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ORIGINAL PAPER

The Effect of Ultraviolet Light on Microbial Inactivation and Quality Attributes of Apple Juice

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Abstract Non-thermal technologies such as UV irradiation can offer advantages for minimal processing of transparent beverages. In this study, reconstituted apple juice was exposed to UV light in a continuous laboratory scale system at energy dosages ranging from 2.66 to 53.10 J/cm^2 by changing the exposure time. Treated juices were then evaluated for microbial inactivation and selected physical and chemical attributes. Product quality was further assessed by sensory evaluation using a 30-member consumer panel. Microbiological analysis was performed by inoculating apple juice with *Escherichia coli* K12 and *Listeria innocua* and microbial numbers were counted pre- and post-processing. UV energy levels did not affect pH, ° Brix, or total phenols content, but decreased non-enzymatic browning ($p<0.01$) and antioxidant capacity ($p<0.05$) compared to unprocessed juice. A colour-lightening effect was noted with increasing energy dose. All UV treatments applied (2.66 J/cm^2 and above) resulted in a reduction below the detection level (<1 log cfu/ml) for both *E. coli* and *L. innocua* in apple juice. Sensory evaluation showed that samples treated with energy dosages up to 10.62 J/cm^2 were comparable to the control in terms of acceptability, though higher dosages produced adverse effects in terms of flavour and colour. Based on these results, UV treatment with low energy dosages could represent a valid alternative to thermal processing to eliminate pathogenic microorganisms while maintaining quality in reconstituted apple juice.

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Introduction

Heat processing is one of the most widely used preservation operations for beverages, but can have adverse effects on nutritional and sensory attributes. The increasing demand for fresher, more natural and nutritionally healthier food has led the food industry to investigate the application of alternative, non-thermal preservation technologies (Deliza et al. 2003), which can maintain the "fresh-like" quality attributes of food products, while ensuring microbiological safety and stability (Gould 2001).

Ultraviolet (UV) light is one such technology that has been shown to be effective against many types of food pathogens and food spoilage microorganisms, including viruses and protozoa (Guerrero-Beltrán and Barbosa-Cánovas 2004). UV light occupies a wide band of wavelengths in the light spectrum (100–400 nm), although the lethal effect on microorganisms is due predominantly to short-wave ultraviolet light (UV-C, 200–280 nm), which is responsible for the inactivation of organisms as a consequence of DNA damage. The photochemical alteration involves the cross-linking between neighbouring pyrimidine nucleoside bases (thymine and cytosine) in the same DNA strand (Harm 1980) which affects DNA transcription and replication, thereby causing cell death.

The initial major use of UV light was decontamination of water, while more recent applications include air sanitation (Shah et al. 1994), surface sterilisation (Kuse 1982; Stevens et al. 1996; Ranganna et al., 1997; Koutchma et al. 2009) and disinfection of liquids other than water

(Hanes et al. 2002; Koutchma et al. 2004; Matak et al. 2005; Koutchma 2009). UV processing under turbulent flow conditions is now approved by the US Food and Drug Administration (FDA 2000) for use in juice products as a treatment to reduce pathogens and other microorganisms. More recently short-wave ultraviolet processing has been successfully applied to vegetable and fruit juices (Shama 1999; Tran and Farid 2004; Guerrero-Beltrán and Barbosa-Cánovas 2005; Keyser et al. 2008). Clarified apple juice is a suitable medium for UV treatment because of its transparent nature. Keyser et al. (2008) showed that the application of a UV-C dosage of 0.234 J/cm^2 was sufficient to eliminate aerobic bacteria, yeasts and moulds from apple juice, whereas in the more opaque orange and tropical juices energy dosages as high as 1.404 J/cm^2 led to <1 log reductions in bacterial numbers. This was attributed to the presence of solids that decreased the penetration of UV light. In the same study, clear apple juice inoculated with *Escherichia coli* K12 and subjected to a UV-C dosage of 1.404 J/cm^2 showed a decrease of 7.42 log in the population, achieving more than the required microbial reduction of 5.0 log cycles recommended by the Food and Drug Administration in the United States (FDA 2001). *Escherichia coli* and *Listeria monocytogenes* have been widely studied as potential pathogens capable of surviving in fruit juices (Guerrero-Beltrán and Barbosa-Cánovas 2004; Basaran et al. 2004).

To the best of the authors' knowledge, no previous studies have taken an integrated approach to investigating the microbiological, physical, chemical and sensory quality effects of UV irradiation of apple juice. As a result, the first objective of the present study was to evaluate the effect of different UV energy dosages against *E. coli* and *Listeria innocua* inoculated in reconstituted apple juice. As it has been shown that changes in odour (Shimoda et al. 2003) and flavour (Su and Wiley 1998) can occur in apple juice after thermal processing, a second objective was to examine whether UV irradiation could be used as an alternative treatment to mitigate adverse effects on quality.

Material and Methods

Juice Production

Apple juice was prepared from a concentrate purchased from a local factory (Batchelors, Cabra, Dublin, Ireland) using a 1:7.8 dilution (*v*/*v*). Samples destined for quality analyses were reconstituted using non-carbonated mineral water (Ballygowan, Newcastle West, Co. Limerick, Ireland) while juices used for evaluation of microbial inactivation were prepared from deionised sterile water (15 min at 121 °C) and inoculated as described in "UV Transparency" section. The pH and the °Brix of the reconstituted juice was 3.70 and 11.2, respectively.

UV Processing Equipment

The UV rising film reactor used in this experiment was based on a tubular reactor manufactured by C-Tech (Chester, UK). It contained a vertical arrangement of concentric tubes. A 30 W low-pressure mercury lamp (70 cm long) was enclosed within a quartz tube with a nominal o.d. of 35 mm, which in turn was surrounded by a glass tube with a nominal i.d. of 37 mm. The apple juice was pumped upwards through the annular space (average gap estimated at 1.26 mm based on flow rate measurements) of the reactor using a peristaltic pump (Model No. L/S 77200-60, Masterflex, Cole-Parmer Instruments, IL, USA). Exposure times of 300, 150, 60, 30 and 15 s corresponded to flow rates of 22, 44, 88, 176 and 352 ml/min, respectively. Before and after use, equipment was put through a cleaning-in-place procedure with distilled water circulated for 10 min, followed by a 30 min circulation of NaOH solution (2% *w*/*v*). Subsequently, water and a 5% (*v*/*v*) hypochlorite-based solution (Milton) were each passed through the device for 10 min in order to disinfect the system, which was finally rinsed with sterile distilled water for 5 min. The rinse water samples were then plated on TSA and incubated at 37 °C for 48 h to determine the total bacteria populations and ensure that the processing unit was free of any contamination.

Dosage Calculation

The irradiance I of the lamp was measured using an UV–VIS radiometer (Model No RM-21, Dr. Gröbel UV-Elektronik GmbH, Germany) supplied with an UV-C sensor (spectral range from 200 to 280 nm) placed at the same distance from the UV lamp as the juices. The radiant exposure (dosage), defined as the energy delivered per unit surface area of the UV reactor, was calculated using the following formula

$$D = I \times t \tag{1}$$

where I was 0.177 W/cm^2 and t being the exposure time (s).

The dosages applied to the reconstituted apple juice were, therefore, 2.66, 5.31, 10.62, 26.55 and 53.10 J/cm^2, based on treatment times of 15, 30, 60, 150 and 300 s, respectively.

UV Treatments

An initial experiment was carried out by exposing apple juice to UV light for 60, 150 and 300 s, corresponding to energy dosages of 10.62, 26.55 and 53.10 J/cm^2, respec-

tively. Analyses were performed to assess the antimicrobial and sensory impacts of the treatments. Following an examination of the results obtained, shorter exposure times were then investigated for the antimicrobial effect (15 and 30 s yielding 2.66 and 5.31 J/cm^2, respectively) and sensory impact (30 s only). Physical and chemical analyses were also conducted on the samples. Untreated reconstituted juice was used in all experiments as control treatment.

UV Transparency

In order to establish the transparency of apple juice to UV light, absorbance was measured in 1 cm-path quartz cuvette at 254 nm using an UV–VIS spectrophotometer (UV-Mini 1240 Shimadzu, Columbia, MD, USA). "Absorbance coefficient" (ε) was calculated by measuring the absorbance of different dilutions of the juice and determining the slope of absorbance versus concentration.

Microbiological Preparation and Analysis

Microbial inactivation was assessed using *L. innocua* NCTC 11288 and *E. coli* K12 DSM 1607. For long-term maintenance these microorganisms were stored in glycerol at −20 °C. Strains were cultured overnight in Tryptone Soya Broth (Oxoid, Basingstoke, Hampshire, UK), at 37 °C in either shaking (*E. coli*) or static (*L. innocua*) water baths. The reconstituted apple juice was then inoculated with either *L. innocua* or *E. coli* to give an initial microbial concentration of approximately 5 log cfu/ml.

Samples of the inoculated juices were taken pre- (control) and post-treatment and serially diluted in sterile Ringers solution. Viable cell counts were obtained by plating the juice samples and the serial dilutions in tryptone soya agar (Oxoid) for total bacterial counts. eosin–methylene blue agar (Oxoid) and *Listeria* selective agar with selective supplement (Oxoid) were used as selective media for *E. coli* and *L. innocua*, respectively. Plates were incubated at 37 °C for 48 h, after which the surviving colonies were enumerated (cfu/ml). Samples of juice treated with UV light were stored at two different temperatures, 30 °C and 4 °C, to study the effect of the storage temperature over time (0, 24 or 48 h) on microbial survival and growth.

Physical and Chemical Analyses

The pH of the juice pre- and post-treatment was measured with a pH metre (Model No. 9450, Unicam Ltd., Cambridge, UK) while the °Brix was measured using a hand held refractometer (0–50% Sugar Refractometer, Bellingham & Stanley Ltd., Tunbridge Wells, UK).

The colour of the juice was evaluated using a tristimulus colorimeter (Model No. CR 300 Chroma Meter, Minolta, Osaka, Japan) in the Hunter Lab colour space. Triplicate measurements were taken for each set of samples and the values for L, a and b were recorded. In addition, the total colour difference (ΔE) was calculated using Eq. 2 in comparison to an untreated control and classified according to Cserhalmi et al. (2006).

$$\Delta E = \sqrt{(\Delta L^2 + \Delta a^2 + \Delta b^2)} \quad (2)$$

The non-enzymatic browning index (NEBI) was determined according to the method of Meydav et al. (1977) in which 5 ml of ethyl alcohol (Analar 950 g/kg) was added to 5 ml of sample, centrifuged for 10 min at 8,700×g (Model No. J2-HS, Beckman Instruments Inc., Palo Alto, CA, USA) and the absorbance of the supernatant was read at 420 nm in a spectrophotometer (Model No. UV-Mini 1240, Shimadzu, China). The total phenols content was determined by the Folin–Ciocalteu colorimetric method (Singleton and Rossi 1965) and results were expressed as gallic acid equivalents (mg/l).

The determination of the total antioxidant activity was based on the method of Kim et al. (2002), but using an initial absorbance reading of 0.80 at 734 nm to provide a greater measurement range. Standard Trolox solutions were also evaluated and the results were expressed as Trolox equivalent antioxidant capacity (TEAC).

Consumer Acceptability Study

A consumer acceptability study was conducted using 30 untrained panellists (19 male and 11 female). Each juice was presented in a randomised order as a 20-ml sample in a clear plastic cup with a 3-digit code number. Unsalted crackers and still water (Ballygowan) were served for cleansing the palate between samples. The panellists were first asked to assess the colour and odour of the juices and were then asked to taste each sample to evaluate its sweetness, acidity, flavour and overall acceptability. A nine-point hedonic scale was used (1=dislike extremely and 9=like extremely; Peryam and Pilgrim 1957) for all the parameters, with the exception of sweetness and acidity for which the midpoint of the scale (5) was considered optimal.

Statistical Analysis

A one-way analysis of variance and a Student's t test for pair wise comparisons were conducted to determine significant differences between treatment means. Differences at $p<0.05$ were considered significant. Experimental treatments were carried out in duplicate ($n=2$) for the all microbiological investigations and in triplicate ($n=3$) for

Table 1 Effect of ultraviolet (UV) irradiation dose on inactivation of *L. innocua* and *E. coli* in apple juice

UV energy dosages (J/cm^2)	*L. innocua*		*E. coli*	
	TSA	LSA	TSA	EMB
0	5.79 ± 0.411	4.80 ± 0.240	5.55 ± 0.215	5.03 ± 0.487
2.66	ND	ND	ND	ND
5.31	ND	ND	ND	ND
10.62	ND	ND	ND	ND
26.55	ND	ND	ND	ND
53.10	ND	ND	ND	ND

Results are expressed as log cfu/ml

TSA tryptone soya agar medium, *LSA* listeria selective agar medium, *EMB* eosin–methylene blue medium, *ND* counts were below limit of detection

the physicochemical analysis. The sensory data for the 30 s exposure time were evaluated against the corresponding controls for comparative purposes. All statistical analyses were performed using SAS (2005).

Results and Discussion

Microbial Counts

A number of studies have been reported on the effects of UV light on fruit juices (Guerrero-Beltrán and Barbosa-Cánovas 2004; Geveke 2005a; Keyser et al. 2008). Koutchma et al. (2004) investigated factors such as pH and °Brix that could potentially impact the lethality rate in UV-treated apple juice and cider and observed that the transparency of the medium is the critical factor in determining the efficacy of UV light inactivation. The reconstituted apple juice used in the current study had a relatively low absorbance coefficient at 254 nm (ε= 5.81 cm^{-1}), thereby making it a suitable medium for UV treatment (Unluturk et al. 2004).

In the present work, counts below the detection limit (1 log cfu/ml) were obtained for the evaluated treatments, which indicate satisfactory inactivation of the inoculated microbial flora (see Table 1). A significant reduction ($p<$ 0.01) of 4.83 and 4.59 log cycles was observed for *L. innocua* and *E. coli* counts, respectively, in processed samples of apple juices compared to the untreated control which contained initial populations of 5.79 and 5.55 cfu/ml for *L. innocua* and *E. coli*, respectively. To optimise the specificity and sensitivity of the microbial assessment, selective and non-selective media were used to detect both injured and non-injured cells. Injured bacteria may not be able to recover on a selective media which could consequently result in an underestimation of surviving cells. In the present study, the reductions in populations of both organisms were below detection levels (1 log cfu/ml) in the two media, and therefore, it was not possible to comment on the differences in counts between injured and inactivated cells. Storing processed apple juice samples for up to 48 h at 4 °C or 30 °C did not result in any detectable levels of the test organisms.

Differences in susceptibility between the microbial species to UV light were not apparent in our study. Geveke (2005b) found that *L. innocua* exhibited a higher degree of resistance to UV light than *E. coli*. Different flow rates (8, 14 and 20 ml/min) and lengths of UV treatment chamber (30, 40 and 50 cm) were tested by Gachovska et al. (2008), who achieved a reduction of 3.46 log cfu/ml for *E. coli* in apple juice when exposed in a 50-cm length of UV treatment chamber at 8 ml/min. Ngadi et al. (2003)

Table 2 Effect of different ultraviolet (UV) irradiation dosages on colour attributes of reconstituted apple juice

UV energy dosages (J/cm^2)	*L*	*a*	*b*	ΔE^a
0	24.4a±1.50	1.3a±1.23	6.2±0.63	–
5.31	24.8b±1.26	0.9bc±1.51	6.3±0.57	0.68a
10.62	25.2c±1.19	0.6c±1.67	6.4±0.67	1.17b
26.55	26.0d±1.09	−0.1d±1.80	5.7±1.51	2.40c
53.10	26.9e±1.19	−0.7e±1.57	4.9±2.27	3.80d
p value	*	*	NS	*

Means not followed by the same superscript within the columns are significantly different ($p<0.05$)

NS not significant

*$p<0.001$

[a] ΔE values calculated from the *L*, *a* and *b* replicate values

Table 3 Effect of different ultraviolet (UV) irradiation dosages on chemical and physical properties of reconstituted apple juice

UV energy dosages (J/cm^2)	ΔNEBI	Total phenols (GAE; mg/l)	TEAC (mM)
0	–	299.7±12.03	1.54a±0.019
5.31	0.002a±0.0072	310.1±11.32	1.46a,b±0.030
10.62	−0.011b±0.0137	301.2±21.98	1.41b,c±0.060
26.55	−0.036c±0.0130	306.9±0.44	1.42b,c±0.058
53.10	−0.061d±0.0122	299.8±10.36	1.37c±0.061
p value	*	NS	**

Means not followed by the same superscript within the columns are significantly different ($p<0.05$)

ΔNEBI difference in non-enzymatic browning index between the untreated control and the treated samples, *GAE* gallic acid equivalent, *TEAC* Trolox equivalent antioxidant activity, *NS* not significant

*$p<0.001$; **$p< 0.05$

investigated the effect of pH (3.5 and 9.1), depth of food medium (1, 3.5, 5 and 10 mm) and UV light dosage (0 to 0.39 J/cm^2) on *E. coli* inactivation in apple juice and liquid egg white. They observed a 5-log reduction for *E. coli* in both liquid products at a sample depth of 1 mm and a dosage of 0.39 J/cm^2.

Physical and Chemical Analysis

The results for the colour attributes (*L*, *a* and *b*) and the total colour difference (ΔE) as a function of UV exposure are shown in Table 2. The ΔE value increased with UV exposure and only became "noticeable" ($1.5<\Delta E<3.0$) at the higher energy dosages (26.55 J/cm^2 and above), while "slightly noticeable" ($0.5<\Delta E<1.5$) changes occurred in the apple juice exposed to lower energy dosages. In particular, an increase in the latter caused a lightening or bleaching effect on the reconstituted apple juice as indicated by a significant linear increase ($p<0.001$) in *L*. Also the *a* value (redness) was significantly affected by the treatment, decreasing linearly ($p<0.001$) from the initial value of 1.29 to −0.68 after 300 s of irradiation. These results are in agreement with a previous study on colour changes induced in fruit juices by UV irradiation (Ibarz et al. 2005), where a brightening effect was observed in apple, lemon and peach juices whereas a decrease in redness suggested photochemical destruction of the polymeric compounds arising from enzymatic browning processes. The latter workers noted a slight decrease in *b* value (5.90% in apple juice). In the present study, no significant change ($p\geq0.05$) was observed, and even though at energy dosage above 26.55 J/cm^2 a reduction in *b* value was observed, the extent of such decrease was not significant ($p\geq0.05$).

A significant reduction ($p<0.001$) in NEBI was observed (Table 3), the extent depending on the duration of the treatment, that matched the trend observed for the *a* value. In contrast to the present results, Donahue et al. (2004) found a darkening effect of UV light on apple cider, but this was attributed to enzymatic browning reactions, which were unlikely to happen in the reconstituted apple juice used in the current study.

Average pH and °Brix were 3.71 and 11.2, respectively, and were not affected by the UV treatments. Results for total phenols and TEAC are reported in Table 3. The total phenols content showed no significant change while increasing the UV dosage led to a decrease in the TEAC value ($p<0.05$). The maximum decrease in antioxidant activity (11%) was observed in samples exposed to 53.10 J/

Table 4 Effect of different ultraviolet (UV) irradiation dosages on sensory attributes of reconstituted apple juice

UV energy dosages (J/cm^2)	Colour	Odour	Sweetness	Acidity	Flavour	Overall acceptability
0	6.1a±1.48	6.5a±1.52	6.2a±1.57	4.3±1.99	6.8a±1.14	6.7a±1.38
5.31	6.0a±0.99	6.5a±1.28	5.6a,b,c±1.45	4.5±1.76	6.3a±1.87	6.2a±1.65
10.62	6.1a±1.25	5.7a±1.63	5.9a,b±1.64	4.7±1.68	6.0a±2.00	5.9a±1.95
26.55	5.8a±1.38	4.8b±1.86	5.2b,c±1.98	4.5±2.08	4.8b±2.03	4.6b±2.07
53.10	4.0b±1.51	3.5c±1.81	4.8c±2.16	5.1±2.15	3.3c±1.68	3.1c±1.56
p value	*	*	**	NS	*	*

Means not followed by the same superscript within the columns are significantly different ($p<0.05$)

NS not significant

*$p< 0.001$; **$p<0.05$

cm^2, whereas those receiving 5.31 J/cm^2 showed no significant changes compared to the untreated control ($p>0.05$). The antioxidant activity of apple juice is mostly due to phenolic compounds and in particular polyphenolic acids, flavonoids and proanthocyanidins (Seeram et al. 2008). Vitamin C is another source of antioxidants in fruit juices, but Gardner et al. (2000) found that in apple juice it contributes less than 5% of the total antioxidant potential with an average content of only 0.9 mg ascorbic acid per 100 g (USDA 2008). Noci et al. (2008) applied UV light to freshly squeezed apple juice using a batch system in which the product was exposed for 30 min at a distance of 30 cm from the light source. Although the system employed was different from the one used in the present study, chemical quality attributes (pH, °Brix, NEBI and relative antioxidant capacity) were similarly unaffected in the UV-treated fresh apple juice compared to an untreated control ($p\geq0.05$), while a significant decrease was found in total phenols ($p<0.05$).

Effect of UV Light on Sensory Attributes of Apple Juice

To our knowledge, this is the first reported study that has investigated the effect of UV treatment on sensory parameters in apple juice. Donahue et al. (2004) reported that the flavour of apple cider exposed to UV light for 4.06 s in a chamber delivering energy dosages of 17.54 mJ/cm^2 showed no significant difference ($p\geq0.05$) to an untreated control. The results of the present study are shown in Table 4. Based on the mean hedonic ratings of colour, odour, flavour and overall acceptability, the apple juice samples exposed to 5.31 and 10.62 J/cm^2 energy dosages proved the most acceptable to the panel. Statistical analysis revealed no significant differences ($p\geq0.05$) between these two samples and the untreated control in all attributes. The panellists showed a significant dislike ($p<0.001$) of the product colour at an energy dosage of 53.10 J/cm^2. This result was in agreement with the instrumental analysis which showed that the colour difference (ΔE) became "noticeable" once the energy dosages exceeded 26.55 J/cm^2. Juices exposed to UV light at 26.55 J/cm^2 or above showed a significant decrease compared to the control ($p<0.001$) in the odour attribute as perceived by the panellists. A significant decrease ($p<0.05$) in the sweetness scores was observed in all the UV-treated samples while the duration of UV treatments did not affect the acidity of apple juice. Hedonic scores for odour, flavour and acceptability decreased significantly ($p<0.001$) after exposure dosages greater or equal to 26.55 J/cm^2 indicating that they caused some adverse changes in the quality attributes of the juice.

A strong positive correlation was found in the initial study between the product acceptability and the sensory evaluation of flavour ($R^2=0.86$), suggesting that the panellists were more influenced by this attribute than by the appearance in making their overall evaluation of the product. As all treatments examined reduced the microbial counts below detection limits, the adverse effects observed at the higher energy dosages would not represent a concern for practical application of UV irradiation for apple juice.

Conclusions

Overall, this study has shown that UV technology applied for short times could represent a valid alternative to thermal processing of reconstituted apple juice by achieving a reduction in *E. coli* and *L. innocua* to below detection limits, while having marginal effects on physical, chemical and sensory properties.

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References

Basaran, N., Quintero-Ramos, A., Moake, M. M., Churey, J. J., & Worobo, R. W. (2004). Influence of apple cultivars on inactivation of different strains of *Escherichia coli* O157:H7 in apple cider by UV irradiation. *Applied and Environmental Microbiology, 70*(10), 6061–6065.

Cserhalmi, Z., Sass-Kiss, Á., Tóth-Markus, M., & Lechner, N. (2006). Study of pulsed electric field treated citrus juices. *Innovative Food Science & Emerging Technologies, 7*(1–2), 49–54.

Deliza, R., Rosenthal, A., & Silva, A. L. S. (2003). Consumer attitude towards information on non conventional technology. *Trends in Food Science & Technology, 14*(1–2), 43–49.

Donahue, D., Canitez, N., & Bushway, A. (2004). UV inactivation of *E. Coli* O157:H7 in apple cider: quality, sensory and shelf-life analysis. *Journal of Food Processing and Preservation, 28*(5), 368–387.

FDA. (2000). Irradiation in the production, processing and handling of food: ultraviolet radiation for the processing and treatment of food. *Federal Register, 65*, 71056–71058.

FDA. (2001). Hazard analysis and critical control point (HACCP): procedures for the safe and sanitary processing and importing of juices. Final rule. *Federal Register, 66*, 6137–6202.

Gachovska, T. K., Kumar, S., Thippareddi, H., Subbiah, J., & Williams, F. (2008). Ultraviolet and pulsed electric field treatments have additive effect on inactivation of E. coli in apple juice. *Journal of Food Science, 73*(9), M412–M417.

Gardner, P. T., White, T. A. C., McPhail, D. B., & Duthie, G. G. (2000). The relative contributions of vitamin C, carotenoids and phenolics to the antioxidant potential of fruit juices. *Food Chemistry, 68*(4), 471–474.

Geveke, D. J. (2005a). *Nonthermal inactivation of Escherichia Coli and Listeria Innocua in apple cider using a novel ultraviolet light apparatus*. Paper No: Food Safety Intervention Technologies Research. American Institute of Chemical Engineers. 606b.

Geveke, D. J. (2005b). UV inactivation of bacteria in apple cider. *Journal of Food Protection, 68*(8), 1739–1742.

Gould, G. W. (2001). Symposium on "nutritional effects of new processing technologies". New processing technologies: an overview. *Proceedings of the Nutrition Society, 60*(4), 463–474.

Guerrero-Beltrán, J. A., & Barbosa-Cánovas, G. V. (2004). Advantages and limitations on processing foods by UV light. *Food Science and Technology International, 10*(3), 137–147.

Guerrero-Beltrán, J. A., & Barbosa-Cánovas, G. V. (2005). Reduction of *Saccharomyces Cerevisiae*, *Escherichia Coli* and *Listeria Innocua* in apple juice by ultraviolet light. *Journal of Food Process Engineering, 28*(5), 437–452.

Hanes, D. E., Worobo, R. W., Orlandi, P. A., Burr, D. H., Miliotis, M. D., Robl, M. G., et al. (2002). Inactivation of *Cryptosporidium parvum oocysts* in fresh apple cider by UV irradiation. *Applied and Environmental Microbiology, 68*(8), 4168–4172.

Harm, W. (1980). *Biological effects of ultraviolet radiation*. Cambridge, UK: Cambridge University Press.

Ibarz, A., Pagán, J., Panadés, R., & Garza, S. (2005). Photochemical destruction of color compounds in fruit juices. *Journal of Food Engineering, 69*(2), 155–160.

Keyser, M., Muller, I. A., Cilliers, F. P., Nel, W., & Gouws, P. A. (2008). Ultraviolet radiation as a non-thermal treatment for the inactivation of microorganisms in fruit juice. *Innovative Food Science & Emerging Technologies, 9*(3), 348–354.

Kim, D.-O., Lee, K. W., Lee, H. J., & Lee, C. Y. (2002). Vitamin C equivalent antioxidant capacity (VCEAC) of phenolic phytochemicals. *Journal of Agricultural and Food Chemistry, 50*(13), 3713–3717.

Koutchma, T., Forney, L. J., & Moraru, C. I. (2009). *Ultraviolet light in food technology: principles and applications*. Florida, USA: CRC Press.

Koutchma, T., Keller, S., Chirtel, S., & Parisi, B. (2004). Ultraviolet disinfection of juice products in laminar and turbulent flow reactors. *Innovative Food Science and Emerging Technologies, 5*(2), 179–189.

Koutchma, T. (2009). Advances in ultraviolet light technology for non-thermal processing of liquid foods. *Food and Bioprocess Technology, 2*(2), 138–155.

Kuse, D. (1982). UV-C sterilization of packaging materials in the dairy industry. *Deutsche Milchwirtschaft, 33*, 1134–1137.

Matak, K. E., Churney, J. J., Worobo, R. W., Sumner, S. S., Hovingh, E., Hackney, C. R., et al. (2005). Efficacy of UV light for the reduction of *Listeria monocytogenes* in goat's milk. *Journal of Food Protection, 68*, 2212–2216.

Meydav, S., Saguy, I., & Kopelman, I. J. (1977). Browning determination in citrus products. *Journal of Agricultural and Food Chemistry, 25*(3), 602–604.

Ngadi, M., Smith, J. P., & Cayouette, B. (2003). Kinetics of ultraviolet light inactivation of Escherichia coli O157:H7 in liquid foods. *Journal of the Science of Food and Agriculture, 83*(15), 1551–1555.

Noci, F., Riener, J., Walkling-Ribeiro, M., Cronin, D. A., Morgan, D. J., & Lyng, J. G. (2008). Ultraviolet irradiation and pulsed electric fields (PEF) in a hurdle strategy for the preservation of fresh apple Juice. *Journal of Food Engineering, 85*(1), 141–146.

Peryam, D. R., & Pilgrim, P. J. (1957). Hedonic scale method for measuring food preferences. *Food Technology, 11*, 9–14.

Ranganna, B., Kushalappa, A. C., & Raghavan, G. S. V. (1997). Ultraviolet irradiance to control dry rot and soft rot of potato in storage. *Canadian Journal of Plant Pathology, 19*(1), 30–35.

SAS. (2005). *SAS user's guide: statistics (Version 9.1.3)*. Cary: SAS Institute Inc.

Seeram, N. P., Aviram, M., Zhang, Y., Henning, S. M., Feng, L., Dreher, M., et al. (2008). Comparison of antioxidant potency of commonly consumed polyphenol-rich beverages in the United States. *Journal of Agricultural and Food Chemistry, 56*(4), 1415–1422.

Shah, P. B., Shah, U. S., & Siripurapu, S. C. B. (1994). Ultraviolet irradiation and laminar air flow systems for clean air in dairy plants. *Indian Dairyman, 46*, 757–759.

Shama, G. (1999). Ultraviolet light. In R. K. Robinson, C. Batt, & P. Patel (Eds.), *Encyclopedia of food microbiology* (pp. 2208–2214). London: Academic.

Shimoda, M., Katoh, T., Suzuki, J., Kawaraya, A., Igura, N., & Hayakawa, I. (2003). Changes in the odors of reconstituted apple juice during thermal processing. *Food Research International, 36*(5), 439–445.

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture, 16*(3), 144–158.

Stevens, C., Wilson, C. L., Lu, J. Y., Khan, V. A., Chalutz, E., Droby, S., et al. (1996). Plant hormesis induced by ultraviolet light-C for controlling postharvest diseases of tree fruits. *Crop Protection, 15*(2), 129–134.

Su, S. K., & Wiley, R. C. (1998). Changes in apple juice flavor compounds during processing. *Journal of Food Science, 63*(4), 688–691.

Tran, M. T. T., & Farid, M. (2004). Ultraviolet treatment of orange juice. *Innovative Food Science & Emerging Technologies, 5*(4), 495–502.

Unluturk, S. K., Arastoopour, H., & Koutchma, T. (2004). Modeling of UV dose distribution in a thin-film UV reactor for processing of apple cider. *Journal of Food Engineering, 65*(1), 125–136.

USDA (2008) *Composition of foods raw, processed, prepared: September 2008 USDA National Nutrient Database for Standard Reference, Release 21, Washington DC, USA*. Available at http://www.ars.usda.gov/nutrientdata. Accessed May 2009.