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## **Process challenges in applying low doses of ultraviolet light to fresh produce for eliciting beneficial hormetic responses**

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

3

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7 **Abstract**

8

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

20

21 **Keywords:** Low UV Doses; Hormesis; Commercialization

22

23

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26 **1. Introduction**

27

28 The term ‘hormesis’ is derived from Greek and has variously been cited as meaning  
29 ‘to urge on, to impel, and to excite.’ Luckey (1980) provided a more functional  
30 definition for hormesis as signifying ‘the stimulation by low doses of any potentially  
31 harmful agent.’ Calabrese (2005), who has written widely on the phenomenon of  
32 hormesis, attributes the first use of the term in this context to Southam and Ehrlich  
33 (1943). It is now known that beneficial hormetic effects can be induced across all  
34 taxons of living organisms - bacteria, fungi, protists, plants and animals. Humans are  
35 not excluded and, at the other end of the evolutionary scale, nor are viruses. The  
36 agents capable of bringing about these stimulatory effects may be either chemical or  
37 physical ones. Included amongst the latter are various portions of the electromagnetic  
38 spectrum, and Luckey (1980) conducted an extensive survey of hormetic effects  
39 induced by both ionising radiation and ultraviolet light (UV).

40

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

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

54

55 Before going on to consider the process aspects of applying low UV doses to fresh  
56 produce, it will prove useful to briefly recapitulate the previously reported benefits of  
57 such treatments. It should be noted that the following citations are not intended as an  
58 exhaustive survey, but rather to convey the scope of previous work. Short  
59 wavelength UV has been shown to reduce storage rots in a number of vegetable crops  
60 including onions (Lu et al., 1997), potatoes (Ranganna et al., 1997), sweet potatoes  
61 (Stevens et al., 1999) and carrots (Mercier et al., 2000) and also fruit, including  
62 tomatoes (Liu et al., 1993), peaches (Stevens et al., 1998), apples (de Capdeville,  
63 2002) mangoes (Gonzalez-Aquilar, 2001), bell peppers (Mercier et al., 2001), grapes  
64 (Nigro et al., 1998) cherries and strawberries (Marquenie et al., 2002), grapefruit  
65 (D’hallewin et al., 2000), kumquats (Rodov et al., 1992), mandarins (Kinay et al.,  
66 2005) and oranges (D’hallewin et al., 1999). Nor are the effects restricted to whole  
67 produce; Erkan et al. (2001) demonstrated positive effects by treating slices of  
68 zucchini squash (*Cucurbita pepo*) as did Lamikanra et al. (2002) for sliced cantaloupe  
69 melons.

70

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

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

81

82

83 Low dose UV treatment has also been proposed as a method of delaying senescence  
84 and ripening in peaches and apples (Lu et al., 1991) and tomatoes (Liu et al., 1993).

85 Whilst a more unusual application is in the production of so-called ‘functional foods’.

86 Resveratrol, for example, displays a number of cardioprotective properties

87 (Bradamante et al., 2004) and Cantos et al. (2002) succeeded in increasing the

88 resveratrol content of grapes by applying hormetic doses of UV.

89

## 90 **2. The UV Spectrum**

91

92 UV radiation constitutes that part of the electromagnetic spectrum lying between

93 visible light and X-rays. This is formally taken as including all wavelengths from

94 approximately 10 to 400 nm. Moreover, all but the shortest UV wavelengths are non-

95 ionising. The UV spectrum has been further subdivided partly on the basis of the

96 characteristics of the radiation, and partly by those who employ UV either in industry,

97 medicine or academia. The shortest UV wavelengths are typically referred to as

98 ‘vacuum UV’ because they are strongly absorbed by air. The other important

99 divisions are UV-A – 315 to 400 nm, UV-B – 280 to 315 nm, and UV-C – 100 to 280

100 nm. The latter has also been referred to as ‘germicidal UV’. The shortest wavelengths

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

104

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

121

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

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

131

### 132 **3. UV Dose and its Measurement**

133

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

141

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

148

149 The conditions that prevail in most previously reported laboratory studies on UV  
150 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

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

182

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

197

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

201 wavelength range for which the quantum yield is accurately known (Kuhn et al.,  
202 2004). In practice this involves measuring a specific chemical change from which the  
203 dose delivered is ultimately derived from the rate of reaction. Actinometric methods  
204 are capable of yielding very precise estimates of dose and are particularly well suited  
205 to fluid systems, as for example when measuring doses in a photoreactor for treating  
206 liquid reactants. There are relatively few actinometric methods for measuring the  
207 doses on the surfaces of a solid object and those that have been described by Kuhn et  
208 al (2004) appear quite involved: one method involves the immobilization of DNA and  
209 the use of monoclonal antibodies directed against specific lesions (Ishigaki et al,  
210 1999).

211

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

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

228

229 In an excellent study on the biological effects of UV, Harm (1980) claimed that the  
230 ‘biological effectiveness’ of UV was almost entirely due to its absorption by nucleic  
231 acids, and DNA in particular. Although, the emphasis of Harm’s study was on UV  
232 inactivation and mutagenesis in micro-organisms, with scarcely a mention of plants,  
233 there is no fundamental reason why plants should be excluded from such a statement.  
234 The absorbing components within nucleic acids are the nucleotide bases, and although  
235 their absorption spectra differ subtly from one another, all have maxima in the 260 to  
236 265 nm region (Harm, 1980). It follows therefore that absorption spectra will be  
237 species-dependant but the differences between individual species of fresh produce are  
238 likely to be slight, although as Terry and Joyce (2004) such investigations have not  
239 been conducted for fresh produce and have yet to be undertaken.

240

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

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

255

256 Although more than adequate for the task, low pressure mercury lamps are not the  
257 only artificial sources of UV that are available. There are a variety of medium and  
258 high pressure sources that yield a far more intense emission than the former (Phillips,  
259 1983). It is usually assumed that a principle termed the ‘dose-time reciprocity rule’ is  
260 universally applicable in considerations of treatment design. The rule states that equal  
261 doses of UV are equivalent irrespective of the intensity of the UV source employed,  
262 as a higher intensity can be compensated for by a shorter exposure time and a lower  
263 intensity by a correspondingly higher time of exposure. Most previous experimental  
264 work seems to support this principle but evidence has emerged of departures from it  
265 (Sommer et al., 1998) and therefore it would seem that investigations should be  
266 carried out to establish whether it is found to hold in the elicitation of hormetic  
267 effects.

268

#### 269 **4. Reversibility of Hormetic Effects**

270

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

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

280

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

301 **5. Process Design for Delivering Hormetic Doses of UV**

302

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

313

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

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

327

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

336

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



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

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

362

363

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

374

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

384

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

397

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

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

414

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

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

## 432 **6. Safety and UV-C**

433  
434 Exposure of humans to UV-C is associated with a number of harmful effects. UV-C  
435 causes acute and inflammatory changes to the cornea (Taylor et al., 1979) a condition  
436 commonly referred to as ‘welder’s eye’. Exposure of skin to UV-C results in  
437 erythema, or delayed reddening (Kelfkens and Van der Leun, 1989), and can also  
438 have profound effects on the immune system which can lead to severe and potentially  
439 lethal consequences (Baadsgaard, 1991).

440

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

450

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

454  
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## 457 **7. Conclusions**

458

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

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

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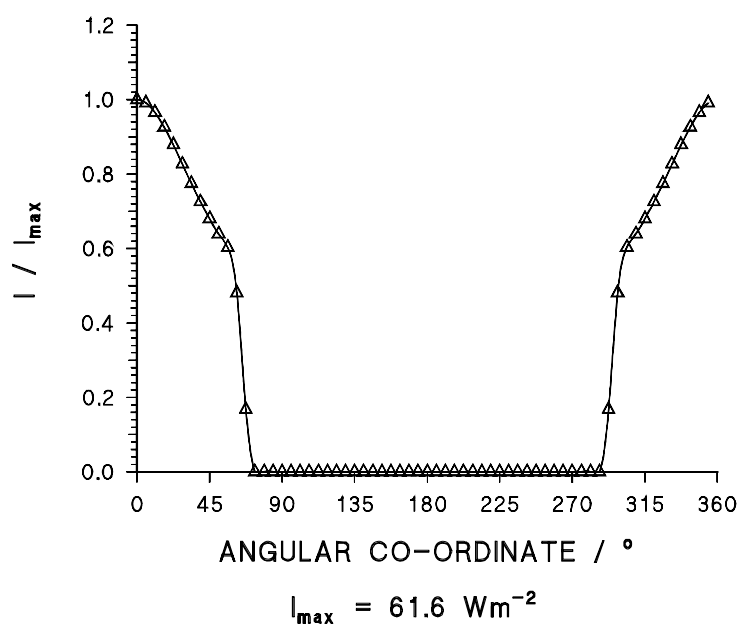
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693 Figure Captions

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

695 Figure 2. Dose Response Curve for Spores of *Bacillus subtilis* Deposited on the

696 Surface of Membrane Filters (Gardner, 1997).



697

698 Figure 1



699 Figure 2

