those of the micro-organisms themselves are more susceptible to the effects of UV than are those which might be present at a surface which contains crevices inside which the organisms might be shielded from the lethal effects of UV-C. Another important determinant of survival is the natural resistance to UV-C of the organism itself. Not surprisingly, micro-organisms differ greatly in the UV doses required to bring about inactivation (Shama, 2005). In practice therefore, the relatively low doses necessary to induce hormetic effects may also result in the inactivation of the organisms most sensitive to UV-C where these occur unshielded by surface features.

Hormetic effects induced by UV-C differ from germicidal ones in a fundamental way: germicidal effects occur over relatively short time scales that are essentially limited to the time of exposure of the organism to the UV source – this will obviously depend on the application, but exposure times typically range from fractions of a second to

perhaps tens of seconds. In other words, germicidal effects may be thought of as 'direct' in that once the organism is no longer exposed to the source of UV-C photons, the formation of potentially lethal DNA lesions ceases. In contrast, hormetic phenomena manifest themselves *after* exposure to UV-C at periods of time ranging from hours to days.

3. UV Dose and its Measurement

The principal requirement of a commercialised hormetic UV treatment process would be to ensure the delivery of a pre-determined amount of energy in the form of UV to every item of produce presented for treatment. The total amount of energy delivered may be derived from a knowledge of the energy incident over the entire surface of the item (the so-called 'energy fluence'), and the time over which the energy is applied – in other words the length of time the item or object remains in the UV field. This yields what is commonly referred to as the 'UV dose'.

If the object is of relatively small dimensions and the UV field within which it is located is uniform, it may be assumed that surface fluence will also be uniform over its entire surface. However, for large objects in non-ideal UV fields, the fluence will almost certainly be different at each surface, and in order to estimate the total amount of energy delivered, it will be necessary to integrate the surface fluence over each surface and to sum these values together.

The conditions that prevail in most previously reported laboratory studies on UV hormesis pertain more closely to the latter case than to the former, but researchers

151 have tended to ignore the possibility of variations in UV intensities over the surfaces
152 of produce. In addition, for reasons of experimental expediency, some researchers
153 have referred to a particular item of fruit as having “sides” even when the item
154 approximates to a sphere (e.g. Stevens et al., 1998). Exposure to a source of UV-C is
155 then typically made on the basis of delivering a fixed dose to each “side” of the fruit.
156 Figure 1 shows the mathematically modelled distribution of surface UV intensity on a
157 cylinder irradiated by a single cylindrical UV source. This serves to illustrate the fact
158 that intensity will decrease with angular orientation from the centre line of source and
159 object. In other words when researchers give the dose per side, the actual delivered
160 dose will be greater than this value multiplied by the number of sides.
161
162 The UV dose is a critical parameter in the induction of hormetic effects in fresh
163 produce and it is therefore essential to have precise knowledge of the dose, or dose
164 range, that induces the desired effects as on scaling-up from laboratory studies, as this
165 parameter must be maintained constant.
166
167 UV source manufacturers nearly always quote point UV intensities at a fixed distance
168 from the source. This enables the intensity at any other point in the UV field to be
169 derived theoretically, as intensity varies as the reciprocal of the square of the distance
170 from the source. This information together with the length of time the object remains
171 within the UV field will enable the theoretical dose to be obtained. In practice the true
172 emission from the source will depend on numerous factors such as the transmittance
173 of the quartz glass envelope, the actual voltage at the electrodes etc. UV emission will
174 also depend on the age of the source i.e. how many hours the discharge has been
175 struck, and will decline according to some exponential function (Schenk, 1987). The

cumulative effect of all possible variations may well result in appreciable differences in emission between apparently identical sources from the same manufacturer, and therefore the theoretical emissivity should only be used as a rough guide at the design stage rather than as a scale-up parameter. In addition, it should be pointed out that such methods can only give estimates of the dose *delivered* as opposed to the dose *absorbed.* It is therefore essential to be able to measure the UV dose.

UV dose measurements in previous studies involving fresh produce have invariably been made using radiometers. A radiometer is a device that measures intensity as a function of wavelength. Radiometers comprise two components; a selective device which isolates part of the spectrum for measurement, and a photosensitive detector (Phillips, 1983). Instrumental detectors rely on a physical response that is measured as a voltage or current. Most modern radiometers give a direct digital readout of UV intensity, and there is something obviously appealing, not to say beguiling, in instruments that are so convenient to use. The selective device, or sensor, which collects the relevant portion of the UV spectrum, typically has the geometry either of a slab or a disc and is of physical dimensions comparable to most individual items of fresh produce. Accurate dose estimation relies on positioning the sensor at precisely known co-ordinates within the UV field. This is not impossible, but difficult to achieve in practice and it is all too easy to gloss over the difficulties in the Materials and Methods sections of papers.

Are there better methods of measuring dose? Two possible alternatives to radiometry are chemical actinometry and biodosimetry. Actinometry makes use of a chemical system that undergoes a light-induced reaction at a particular wavelength or

wavelength range for which the quantum yield is accurately known (Kuhn et al., 2004). In practice this involves measuring a specific chemical change from which the dose delivered is ultimately derived from the rate of reaction. Actinometric methods are capable of yielding very precise estimates of dose and are particularly well suited to fluid systems, as for example when measuring doses in a photoreactor for treating liquid reactants. There are relatively few actinometric methods for measuring the doses on the surfaces of a solid object and those that have been described by Kuhn et al (2004) appear quite involved: one method involves the immobilization of DNA and the use of monoclonal antibodies directed against specific lesions (Ishigaki et al, 1999).

Biodosimetry is based on the response of an organism to a specific UV wavelength or range of wavelengths. Typically, this necessitates the determination of a 'dose-response curve' for the organism in question. This is a plot showing reduction in viability as a function of dose. Spores of the bacterium *Bacillus subtilis* are particularly well suited for this purpose, as the organism is non-pathogenic and the spores can be prepared in advance and stored for long periods without deterioration. Moreover, the method is applicable for dose determination either in liquids or on solid surfaces. For surface dose estimation, spores may be deposited onto membranes which are then attached to the object in such a way that the membranes are in intimate contact with the surface of the object. The membranes need to be attached with precision so that their co-ordinates on the surface of the object are known. After irradiation the membranes are removed and the spores are recovered so that a determination can be made of the fraction of spores that have survived exposure to UV light. From the dose-response curve, the UV dose absorbed can be read off

(Gardner and Shama, 1999). Figure 2 shows the dose response curve for spores of *B. subtilis.*

In an excellent study on the biological effects of UV, Harm (1980) claimed that the 'biological effectiveness' of UV was almost entirely due to its absorption by nucleic acids, and DNA in particular. Although, the emphasis of Harm's study was on UV inactivation and mutagenesis in micro-organisms, with scarcely a mention of plants, there is no fundamental reason why plants should be excluded from such a statement. The absorbing components within nucleic acids are the nucleotide bases, and although their absorption spectra differ subtly from one another, all have maxima in the 260 to 265 nm region (Harm, 1980). It follows therefore that absorption spectra will be species-dependant but the differences between individual species of fresh produce are likely to be slight, although as Terry and Joyce (2004) such investigations have not been conducted for fresh produce and have yet to be undertaken.

Fortuitously, the peak emission of low-pressure mercury burners occurs at 253.7 nm, i.e. close to the absorption maxima of most types of DNA, and the majority of studies undertaken using fresh produce have been made with this type of UV-C source. Low-pressure mercury sources are commonly, but mistakenly, referred to as 'monochromatic.' They do in fact emit over a broad spectrum, with some 60 % of the spectral energy emitted being at 253.7 nm (Schenk, 1987). The use of such sources is particularly convenient because they are relatively inexpensive and run at temperatures (circa 60° C) that do not require cooling. However, excimer sources are now commercially available and are able to emit at a number of specific wavelengths (Endert et al., 1999). Though considerably more expensive than low pressure UV-C

sources, it may emerge from future studies that beneficial hormetic effects may have different wavelength optima effects to those of some or all of the undesirable effects that UV-C can induce (see below) and that therefore the use of more expensive UV sources may become justified.

Although more than adequate for the task, low pressure mercury lamps are not the only artificial sources of UV that are available. There are a variety of medium and high pressure sources that yield a far more intense emission than the former (Phillips, 1983). It is usually assumed that a principle termed the 'dose-time reciprocity rule' is universally applicable in considerations of treatment design. The rule states that equal doses of UV are equivalent irrespective of the intensity of the UV source employed, as a higher intensity can be compensated for by a shorter exposure time and a lower intensity by a correspondingly higher time of exposure. Most previous experimental work seems to support this principle but evidence has emerged of departures from it (Sommer et al., 1998) and therefore it would seem that investigations should be carried out to establish whether it is found to hold in the elicitation of hormetic effects.

4. Reversibility of Hormetic Effects

Many of the effects induced in living systems by UV-C have been shown to be partly, or in some cases wholly, reversible by subsequent exposure to light of a longer wavelength, typically either UVA or visible light. This phenomenon was first described by Kelner (1949) and has subsequently come to be known as 'photoreactivation' or 'photoreversibility'. These longer wavelengths activate repair

processes that are directed towards DNA. Whilst UV can affect a number of cellular components, damage to DNA will have the most severe consequences for the cell and the most important enzymatic repair processes are those that restore sections of damaged DNA.

This will have obvious consequences for treatment, as any produce that is treated using UV will have subsequently to be stored under conditions that are designed to eliminate certain wavelengths. Optimal wavelengths for the activation of repair processes have been shown to be species-dependent, and in contrast to the relatively subtle differences previously mentioned above for lethal effects of various UV-C wavelengths, some quite substantial differences have been identified. For *E. coli* B the optimum lies at 340 nm whereas for *Streptomyces griseus*, it is just below 440 nm (Jagger, 2004). Relatively little work of this type has been done with fresh produce. Stevens et al. (1998) exposed UV-C-treated peaches to ordinary fluorescent white light sources at high light intensity continuously for 48 hrs and found that the beneficial effects of the UV-C in reducing brown rot disease caused by *Monilinia fructicola* were completely eliminated. Whilst it might be argued that this was an unrealistically long exposure at relatively high intensity, it nonetheless serves to illustrate the point. There appears to be currently no information in the literature concerning the length of time after irradiation that produce should be protected from exposure to photoreversing wavelengths. In other words, after what period of time after treatment does UV-C-induced damage become irreparable? Presumably after the elapse of time it would be safe to permit exposure of the treated produce to visible light. The answers to these questions will be vital in designing suitable post irradiation conditions.

5. Process Design for Delivering Hormetic Doses of UV

All previously published work on the delivery of low doses of UV to fresh produce has concerned itself with only relatively small numbers of fruits treated under laboratory conditions, and little consideration has been given to how produce may be treated on a large scale under industrial conditions. Any process for irradiating produce must fulfil certain essential requirements. 1. Produce should not be subjected to any form of mechanical handling during irradiation that might cause it to become damaged. 2. There should be provision for both varying the UV dose delivered and controlling the dose. 3. UV-C treatment should not add unduly to processing costs. 4. The design of equipment should enable high throughputs to be treated. 5. Ideally a wide variety of different types of fruit and vegetables should be treatable.

Produce that is easily damaged will require special handling. One possible solution would be to protect it by placing it inside a container or other form of packaging. This will naturally place certain constraints on the material from which such packaging may be manufactured. Most polymers currently used for packaging fresh produce contain plasticisers that generally absorb UV-C quite strongly. Notwithstanding, commercially produced materials differ widely in this regard and some current formulations may prove acceptable (Brown, personal communication, 2005) provided that their UV-attenuating effects are properly accounted for at the design stage, and provided that the attenuation is not so great as to require additional UV sources which would incur both additional capital and running costs. It may be possible to replace materials currently employed with novel ones that exert a lower UV-C- attenuating

effect. Although fluorinated polymers have exceptionally high UV-C transmittance (Korinek, 1994), their cost would almost certainly be prohibitive.

Treatment of produce in this way will also inevitably influence the way in which it is retailed. Marquenie (2002) has investigated treating strawberries in punnets fabricated from a variety of polymers with low doses of UV. Unsurprisingly, those fruit in the interior of the punnet received very low, or even no, UV-C and thus became spoilt by various fungi on storage. Produce would therefore have to be packed in a single layer to ensure that the correct UV dose was delivered. Such forms of retailing berry fruit are currently employed, particularly at the beginning and end of the growing season when the fruit commands a higher price.

The issue of correct dose delivery is by no means a trivial one, as exceeding the optimal UV dose will inevitably result in damage to the produce. The precise values of doses leading to the onset of unacceptable changes in individual species of produce have rarely been determined. This is because researchers have, on the whole, tended to increase the doses of UV applied to fresh produce by relatively large increments in order to obtain readily identifiable responses. However, there have been some exceptions to this: D'hallewin et al., (2000) showed that UV-C doses of 0.5 kJm^{-2} were optimal in reducing decay in grapefruits but that doses of 1.5 kJm^{-2} could cause rind browning and tissue necrosis. Gonzalez-Aguilar et al., (2001) showed that for mangoes a dose of 4.93 kJm^{-2} was beneficial whereas a dose of twice that amount revealed evidence of damage. Baka etal., (1999) treated strawberries with UV-C doses of 0.25 and 1.0 kJm^{-2} and reported that the higher dose was damaging to the fruit. Conversely, under-dosing will lead to a failure to derive maximum benefit from the

investment made in equipment and may result in reduced shelf life or loss in quality. Any commercial process will inevitably result in the delivery of a distribution of doses to individual items of produce. It is clear therefore that precautions would have be taken to determine not only the peak dose but also the lower and upper limits of dose.

An additional consideration in the delivery of the correct UV dose is revealed by the work of D'hallewin et al., (2000), who showed that optimal UV dose was dependent on date of harvesting. Grapefruits harvested before being commercially mature were more easily damaged by UV-C exposure than were fruits harvested mid- or late-season. This would have obvious processing consequences and would require suitable provision to be made for varying the UV dose delivered within quite narrow limits.

In the assessment of treatment costs, allowance would need to made for reductions in chemical fungicide applications. In addition, produce treated with fewer chemicals could presumably be retailed at a premium. Being able to treat a wide variety of produce using a single type of processing equipment is obviously attractive but might be difficult to achieve in practice due to the diversity of size and shape of produce. Notwithstanding, Brandt and Klebaum (2000) described an inclined rolling conveyor that causes spherically shaped produce to rotate whilst being irradiated by UV-C sources. The invention also incorporated an automatic actuator that enabled the height of the sources to be adjusted according to the dimensions of the produce undergoing treatment.

There are clearly some types of produce that it would be very difficult, not to say impossible, to treat: bunches of grapes present an obvious problem. It is conceivable that most of the grapes at the exterior of the bunches could be irradiated, however those at the centre would receive little or no UV and any attempts to deliver the correct dose to those at the core would inevitably result in over-dosing of the exterior grapes (Lagunas-Solar, personal communication, 2005). The only way of achieving even treatment would be by treatment of grape berries removed from the bunch – this will have obvious limitations on marketing but individual berries do form components of ready-to eat fruit salad mixtures and thus could be treated in this way.

Equipment for delivering low doses of UV to produce would not necessarily need to be of complex design; simply allowing produce to roll down an inclined plane with UV-C sources suspended above it may be one method of obtaining a high surface irradiation. Alternatively it would be possible to modify existing equipment designs intended for other purposes. In particular, the field of UV-curing could prove a rich source of potential designs. Manufacturers of equipment for this sector have had the task of designing methods for achieving full surface irradiation of a variety of 3D objects for the application of inks, adhesives and decorations that become cured only on exposure to UV. Stowe (1993) has reviewed ways in which this can be achieved for mass produced articles through the arrangement of sources, provision of reflectors and the use of mechanical mechanisms most, if not all, of these techniques could readily be adapted for delivering low doses of UV to fresh produce.

It seems tacitly to have been assumed by previous workers that hormetic effects require the entire surface of the produce to be irradiated with UV, and most workers

have taken steps to achieve this in their laboratories. However, the question must be asked 'is it necessary to irradiate the entire surface of the produce in order to elicit a hormetic response?' Certainly, Mercier et al., (2000) in attempting to induce resistance to *Botrytis cinerea* in stored carrots, found that UV-C did not have a systemic effect and that disease resistance, partially mediated by 6-methoxymellein, was only induced in tissue that had received direct exposure to the UV. However, in contrast, Stevens et al (2005) showed that for apples peaches and tangerines it was sufficient to deliver a UV-C dose, previously established as being beneficial, wholly at the stem end of the fruit. These authors went on to suggest that vascular tissue in these fruits might play a role in signal transduction from the receptor tissue at the stem end. Clearly, further investigations are warranted to establish whether this might also hold for other types of fresh produce. If this were confirmed to be more widespread it would have significant consequences for treatment as produce could be packed in a certain way as to enable their stem ends to be exposed for treatment with UV-C.

To date the application of low UV doses has been entirely restricted to fresh produce once it has been harvested. There may be virtue in extending treatment to certain types of produce *before* it is harvested: strawberries, for example, are picked directly into punnets and applying post harvest doses would, as discussed above, necessitate significant changes to current practices in delivering the fruit for retail or the introduction of an additional process step. Moreover, because the fruit are fairly fragile, this would constrain the sorts of treatment that could be applied. Strawberries are increasingly grown in polytunnels designed under conditions designed to facilitate picking and which, coincidentally, render the fruit amenable to UV treatment whilst it is still 'on the vine'. This would be a challenging task as account would have to be

taken of shading effects by other fruit and also foliage. Moreover, it would have to be ascertained that 'stray' UV-C did not damage the plant itself, although Hadwiger and Schochau (1971) showed that hormetic doses of UV-C did not cause significant damage to plants. One possible way of achieving this would be to modify an invention described by Michaloski (1991). The invention was originally intended for treating grape vines in the field affected with mildew and comprises a carriage bearing banks of UV-C sources on its side arranged vertically so as to irradiate the plants efficiently.

6. Safety and UV-C

Exposure of humans to UV-C is associated with a number of harmful effects. UV-C causes acute and inflammatory changes to the cornea (Taylor et al., 1979) a condition commonly referred to as 'welder's eye'. Exposure of skin to UV-C results in erythema, or delayed reddening (Kelfkens and Van der Leun, 1989), and can also have profound effects on the immune system which can lead to severe and potentially lethal consequences (Baadsgaard, 1991).

If consideration were being given to the scale-up or commercialisation of UV-based treatments, suitable measures would have to be put into place to protect any personnel working in the vicinity of UV sources. These issues have already been addressed with reference to UV transilluminators which are commonly used in molecular biology laboratories (Klein, 2000). Instructing personnel in the hazards associated with UV would be an important first step. Provision of suitable safety equipment would naturally have to be made, and this would typically include goggles and skin protection. In addition, processing equipment can be designed so as to minimise, or even eliminate, 'stray' UV, through the use of shields and non-reflective surfaces.

In short, awareness of the hazards associated with UV-C is key as are the implementation of adequate protective measures. In purely economic terms, the latter need not entail excessive additional costs.

7. Conclusions

There is a wealth of laboratory-obtained data attesting to the positive benefits of applying low doses of UV to a variety of produce, however, to date little evidence of its application on a commercial scale. This must in some part be due to the impression that one is in effect 'playing with fire', as UV-C can, at sufficiently high dose, cause a number of harmful effects that would render the produce as unmarketable as if it had been attacked by soft rot fungi. Successful commercialisation will require that careful attention be paid to the delivery of specific doses within some quite tight constraints, as has been described above, as well as to the immediate post-treatment regime to which the produce is subjected to. There is no doubt too that additional research is needed to demonstrate categorically that the nutrient status of the treated produce is not in any way adversely affected. Although all available evidence points to quite the contrary, specific assays for, vitamins say, need to be conducted, as do a variety of other tests of quality as well as consumer acceptability surveys. With regard to the latter, it must be acknowledged that it is important to win over the minds of the consumer; this is ultimately as important as being assured of the science underlying the treatment. The term 'irradiate' means to treat with any type of electromagnetic radiation. In the popular mind it has become synonymous with ionising radiation - which is generally held to be 'a bad thing'. If

UV treatment is to be applied on a commercial basis, ways must be found of promoting its benefits without arousing negative reactions in the consumer.

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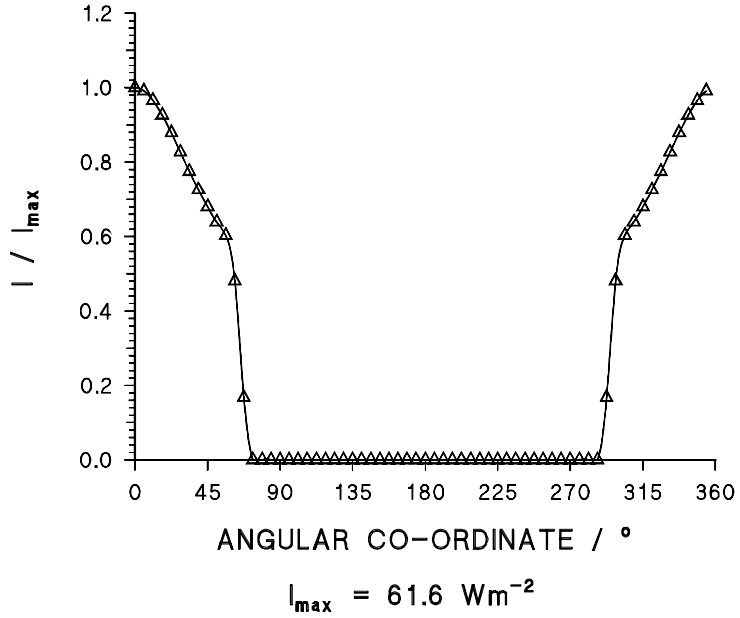
Figure Captions

Figure 1. UV Intensity on the Curved Surface of a Cylinder

Figure 2. Dose Response Curve for Spores of *Bacillus subtilis* Deposited on the Surface of Membrane Filters (Gardner, 1997).



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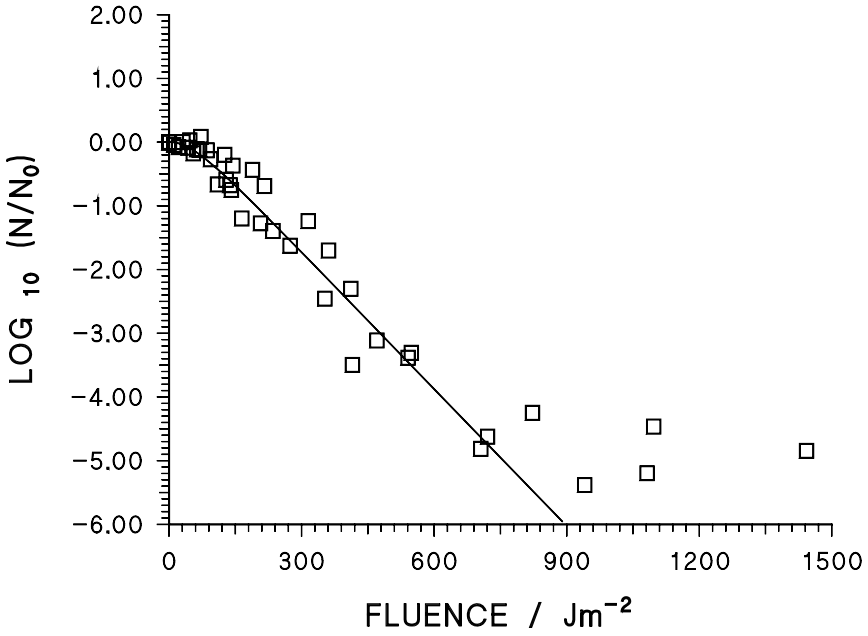
698 Figure 1

699 Figure 2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