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Ultraviolet treatment of orange juice

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Abstract

Ultraviolet (UV) with a wavelength of 254 nm tends to inactivate most types of microorganisms. Most juices are opaque to UV due to the high-suspended solids in them and hence the conventional UV treatment, usually used for water treatment, cannot be used for treating juices. In order to make the process efficient, a thin film reactor was designed and constructed from glass with the juice flowing along the inner surface of a vertical glass tube as a thin film. The decimal reduction doses required for the reconstitute orange juices (OJ; 10.5° Brix) were 87 ± 7 and 119 ± 17 mJ/cm^2 for the standard aerobic plate count (APC) and yeast and moulds, respectively. The shelf life of fresh squeezed orange juice was extended to 5 days with a limited exposure of UV (73.8 mJ/cm^2). The effect of UV on the concentration of Vitamin C was investigated using both HPLC and titration methods of measurements. The degradation of Vitamin C was 17% under high UV exposure of 100 mJ/cm^2, which was similar to that usually found in thermal sterilization. Enzyme pectin methylesterase (PME) activity, which is the major cause of cloud loss of juices, was also measured. In contrast to the heat treatment, UV processing does not inactivate enzyme pectin methylesterase. The energy required for UV treatment of orange juice (2.0 kW h/m^3) was much smaller than that required in thermal treatment (82 kW h/m^3). The color and pH of the juice were not significantly influenced by the treatment.

Keywords: Aerobic plate count (APC); Yeast; Moulds; Colony-forming units (cfu); Sterilization; Ultraviolet (UV); Vitamin C (L-ascorbic acid); Pectin methylesterase (PME); Orange juice (OJ)

Industrial relevance: This paper is of interest since it suggest — despite the low UV transmittance in orange juices — the use of a thin film UV reactor. The data suggest that shelf life extension from 2 to more than 5 days could be achieved with less energy requirements than for thermal processing. However, it seems unlikely that such thin film reactors could provide a real alternative to current conventional or new (e.g. high pressure pulsed electric field) processing.

1. Introduction

Ultraviolet (UV) treatment is a disinfection method that can be applied to inactivate harmful microbes in food. The treatment can be carried at low temperature, therefore, it can be grouped with other nonthermal methods such as pulsed electric fields (PEF), high pressure (HP), and irradiation. Each method has different mechanisms of inactivation (Tran, 2001). Since 1985, UV radiation has been used for water disinfection and has replaced some of the conventional chlorination processes in some countries (Gibbs, 2000). The peak UV absorption efficiency for DNA lies between 250 and 280 nm. The UV rays at this germicidal wavelength alters the genetic material in cells so that bacteria, viruses, moulds, and other microorganisms can no longer reproduce and may be considered inactive (Billmeyer, 1997; Bolton, 2001; Giese, 1997). In food processing, UV disinfection of water has been used in some processes such as brewing (McCarty & Scanion, 1993), soft drink processing (Gibbs, 2000), and in the cheese-making processes (Honer, 1988). UV has been also used in sterilizing sugar syrup (Stother, 1999). However, the use of UV for disinfection of liquid food such as juices has not been widely studied (Anon., 1987, 1988; Nakayama & Shinya, 1981).

Fresh orange juice (OJ) is spoiled with time due to the growth of microorganisms. Yeast and moulds, *Lactobacil-*

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lus, *Leuconostoc* and thermophilic *Bacillus* (*Bacillus subtilis* and/or *Bacillus pumilus* spore formers) are common microorganisms growing in orange juice (Kimball, 1991, 1996). Recently, *Alicyclobacillus acidoterrestris*, which can be seen as a novel thermoacidophilic spore-forming bacterium and the target of juice industry due to their heat resistance, has been reported to cause the spoilage in fruit juice (Walls & Chuyate, 2000; Yamazaki, Kawai, Inoue, & Shinano, 1997). Therefore, orange juice should undergo some type of processing to inactivate most of the microorganisms; otherwise, its shelf life will be very short. Thermal sterilization is widely used; however, in this type of treatment, the juice changes color and lose some of its aromas and vitamins during the process of heating. One of the objectives of this work is to study the influence of UV on the different types of microorganisms, which are the standard aerobic plate count (APC) of viable microorganisms and yeast and moulds. The microorganisms in treated and untreated juices were analyzed based on plate count technique.

The loss of nutritional quality during the processing and storage of foods has become an increasingly important associate with the introduction of nutrition-labeling regulations (Laing, Schlueter, & Labuza, 1978). Vitamin C is an important vitamin in orange juice and plays an important role in human health and preservation. In the food industry, Vitamin C is used as a food additive (Somogyi, 1996). It is frequently added to fruit juices to preserve and protect them from any color changes. Therefore, the effect of UV on Vitamin C in orange juice was investigated in this study.

Moreover, the quality of juice during storage is usually related to “cloud loss”, a serious quality defect of orange juice due to the effect of enzyme pectin methylesterase (PME), which tends to deesterify the pectin (Bennett, 1987). Consequently, the low-methoxyl pectin, or pectate, coagulates with calcium ions in the juice, causing cloud loss (Joslyn & Pilnik, 1961; Krop, 1974). In order to prevent this quality defect, it is necessary to inactivate the enzyme pectin methylesterase by 99.9%. This is usually achieved during thermal processing of orange juice at 90 °C for 60 s (Eagerman & Rouse, 1976). In the ultraviolet processing, orange juice is treated at about 25 °C. The effect of UV, at such low temperatures, on the activity of enzyme pectin methylesterase is not known yet and will be discussed in this paper.

UV treatment of juices is difficult due to their low UV transmittance through the juice containing high-suspended solids. Hence, for the treatment to be effective, the juice has to be exposed to UV as a thin film, unlike the conventional way used in water disinfecting systems. In this work, a small falling film UV reactor was designed and constructed to treat orange juice. The effects of UV dose on total bacteria counts (APC), yeast, and moulds were investigated in addition to its effect on Vitamin C and enzyme pectin methylesterase present in the juice.

2. Materials and methods

2.1. Materials and chemicals

Plate Count Agar (Standard Methods Agar), Potato Dextrose Agar (PDA), Tryptone Glucose Extract Agar (GTA) were manufactured in USA and purchased from Fort Richard, Auckland, New Zealand. Tartaric acid (Acs-grade) was obtained from Sigma (USA). Ammonium dihydrogen orthophosphate was obtained from Analytical Univar, Ajax Chemicals, Sydney, NSW, Australia. Metaphosphoric acid was purchased from J.T Baker Chemical, NJ, USA. Orthophosphoric acid was obtained from BDH Chemicals, Poole, England, and UK. Sodium hydroxide was obtained from Scharlau Chemie, Spain. L-Ascorbic acid (Vitamin C), Citrus pectin, and 2,6-dichloroindophenol sodium salt were obtained from Sigma, St Louis, MO, USA. Concentrated orange juice was provided by Rio Gold Beverage, New Zealand. Navel New Zealand orange fruit was purchased from local market and squeezed to provide fresh orange juice.

2.2. Orange juice preparation

2.2.1. Preparation of reconstituted and fresh squeezed orange juice

Reconstituted orange juice was prepared from concentrated orange juice. The dilution ratio was 1 l of concentrated orange juice (1.321 kg) to 6.9 l distilled water. In order to increase the number of microorganisms in the juice, 2 l of the reconstituted juice was partially fermented by keeping it at room temperature for 5 days. The fermented juice was mixed with 15 l of fresh reconstituted orange juice before starting the UV treatment.

Fresh squeezed orange juice was prepared by hand squeezing of New Zealand Navel orange fruit and filtered through a stainless filter with net square hole of 1 mm^2 (1 mm×1 mm) to provide about 18 l of filtered orange juice. The juice was kept in the refrigerator at 4 °C for 8 hours, followed by 8 h at room temperature before starting the UV treatment. Fifteen to eighteen liters of orange juice were consumed in each experiment. For the study of deactivation of enzyme pectin methylesterase, only fresh squeezed juice was used because the enzyme will not be active in the reconstitute juice.

2.3. Ultraviolet processing of orange juice

A small UV reactor was designed and manufactured at the workshop of the University of Auckland, New Zealand in 1997 (Farid, Chen, & Dost, 2000). Using 50-mm-diameter and 450-mm-long glass tube, the UV reactor was fixed vertically with the orange juice flowing by gravity as a thin uniform film along its inner surface, as shown in Fig. 1. A low-pressure UV lamp with a length of 40 cm and 30-W total power, emitting 6 W of germicidal UV

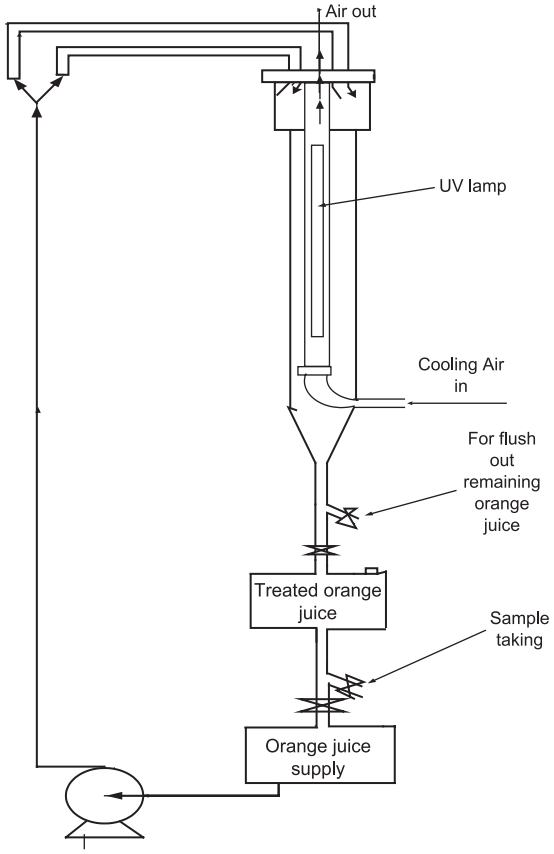

Fig. 1. Process flow diagram of the ultraviolet experimental setup. Orange juice is pumped from the feed tank through a rotameter and is distributed by 4 injections small pipes, where the orange juice flows as a thin film running along the inner surface of the reactor. Under UV exposure, orange juice is treated and contained in the treated tank then transferred to the feed tank, where it is prepared for the next cycle. Cooling air was pumped through the annular space for cooling the lamp.

(254 nm) was fixed at the axis of the glass tube and enclosed by a quartz tube to prevent direct contact of the lamp with the juice. The quartz tube was selected due to its very high UV transmission. Air was pumped through the annular space surrounding the lamp for cooling because lamp efficiency drops at high temperature, with a maximum effectiveness at a temperature around 40 °C. The orange juice was pumped from a feed tank using a small Peristaltic pump 6–600 rpm, Cole-Parmer Instrument. The flow rate of juice was controlled with Masterflex speed controller, which was produced and obtained from the same company of the peristaltic pump. The effect of UV dose was studied by circulating the juice more than once through the reactor rather than changing the lamp intensity. The juice film thickness was controlled by adjusting its flow rate, which was necessary to insure a good penetration of the UV light. The thickness of the thin film of orange juice in this study was in the range of 0.21 mm to 0.48 mm, which corresponds to juice flow rate of 0.6 l/min. This range of film thickness allows UV transmission during the disinfection process. It has been reported that any opaque liquid maybe considered transparent to UV light if it is in the form of a liquid film having a thickness less than 1.6 mm (Sarkin, 1977).

2.4. Microorganisms analysis

One milliliter of decimal dilution of untreated and treated orange juice samples were pipetted to petri dishes. Total aerobic plate counts were enumerated using pour plate method on Plate Count Agar. Incubation was performed at 35 °C for 48 h. Total yeast and moulds were enumerated on Potato Dextrose Agar by pour plating technique. The incubation for total yeast and mould counts was done at 26 °C/5 days. Each test was performed in duplicate and results were expressed as colony-forming units (CFU) per milliliter. For shelf life testing of fresh squeezed orange juice, the total plate counts and total yeast and moulds counts of treated and untreated orange juice stored at 4 °C were determined every 2 to 3 days for 2 weeks.

2.5. Vitamin C analysis

Vitamin C (L-ascorbic acid) concentration was determined using a modification of the HPLC method (Wilson & Shaw, 1987) and FAO (Food and Agriculture Organization) method employing 2, 6-dichloindophenol titration procedure (FAO, 1986).

2.5.1. HPLC method for Vitamin C analysis

Orange juices samples (10 ml), exposed to different UV doses, were centrifuged in Sorvall centrifuge (RC-28S, Du Pont USA) for 20 min at 4 °C, to remove suspended solids. A supernatant (4 ml) of each sample was mixed with 4 ml of 6% meta-phosphoric acid then filtered successively through 0.2-μm PTFE membrane filter (Alltech Associates, Deerfield, IL, USA) and placed in a 1.1-ml glass auto sampler vial prior to HPLC injection. Each sample was prepared in triplicate to provide reliable measurement of Vitamin C concentration. The instrument used was a Hewlett-Packard (Palo Alto, CA, USA) series 1100 System, comprising online degasser, HPLC pump with quaternary low-pressure mixer, and auto sampler. These are connected to HP series 1100 diode-array detector. Data acquisition was performed using Hewlett-Packard ChemStation Software. The mobile phase was aqueous ammonium dihydrogen orthophosphate (2% w/v) adjusted to pH 2.8 with phosphoric acid (Wilson & Shaw, 1987) at a flow rate of 0.7 ml/min. A Luna C18, 250×4.6 mm I.D., stainless steel column (Phenomenex, Torrance, CA, USA) was used. The column temperature was set to 20 °C. For orange juice samples and ascorbic acid standards, the injection volume was 5 μl. The wavelength monitored was 245 nm and the time for each sample was set up to 20 min. A series of standards ascorbic acid were prepared in 3% meta-phosphoric acid solution for the peak area integration, which was used for the calibration. The calibration curve was reproduced in triplicate and the standard samples were also run in triplicate.

2.5.2. Titration method for Vitamin C determination

The orange juice sample was centrifuged at 4 °C for 20 min. The supernatant (50 ml) was mixed with 25 ml of 20% meta-phosphoric acid as a stabilizing agent (FAO, 1986) and diluted to a volume of 100 ml. The mixture (10 ml) and 2.5 ml of acetone were titrated with 2, 6-dichloindophenol solution until a faint pink color persists for 15 s. A 10 ml of standard ascorbic acid solution was prepared by adding 50 mg of pure ascorbic acid into 60 ml of 20% meta-phosphoric acid. The solution was diluted with water to 250 ml and titrated with 2, 6-dichloindophenol until a faint pink color persisted for 15 s.

2.6. Pectin methylesterase (PME) assay

Fresh squeezed orange juice (12° Brix) samples, which were treated with different UV doses at room temperature and with heating at 70 °C for 2 s, were tested for PME activity. PME activity was determined by enzyme activity assay as detailed by Kimball (1991). Citrus pectin isolated from orange juice was used as a substrate. The rate of acid formation at pH 7.5 and 30 °C can be calculated in pectin methylesterase units (PMEU) as:

$$PMEU/\text{ml }^{\circ}\text{Brix} = \frac{(\text{ml NaOH})(\text{NaOH normality})}{(\text{reaction time})(\text{ml sample})^{\circ}\text{Brix}} \quad (1)$$

3. Results and discussion

3.1. UV disinfection of orange juice

3.1.1. Effect of UV on standard aerobic plate count and yeast and moulds in reconstituted orange juice (10.5° Brix)

Fig. 2 demonstrated the destruction kinetics of APC in reconstituted orange juice. The plot of Ln (N/N_0) versus UV dose gave a straight line with a slope of −0.0252 with a confidence interval of the APC death constant of 0.025±0.004. The statistical analysis of the kinetics of APC population was tested and the results showed that there is a significant difference of the population of APC on different UV dose inactivation (p=0.000). We may conclude that UV is a significant predictor for Log survivor of APC population and that the degradation constant −0.0267 is sufficient death constant of APC with UV treatment (p=0.000), which is also supported by the high correlation coefficient of 0.98 for the relationship. Fig. 2 also demonstrates the destruction kinetics of yeasts and moulds in reconstituted orange juice. The plot of Ln (N/N_0) versus UV dose gave the straight lines with a slope of −0.0166 with confidence interval of yeasts and moulds of −0.017±0.004. The statistical analysis of the kinetics of yeasts and moulds population was also tested and the results showed that there is a significant different of the population of yeasts and moulds on different UV dose inactivation (p=0.000).

The UV treatment of orange juice was done at 25 °C; hence, the value of death constant is correct only for cold treatment. From Fig. 2, the kinetics equation for the destruction of APC can be written as follows:

$$N = N_0 e^{-0.025X} \quad (2)$$

and the kinetics equation for the destruction of yeasts and moulds can be written as follows:

$$N = N_0 e^{-0.017X} \quad (3)$$

where N is the number of viable microorganisms in reconstituted orange juice (10.5° Brix), X is the ultraviolet dose (mJ/cm^2), and N_0 is the initial number of microorganisms in the juice before treatment.

The Decimal reduction constant (D_{10}) for any microorganism is defined as the UV dose necessary to inactivate 90% of viable microorganisms (Stother, 1999). The value of D_{10} of APC, yeast, and moulds in reconstituted orange juice (10.5° Brix) were calculated and found to be 87±8 mJ/cm^2 for APC, with the 95% confidence interval, and to be 119±17 mJ/cm^2 for yeasts and moulds, with 95% confidence interval.

Yeast and moulds were more resistant to ultraviolet treatment compared to APC. This result is in agreement with the findings of Tran and Farid (2002) for UV treatment of carrot juice. Their results showed that a UV dose of 123 mJ/

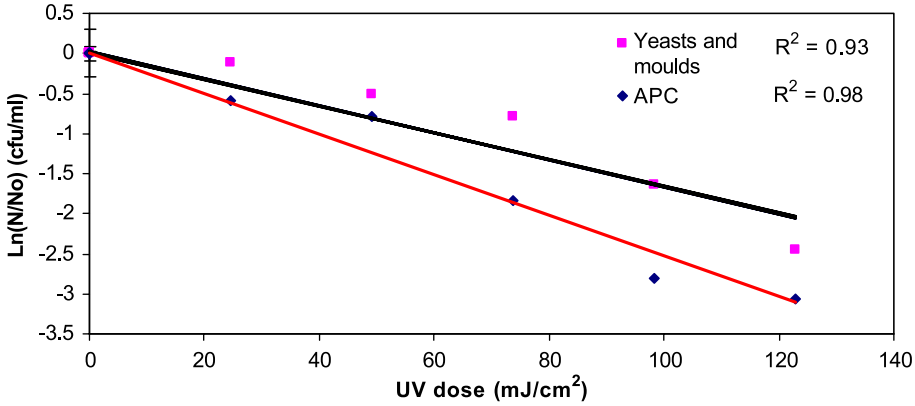

Fig. 2. Kinetics of aerobic plate count (APC), yeast and moulds degradation under UV treatment in reconstituted orange juice. Each data point represents the mean of duplicate experiments.

cm^2, caused 97.8% reduction in APC and 94.7% reduction in yeasts and moulds.

It is important to note that the arrangement made in this work to avoid using large surface area by circulating the juice several time would provide only a conservative effect of UV dose on microbial count. The operation was similar to a closed loop chemical reactor with high degree of mixing between the feed and the product. In industrial reactors, once through process will be used, which will provide higher rate of destruction of APC and yeasts and moulds.

Hansen (1976) has reported that moulds are the most resistant to UV-radiation because of their sizes being larger than bacteria. The different deactivation is also probably due to the DNA absorption of the UV light, causing cross-linking between neighboring pyrimidine nucleosides (thymine and cytosine) in the same DNA strand (Miller, Jeffrey, Mitchell, & Elasri, 1999). These are the causes of disruption in the DNA chain, such that when the cell undergoes mitosis (cell division), the replication of DNA is inhibited (Bolton, 2001). In other words, due to the changing of the formation of the chemical bond in DNA (when the cell absorbed UV light), the microorganisms are killed or rendered inactive (Morgan, 1989; Stother, 1999). Yeasts and moulds are more resistance than other bacteria probably due to DNA structure of yeast and moulds being less of pyrimidine base (principally thymine). Moreover, the chemical composition of the cell wall and its thickness of yeast and moulds cells are probably different than bacteria. Montgometry (1985) has demonstrated that the chemical composition of the cell wall and its thickness ultimately determines the relative UV resistance of an organism.

Although all microorganisms are susceptible to ultraviolet radiation, the sensitivity varies according to their resistance to UV penetration. The different microorganisms also undergo different intrinsic repair mechanisms, which depends largely on environmental factors. It has been suggested that:

Firstly, the growth medium, in which the organism is suspended, affects the rate of killing by ultraviolet radiation. Rich organic media, such as peptones and sera, provide a protective effect for the organisms. Because rich media has been attributed to the increasing in the number of ribosomes within the cell, the ribosome provides a shield for the DNA against the ultraviolet light (Snowball & Hornsey, 1988).

Secondly, the phase of growth cycle of an organism can affect its sensitivity to ultraviolet radiation. For example, *Escherichia coli* cells in the lag phase of growth are more resistant to ultraviolet light than cells in the logarithmic and stationary phase (Snowball & Hornsey, 1988). In order to avoid the different lag phase of growth, all microbiological testing were carried out at the same time.

Lastly, the treatment temperature influences the efficacy of UV disinfection. It has been proven through in vitro studies that the rate of dimer formation between adjacent thymine nucleotides in single-stranded DNA is faster at temperatures below 25 °C than at higher temperature (Rahn, 1970). At low temperatures, the natural state of single-stranded DNA is a stacked structure that effects the dimerization. At higher temperatures, a slightly higher UV dose is required to produce 99% inactivation in *E. coli*. (Severin, Suldan, & Engelbrecht, 1983). In the investigation presented here, the effect of treatment temperature has not been studied, as the temperature was kept close to ambient temperature by blowing air through the reactor to remove the heat generated from the UV lamp.

3.2. Shelf life of UV-treated orange juice

The shelf life of orange juice was based on the microbial specification which does not allow more than 5000 cfu /ml for a commercial single orange juice (Kimball, 1991). The effects of UV exposure of 73.8 mJ/cm^2 UV on the total aerobic plate counts (APC) and the total yeast and moulds counts of squeezed orange juice (12° Brix) are shown in Table 1. The treated and nontreated juices were stored at 4 °C for almost 2 weeks. The decrease in bacteria count from day 0 to day 2 may be due to chilling injury of some mesophilic bacteria. As a result of the treatment, shelf life of fresh squeezed orange juice was extended to more than 5 days and could be extended further by applying higher UV doses. This allows expanding the juice distribution areas considerably, which will have significant economical benefits.

3.3. Effect of UV on Vitamin C

Studying the effect of UV on Vitamin C in orange juice is one of the objectives of this study. There was no significant difference between the concentrations of Vitamin C measured by the HPLC and titration methods. Fig. 3 shows Vitamin C content in reconstituted orange juice (1:7 diluted from concentrated orange juice) following exposure to UV

Table 1
Total plate counts and total yeast and mould counts in treated (73.8 mWs/cm^2) and untreated fresh squeezed orange juice (12 °Brix) during storage (4 °C)

Standard aerobic plate counts (cfu/ml)			Total yeast and mould counts (cfu/ml)	
Storage day (4 °C)	Untreated orange juice	Treated orange juice (73.8 mWs/cm^2)	Untreated orange juice	Treated orange juice (73.8 mWs/cm^2)
0	6900±150	2050±40	6400±1600	2845±105
2	4475±175	1900±100	7900±200	2205±105
6	10850±550	5450±650	25000±500	5500±500
12	39100±500	21350±850	88500±7500	19150±1150

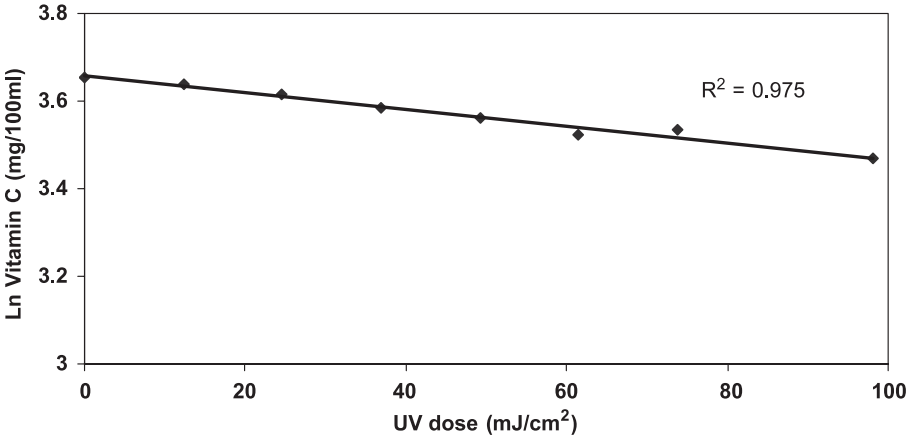

Fig. 3. Degradation of Vitamin C in reconstituted orange juice following UV treatment. Each data point represents the mean of triplicate experiments.

of different doses. The results show that Vitamin C content in reconstituted orange juice was consistently degraded as UV dose increased. The semilog plot of average Vitamin C concentration (mg/100 ml) versus UV dose (mJ/cm^2) gave a straight line with slope of −0.0019. The high correlation coefficient of 0.9754 is a good indication of the strong relationship between the UV dose and Vitamin C concentration in orange juice. As shown in Fig. 4, the first-order model fits the data well (Doran, 1995), and the best fit is defined by the equation:

$$C = C_0 e^{-0.0019X} \tag{5}$$

where C is Vitamin C content (mg/100 ml) in orange juice following UV treatment (at X dose, mJ/cm^2) and C_0 is Vitamin C concentration (mg/100 ml) before treatment.

Some of the Vitamin C destruction could have been due to air oxidation. Therefore, it was decided to independently measure the effect of air oxidation of Vitamin C at 20 °C. The measured Vitamin C destruction due to air oxidation was found to be only 0.0029±0.00014 mg/100 ml of orange juice per minute, which was equivalent to only 0.0085%/min (Fig. 4). The high correlation coefficient of 0.997 supports the conclusion that time is a significant predictor for the degradation of Vitamin C by air.

The results show that lengthy storage of orange juice could cause Vitamin C loss as much as that caused by UV treatment. However, the total processing time required in the UV treatment was approximately 2 h due to the number of treatment cycles required for the UV dose to reach 100 mJ/cm^2. Accordingly, the Vitamin C loss in orange juice due to air oxidation was only 1.0%, compared to 17.0% caused by UV exposure. Hence, the measured destruction of Vitamin C, reported in this paper, is believed to be mainly due to UV effect.

The UV destruction of Vitamin C is similar to that found in thermal treatment. Lopez, Krehl, and Good (1967) have reported 12% to 21% loss of Vitamin C during thermal treatment of 10 minutes. Lifshitz, Stepak, and Brown (1974) also showed that 18% of the ascorbic acid in fresh Shamouti juice could be lost during pasteurization.

Based on the destruction kinetics of APC, yeasts and moulds, and Vitamin C, the percent destructions per one unit dose of UV (mJ/cm^2) are 2.35%, 2.0%, and 0.175%, respectively.

3.4. Effect of UV on enzyme pectin methylesterase activity

The effect of UV on the enzyme pectin methylesterase was studied in this work by exposing fresh squeezed

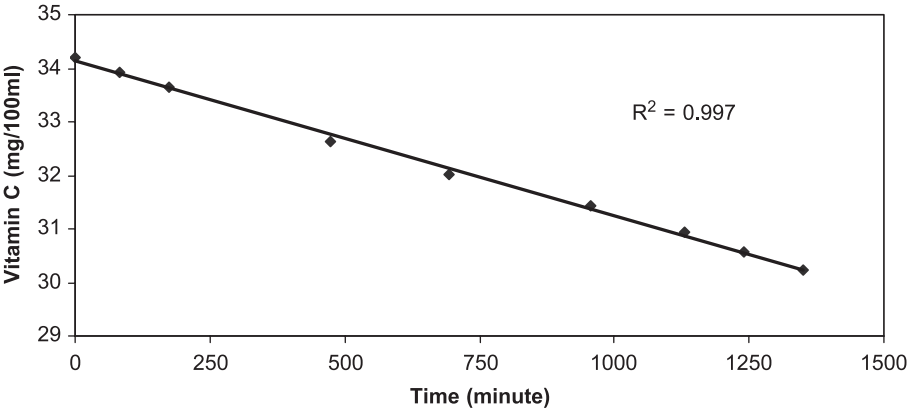

Fig. 4. Degradation of Vitamin C in orange juice due to air oxidation at 20 °C.

orange juice to UV dose of 73.8 mJ/cm^2. The statistical analysis showed that UV is not a significant factor to predict the pectin methylesterase activity (p-value=0.427, accept the null hypothesis). There is not enough sufficient evidence to conclude that there is a significant different in the level of enzyme activity of pectin methylesterase on different UV level doses, as may be observed from the calculated correlation coefficient of 0.222. In other words, enzyme pectin methylesterase was not affected by UV treatment.

Table 2 shows the effect of UV and thermal treatment on pectin methylesterase activity. The activity due to thermal treatment was reduced by 70% within a very short heating time of 2 s. This is in agreement with the high reduction of 99.9% (at 90 °C and for 60 s) reported in the literatures for thermal sterilization (Eagerman & Rouse, 1976). The corresponding reduction in the activity due to high UV dose was only 5%. This suggests that UV treatment may not prevent juice cloud loss. On the other hand, orange juice will maintain its freshness during UV treatment unlike thermal treatment, which will causes significant loss of freshness "cooking effect".

Color is one of the sensory characteristics and is an indication of the freshness of the orange. No visible change in color of the orange juice was observed due to the UV treatment even with high doses.

3.5. UV dose and energy needed for treatment. The UV dose of each cycle was calculated as follows:

$$U = It/A \tag{6}$$

where: I is UV intensity of the lamp ($\cong$6 W), as measured by the supplier during the experimental work; t is UV exposure time of orange juice, s; A is UV exposure surface area, cm^2

with: $A=\pi DL$, cm^2

where: D is the inner diameter of UV reactor (D=4.5 cm); L is the length of UV reactor (L=40 cm).

Therefore: U=6 W×1.16 s/3.1416×4.5 cm×40 cm= 0.0123 J/cm^2 or 12.3 mJ/cm^2

The UV exposure time of 1.16 s was obtained by measuring the residence time of orange juice in the reactor using a tracer introduced at the top of the column. This value was an average value of over 30 measurements made at the same flow rate of 0.6 l/min. In order to achieve doses higher than 12.3 mJ/cm^2, the juice was circulated through the reactor up to twelve times, which provided UV exposures from 12.3 to 147.6 mJ/cm^2. Each sample was tested for changes in viable microorganism's aerobic plate count and yeast and moulds. The actual UV intensity was not measured inside the column; instead, the lamp intensity was periodically measured and found to maintain its original UV power intensity close 6 W.

Table 2
Effect of UV and thermal treatment on enzyme pectin methylesterase activity

Heat treatment (70 °C, 2 s)		UV treatment (73.8 mWs/cm^2)
Sample	(PMEU/PME$_0$U)100	(PMEU/PME$_0$U)100
Untreated	100	100
Treated	30.0	95.0

Based on thermal processing temperature of 90 °C, the energy required to treat 1 m^3 of orange juice is about (using the physical properties of water):

$$Q_{\text{th}} = 1000 \times 4.2(90-20)/1000$$
$$= 294 \text{ MJ/m}^3 \text{ or } 81.67 \text{ kW h /m}^3$$

With efficient energy utilization, by capturing the heat available in the product juice to preheat the fresh juice, this amount of energy may be reduced to 20–30% of this value.

The amount of UV energy needed for the treatment, based on using 6-W UV lamp and juice flow rate of 0.6 l/min (0.036 m^3/h), circulated 12 times to provide sufficient killing of microorganisms is:

$$Q_{\text{uv}} = 12 \times 6 \times 10^{-3} \text{ kW}/\left(0.036 \text{ m}^3/\text{h}\right) = 2.0 \text{ kW h/m}^3$$

The electrical energy needed for the treatment could be as high as 10.0 kW h/m^3, but may be reduced significantly with the use of more efficient UV lamps. In addition, as explained earlier the UV dose needed in industrial size, units will be much lower than that used in this laboratory size reactor, as treatment will be conducted in a once through process.

4. Conclusions

Ultraviolet processing was found effective in reducing total aerobic plate count and yeast and moulds in orange juice using a thin film UV reactor. The death constant of APC and yeasts and moulds were found -0.025 ± 0.004 and -0.017 ± 0.004, respectively. The decimal reduction constant of APC and yeasts and moulds were 87 ± 7 and 119 ± 17 mJ/cm^2, respectively. The shelf life of fresh squeezed orange juice was extended from 2 days to more than 5 days after UV treatment, with a limited dose of 73.8 mJ/cm^2. Although this treatment was found effective in increasing the shelf life of orange juice, the process is unlikely to completely replace thermal processing, especially whenever complete sterilization is required. The energy required for UV treatment is smaller than that required for thermal sterilization.

Vitamin C in reconstituted orange juice was found to degrade under UV treatment. The degradation was about 12% when UV dose of 73.8 mJ/cm^2 was used. The activity of enzyme pectin methylesterase was not influenced by the UV treatment, whereas the activity of this enzyme was significantly decreased (70%) by mild heat treatment at 70

°C for 2 s. No significant change in the orange juice color or pH was observed.

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