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Review

Fruit Juice Production Using Ultraviolet Pasteurization: A Review

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Abstract: Ultraviolet (UV-C at 253.7 nm) technology has been the go-to alternative pasteurization and shelf-life extension treatment for beverages for the last two decades. It has been the focal point of non-thermal methods for fruit juice processing and has been studied extensively. UV-C technology has been proven to produce microbiologically safe products with minimal negative impact towards quality of the products. However, due to the physicochemical characteristics of fruit juice, application of UV-C does have certain limitations and thus, there is a need to further study the effects of UV-C-treatment and equipment design. Critical decisions on the type of fruit product, juice color, juice composition, and juice physical characteristics, among other variables, are imperative to produce a safe and wholesome juice. Therefore, this paper serves as a source for development of UV-C technology for pasteurization and shelf-life extension of fruit juice to successfully obtain a final product with minimal changes of its nutritional component without neglecting the microbial safety. It reviews previous literatures involving ultraviolet-treated fruit juices, ranging from popular apple and orange juice to lesser-known pummelo and pitaya juice. The review also covers the aspect of microbiological and chemical safety, quality, and sensory characteristics as well as hurdle technology involving UV-C as the main method and the market potential with its cost implication of UV-C technology.

Keywords: ultraviolet irradiation; fruit juice; pasteurization; quality; beverages

1. Introduction

Food processing and preservation techniques are continuously being developed to conform to modern consumer demands for safe and healthier foods. Higher income, urbanization, demographic shifts, improved transportation, and consumer perceptions regarding quality and safety are changing global food consumption [1]. Modern consumers demand tasty, healthier, natural and fresh-like foods, produced in an environmentally friendly manner with sustainable methods and small carbon footprints [2–4]. As a consequence, in the past two decades non-thermal technologies have received increasing attention due to its potential for inactivating spoilage and pathogenic microorganisms [5]. Ultraviolet (UV-C) light system is a non-thermal technology which has acquired interests among food researchers. Numerous studies have proven that the germicidal UV-C light treatment holds considerable promises in juice processing as an alternative to traditional thermal treatment. When compared with traditional thermal pasteurization method for liquid foods such as High Temperature-Short Time (HTST), UV-C treatment was shown to have had a minimal effect on the

quality of juice. However, effects of UV-C towards the physicochemical characteristics and nutritional composition of UV-C treated juice cannot be overlooked. Depending on the UV processing dose and specific nutrient(s), UV light may have varying effect on nutrient and enzyme retention as the success of UV technology depends on the correct alignment of the UV source and system parameters to the specific demands of the UV juice application [2,6].

UV-C light is the short electromagnetic spectrum between 200 to 280 nm. With its positive consumer image and low processing cost, UV-C treatment is proven to be suitable for fruit juice stabilization [3]. Its bactericidal mechanism is based on the absorption of UV-C light by microbial DNA or RNA structures. The primary mechanism is the creation of pyrimidine dimers, which prevent microorganisms from replicating, further rendering them inactive and unable to cause infection [7]. The use of UV-C light for water treatment is well established, however, the application of UV-C on liquid foods presents a relatively new challenge to beverage producers. Compared to water, liquid foods have a range of optical and physical properties and diverse chemical compositions that influence UV-C light transmittance, dose delivery, momentum transfer and—consequently—microbial inactivation. The United States Food and Drug Administration (USFDA) and United States Department of Agriculture (USDA) [8], have concluded that the usage of UV-C light at 253.7 nm for food processing is safe and has further approved the usage as an alternative treatment to reduce pathogens and other microorganisms. USFDA issued Code 21CFR179.41, which approved the use of UV-C light in the production, processing, and handling of food. Critical factors to ensure efficient UV-C treatment include; transmissivity of the product, geometric configurations of the reactor, power, wavelength and physical arrangement of the UV-C sources, product profile and radiation path length [2,4].

This paper provides a general review of the UV-C light applications and its effect on the quality and shelf-life extensions, sensory effects of UV-C-irradiated juice, and the hurdle pasteurization technology involving UV-C-irradiation. The market potential and cost implications were also discussed.

2. Quality and Shelf Life Extension of UV-C-Irradiated Juices

The use of non-thermal processing technology such as ultraviolet irradiation is motivated by the fact that fruit juices contain nutrients and other compounds which are heat sensitive. Various studies have highlighted the benefits of using ultraviolet irradiation with regard to nutrient retention and storage stability and in the past twenty years the usage of UV-C light are well documented with samples ranging from citrus juice to tropical juices. This is reflected in Table 1 where the effects of UV-C-irradiation on treated fruit juices is also highlighted. As a consequence, crucial precaution in terms of dosage and exposure applied to the fruit juice should be monitored.

Table 1. Effects of UV-C-irradiation on quality improvement and shelf life extension of fruit juices.

Medium	Variables	Effects	References
Orange juice	UV-C dose = 299 mJ/cm^2	17% reduction of ascorbic acid after 7 passes.	[2]
	UV-C dose = 12.3–148 mJ/cm^2	5% reduction of PME activity and pH change 17% losses of ascorbic acid.	[9]
	UV-C dose = 12–48 kJ/L	Ascorbic acid losses increased in line with the UV-C doses, significant after 48 kJ/L of UV-C dose. No significant reduction total phenols and antioxidant capacity. No significant changes towards pH, total soluble solids content and titration acidity.	[10]
Mango nectar	UV-C dose = 45 J/cm^2	Reduction of polyphenol oxidase activity to 25%.	[4]

Table 1. *Cont.*

Medium	Variables	Effects	References
Apple juice	UV-C dose = 2.66–53.1 J/cm^2	Significant decrease in total phenol content, while antioxidant capacity was not reduced significantly. No significant changes in pH, soluble solids content and titration acidity.	[5]
	UV-C dose = 10 mW/cm^2	UV-C induced minimal of furan at dose less than 3.5 J/cm^2. At 8.8 J/cm^2, ~14 ppb furan was formed. Furan formation was increased at a rate of 11 ppb per J/cm^2.	[11]
	UV-C (NA)	No significant changes in pH, soluble solids content, and titration acidity. Reduction of vitamin C is highly dependent on juice varieties. Golden's vitamin C reduction = 5.7%, Starking's = 5.6%, Fuji's = 4%, King David's = 70%. The losses can be attributed to the lack of pigmentation of juice. No PME activity was found after UV-C treatment and it completely inactivate PPO and peroxidase after 100 and 15 min, respectively.	[12]
	UV-C dose = 2.66, 5.31, 10.62, 26.55 and 53.1 mJ/cm^2	No significant changes in pH, soluble solids content, total phenol content, and titratable acidity. While color attributes showed significant effect with direct impact towards non-enzymatic browning index and TEAC decreased as UV-C doses increased.	[13]
	UV-C dose = 39–245 mJ/cm^2	The study did not have a noticeable effect on enzyme activities of naturally cloudy apple juice (α = 61 cm^{-1}) Furan was seen to increase from 2.3 to 3.7 µg/kg.	[14]
Apple cider	UV-C dose = 4.45, 6.67 and 13.34 mJ/cm^2	Significant effects were detected on viscosity, turbidity, PPO residual activity.	[15]
	UV-C dose = 14 mJ/cm^2	Titratable acidity was found to increase, whereas turbidity decreased. No significant difference was found on soluble solids content and pH.	[16]
	UV-C (NA)	No significant effect was found on pH, sedimentation, and glucose and fructose. Whereas, significant decrease was detected on turbidity, soluble solids content and significant increment was shown on total color changes.	[17]
	UV-C dose = 8.77–35.11 mJ/cm^2	Significant decrease on color *L** values, turbidity, and viscosity, whereas pH seemed to increase. Storage studies: Color *L** increased, no significant changes toward turbidity and pH, whereas viscosity seemed to increase.	[18]
Apple and grape juice	UV-C dose = 4.02 kJ/L	A decrease in color *L** value and viscosity was detected in both juice.	[19]
Grape juice	UV-C dose = 40–300 mJ/cm^2	Turbidity of pasteurized clear grape juice (PCGJ) was observed to have decreased, whereas turbidity of freshly squeezed turbid grape juice (FSTGJ) was unchanged after the UV-C treatment. Other physicochemical characteristics tested (pH, titratable acid, total soluble solids content and color *LAB**) were found unchanged with the ultraviolet treatment.	[20]
Grape juice (White)	UV-C dose = 0.90 mL/s	Significant change was detected on turbidity and browning index of freshly squeezed white grape juice, whereas ascorbic acid was found to decrease considerably. Color *LAB**, titratable acid and total soluble solids content was found unchanged. Yeasts, lactic acid bacteria, and aerobic plate count was found to increase as storage life increased. The sample was found to spoil at the 7th day.	[21]

Table 1. *Cont.*

Medium	Variables	Effects	References
Pineapple juice	UV-C dose = 10.76 mJ/cm^2	Turbidity, vitamin C, and phenolic content were found to decrease, whereas pH, total soluble solids content, and titrable acidity had no significant changes.	[22]
	UV-C dose = 7.5 mJ/cm^2	Total soluble solids lower than thermally treated juice in 13 weeks of storage and decreased steadily in the seventh week onwards. pH of UV-C-treated juice was higher than thermally treated juice. Significant decrease of titratable acidity. Ascorbic acid decreased significantly during the 13 weeks of storage. *L** value was found higher and retained higher chroma value. Turbidity was observed to increase significantly during storage time. No significant changes were found on the total phenolic content but decreased after the fifth week of storage.	[23]
	UV-C dose = 0.00154 L/s for 20–35s	No significant effect was detected in pH, total soluble solids content, ascorbic acid content, *L** value.	[24]
	UV-C dose = 10.76 mJ/cm^2	No significant difference in the plastic viscosity between the UV-C-irradiated and untreated juice at temperatures of 5, 10, 15, 20, and 25 °C. Thus, rheological attributes of UV-C-treated juice were preserved.	[25]
	UV-C dose = 53.42 mJ/cm^2	Ascorbic acid, carotenoids, phenolic acids, and antioxidant capacity were found to lower significantly after UV-C treatment, but were significantly higher than the thermal treatment. Exception for flavonoids, where the content is much lower than thermally pasteurized juice. Total phenolic contents and flavonoids were found to decrease significantly throughout 14 days of storage. With the exception for carotenoids, where it was found to increase within the 14 days of storage.	[26]
Pummelo (*Citrus Grandis* L. Osbeck) juice	UV-C dose = 15.45, 18.18 and 27.63 mJ/cm^2	Significant decreases were observed on pH, total soluble solids content, ascorbic acid, total phenolic acid, and antioxidant activity. However, clarity and color were detected to increase.	[27]
Starfruit	UV-C dose = 2.158 J/cm^2	No significant changes in pH and total soluble solids content. Significant decrease in the acidity. An increase in *L** value but *a** and *b** seemed to decrease. A non-significant increase in DPPH inhibition. A significant decrease in vitamin C.	[28]
Watermelon juice	UV-C dose = 2.4, 4.8, 7.3 and 9.7 kJ/L	UV-C dose of 4.8 kJ/L had reduced PME activity to 75% its original content in 5 min of exposure in comparison to heat treatment at 60 °C in 20 min. Color *L** value was found to increase as UV-C dose increased.	[29]
	UV-C dose = 2.7, 5.4, 9.4 and 37.5 mJ/cm^2	A significant increase was seen on pH and total soluble solids content after 25 days of storage. No significant changes on the total phenolic content. Total color change was seen to increase in accordance to increment of UV-C doses.	[30]
Lemon-melon juice mix	UV-C dose = 0.44–2.86 J/mL	No significant changes detected on pH, total soluble solids content, total acidity, turbidity, and *L** value. Shelf life was increased from 2 days to 30 days.	[31]
Pomegranate juice	UV-C dose = 12–62 J/mL	No significant changes to total phenol content and TEAC values. No significant changes in pH, total soluble solids content, DPPH, and titration acidity.	[32]

UV-C irradiation treatment aims to prolong the shelf life of food in addition to reduce health hazards associated with presence of pathogens while maintaining the natural nutritional components. Basic UV-C irradiation mechanisms involves photochemical reactions which can be initiated in two ways: (1) Direct reactions—absorption of a photon of light by a molecule can produce a chemical reaction and change its state. The extent of chemical reaction depends upon the quantum yield and fluence of incident photos. UV-C light at 257.3 nm has a radiant energy of 112.8 kcal/Einstein, thus it is theoretically possible to affect the O–H, C–C, C–H, C–N, H-N, and S–S bonds, if UV-C light is absorbed [2]. (2) Photosensitized—the most common type of photosensitizing reaction is photo-oxidation. Photosensitizers are typically excited from the ground state to a short-lived singlet excited state that undergoes conversion to a long-lived triplet state that mediates the process. The triplet

sensitizer can react further by two major pathways: by hydrogen- or electron-transfer processes, or by energy-transfer reactions [33].

Meanwhile, the effects on food quality are measured in two ways: (1) juice characteristics; and (2) sensorial. The former involves physical and chemical measurements including pH, vitamins, polyphenols, color, and antioxidant activity, among others. While the latter involves an evaluation of organoleptic qualities or sensory evaluation of the food entailing taste, smell, appearance, and texture.

In general, there are no predictable effects of UV-C treatment on fruit juices as can be seen from Table 1. However, it can be concluded that the UV-C effect on liquid food is highly dependent on the amount of UV-C light absorbed by treated juice. Spikes [34] observed that at a wavelength specific for UV-C (257.3 nm), compounds containing conjugated bonds, such as aromatic-ring and double-ring molecules, as well as compounds containing disulfide bonds were found to be effective UV-C light absorbers. He also stated in the same study that vitamin A, B2, B12, D, E, K, carotenes, folic acid, tryptophan, and unsaturated fatty acids are 'light-sensitive' and can degrade with the exposure of UV-C light. Vitamin C was also observed to be the strongest absorber of UV-C light, even at the lowest concentration. Fan and Geveke [11] in their study noted that the major components of fruit juice could also be the main cause of limited UV-C absorption. Sugars, such as fructose, sucrose, and glucose, were found to have high UV-C absorbance in the range of 240–360 nm, where, fructose was found to be the highest UV-C absorbent at 260–280 nm. Therefore, it is considered normal for a fruit juice with high vitamin C, vitamin A, and fructose contents to lose considerable amounts of its original content after being irradiated by UV-C light.

In a study by Falguera et al. [12], the loss of ascorbic acid was observed to be between 4% and 6% in the irradiation of apple juices of different varieties (Golden, Starking, and Fuji). Significant losses of ascorbic acid were found for the variety King David (70%), even with the same processing conditions (120 min). Tran and Farid [9] irradiated orange juice with UV-C dose of 73.8 mJ/cm^2 had a degradation of ascorbic acid by 12%. Ye et al. [35] had also found that 50% degradation of vitamin C was found on commercially-made apple juice. These findings are similar to that found in thermal treatment, where Lopez et al. [36] reported 12% to 21% loss of ascorbic acid during thermal treatment of 10 min. A significant decrease of 19.5% of ascorbic acid in a study by Shamsudin et al. [22] of UV-C treated pineapple juice further confirmed the findings of Davey et al. [37] which stated that the reduction of ascorbic acid content can be attributed to the oxidation process together with the activities of ascorbate oxidase and peroxidase enzymes, which can also affect the phenolic and antioxidant compounds within the UV-C treated juice.

These reductions of vitamin C were also blamed for lessening pigmentation in the juice, where it was observed by Koutchma et al. [2] that certain food pigments are light sensitive. Falguera et al. [12] stated that melanins and melanoidins contained in fruit derivatives are polymeric compounds that can degrade to a brown coloration, which is detrimental to sensory quality. Melanins were also touted to be the protective shield for various enzymes from UV-C irradiation [38]. However, for fruit juice with absent or degraded melanins, the luminosity (or color L^* value) is expected to increase, thus exaggerating the reduction of vitamin C. This observation is consistent with the results from Shah et al. [27], Chia et al. [23] and Bhat et al. [28], where the L^* value of treated pummelo (*Citrus Grandis* L. Osbeck), pineapple, and starfruit juice was found to increase, indicating that the pigments and browning coloration (or perhaps to be more specific, polyphenol oxidase enzyme) was destroyed by UV-C irradiation, whereas the vitamin C of each fruit juice was found to decrease significantly. As proved in a study of UV-C treated mango nectar, the color of the juice concentrates maintained for 26 days as polyphenol oxidase enzyme was observed to decrease to 5-log$_{10}$ reduction [4].

The denaturation of enzymes in fruit juice was also highlighted by several studies. Naturally occurring enzymes in fruit juice play an important role in assessing the shelf life of those juices. Enzymes that were found in abundant in fruit juices are; polyphenol oxidase (PPO)—protein that causes the enzymatic browning, pectic enzymes; such as pectin methylesterase (PME) and polygalacturonase—proteins that are responsible in causing "cloud-loss" in fruit juice. Inactivation

of these enzymes is crucial in order to prolong the shelf-life of juice. Seiji and Iwashita [38] have reported that polyphenol oxidase, ATPase, and acid phosphatase molecules may be denatured when irradiated by UV-C light. The loss of enzymes is highly dependent on the intensity of UV-C irradiation as highlighted by Falguera et al. [12], where PME, PPO, and peroxidase in apple juice was completely inactivated after 100 and 15 min, respectively. Zhang et al. [29], in their study of watermelon juice, found 75% reduction of PME, whereas, Tran and Farid [9] had a 5% reduction on PME of orange juice. Contrarily, Muller et al. [19] and Shah et al. [27] found no significant effect on enzyme activity was detected in UV-C irradiated apple juice and pummelo (*Citrus Grandis* L. Osbeck) juice. Both studies had perused dean vortex UV-C technology and it is unclear if this reactor had limited the UV-C emission. As stated by Falguera et al. [12], a wider emission spectrum of UV-C should be applied in order to effectively inactivate these enzymes.

Carbohydrates, were not affected by UV-C irradiation, specifically. However, singlet oxygen and hydroxyl radicals can produce some sensitized photoreactions, which can result in the photochemical depolymerization of polysaccharides in foods, producing softening in fruit pulp, which may be the main reason for decrement of turbidity in some fruit juice. Muller et al. [19], Kaya and Unluturk [20], Unluturk and Atilgan [21], and Shamsudin et al. [22], had observed that the turbidity of the treated fruit juice (apple and grape juice, white grape juice, and pineapple juice, respectively) had decreased significantly, altering the absorption coefficient for each juice.

UV-C reactor types were also theorized to have a consequence towards the physicochemical changes of fruit juice treated. Koutchma et al. [2] had stated that, in order to achieve 5 $\log_{10}$ microbial reduction, critical factors include the transmissivity of the product, geometric configurations of the reactor, power, wavelength, and physical arrangement of the UV-C sources, the product profile and the radiation path length are imperative and must not be overlooked. For the UV-C pasteurization to be effective (with minimal path length), specific optimization of the model system has to be made to the selected juice. It was asserted by Orlowska et al. [15] that Taylor-couette UV-C unit producing 4.45 to 13.34 mJ/cm^2 had a significant effect towards viscosity, turbidity, and polyphenol oxidase (PPO) of apple juice. These significant changes were presumed to be attributed with the fluid-mechanical sensitivity of plant tissues [39]. The superposition of laminar axial flow (1500 mL/min) and circular flow (200 rpm) in an annulus resulted in the formation of turbulent vortices' flow. Under such condition, the apple particles encountered the shear forces associated with the flow gradients of the parallel laminar layers and centrifugal forces generated by the counter-rotating helical vortices. Due to the disruptive effects of the hydrodynamical stresses, the biological tissues are fragmented and content of small particles increases.

Whereas, in a study by Muller et al. [19], UV-C inactivation of apple and grape juice utilizing a coiled tube UV-C reactor, with UV-C dose of 4.02 kJ/L, reductions of PPO, color L^* value, and viscosity were again significant. These effects were again presumed to be caused due to pumping and flow conditions in the reactor with absorption coefficient of each juice played a supplemental factor. The highest effect of UV-C on PPO activity was in apple juice (α = 52.4 cm^{-1}), followed by grape juice (α = 43.4 cm^{-1}) and can be explained by the attenuation of UV-C energy due to the absorption of soluble compounds in apple and grape juices as well as by the lower mixing efficiency in the juice (Re_{AJ} = 1002, Re_{GJ} = 1015). However, studies by Caminiti et al. [13] and Falguera et al. [12] utilizing vertical concentric tubes and collimated beam apparatus, respectively had shown no significant effects in the total phenol content, pH, soluble solids content, and titratable acidity. It is thus advised to optimize the reactor specification (flow rate, velocity or even the gap width) to be optimized to ascertain that the juice is effectively pasteurized with minimal changes to the juice quality.

Shelf life of UV-C irradiated fruit juice is highly depended on the amount of polyphenol, ascorbic acid, and sugar left within the juice, coupled with the amount of pertinent microorganisms found in the fruit juice during a standard 12-weeks storage. These are naturally decaying properties of juice being kept at 4 °C (standard chiller temperature). While minimal studies have been reported on shelf life of UV-C irradiated fruit juice, it was found that Tandon et al. [16] in his study perusing CiderSURE had noted that the quality of apple cider did not maintain after one week of storage, whereas, orange juice treated with a minimal dosage of 73.8 mJ/cm^2 was found to extend to only five

days [9]. Contrarily, in a study by Kaya et al. [31] on UV-C irradiated lemon-melon juice mix with UV-C dose of 0.44 to 2.86 J/mL, was prolonged the shelf-life of the juice from 2 to 30 days, with very little significant changes on the physicochemical characteristics of the juice, with the exception of turbidity. Decrement of turbidity throughout the storage of lemon-melon juice mix was theorized on the lack of microbial growth and inactivation of proteins and polyphenol complexes [40]. Shah et al. [27] in her study of UV-C treated pummelo (*Citrus Grandis* L. Osbeck) fruit juice had found that the juice is able to withstand up to six weeks in comparison to less than one week for freshly-squeezed non-pasteurized pummelo (*Citrus Grandis* L. Osbeck) fruit juice. This assumption was based on the minimum requirement of ascorbic acid of 0.25 mg/mL [41].

In general, different juice types with varying nutritional and physicochemical contents can result in different ranges of absorption coefficient which subsequently, absorb varying amounts of UV-C doses to significantly change their physicochemical characteristics. Thus, limitation towards exposure of UV-C is crucial in order to avoid overexposure to the UV-C light which may lead to adverse effects on the quality and nutritional values of fruit juices.

3. Sensory Properties of UV-C-Irradiated Juices

Sensory quality of fruit juices plays an important role in consumer satisfaction. Most studies reported that UV-C treated juices were not significantly different than fresh juices but were significantly different from heat treated juices (Table 2). The pasteurized samples were significantly less preferred for odor, color, cloudiness, acidity, overall flavor and overall likeness than the control and UV-C-treated samples [17]. After non-thermal treatments, juice samples exhibited the lowest variation in hedonic scores, when compared to the control [42,43]. Panelists rated non-thermal-treated juices as 'like slightly' for color, odor and taste. Correspondingly, Hazila et al. [44] reported slightly rancid smell of UV-C treated pitaya juice while significantly lower hedonic scores for flavor and aroma of UV-C processed orange juice was reported by Pala and Toklucu [32]. In addition, the development of browning compounds due to UV-C photo-degradation may cause a decrease in hedonic scores [13,28,29,45].

Table 2. Sensory properties of UV-C-irradiated fruit juices.

Juice Type	Irradiation Condition	Observation	References
Apple juice	UV-C dose = 2.66–53.10 J/cm^2	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 flavor and color.	[13]
Apple cider	UV-C dose =14 mJ/cm^2	UV-C-treated apple cider was found to be at par with flash-pasteurized and hot-filled apple cider. However, the ranking preference decreased as storage week increased.	[16]
	UV-C dose = NA	Consumer acceptability study showed no significant difference between untreated cider samples and UV-C-pasteurized samples.	[17]
	UV-C dose = 17.55 mJ/cm^2	The triangle test indicated non-significant differences between untreated and UV-C-treated apple cider.	[18]
Orange juice	UV-C dose = 12–48 kJ/L	Triangle test indicated a significant difference between UV-C and heat treated orange juice in terms of overall flavor and aroma characteristics. UV-C-treated orange juice was found to have an overall score of 4.1 and 3.8 for flavor and aroma attributes, ranking it as "neither like nor dislike".	[10]
Mango juice	UV-C treatment (for 15, 30 and 60 min at 25 °C)	The sensory evaluation verified that non-thermal-treated juice was preferred more than thermally-treated juice.	[42]
Pineapple juice	UV-C dose = NA	UV-C treated juices were preferred to thermally pasteurized juice.	[43]
Blend of orange and carrot	UV-C dose =10.6 J/cm^2 or high intensity light pulses (HILP) (3.3 J/cm^2 combined with manothermosonication technology (400 kPa, 35 °C, 1000 W, 20 kHz)	The juice processed by UV-C + MTS was the most preferred samples in terms of flavor (4.8) and was not significantly different from the pasteurized samples.	[46]
Guava and passion fruit nectar	UV-C dose = 6.2–23.6 J/mL	Significant differences were found for both nectars as panellists describing changes of colors and aroma with metallic flavor, which might indicate lipid oxidation.	[47]

4. Safety of UV-C-Irradiated Fruit Juices

4.1. Microbiological Safety

UV-C light has broad antimicrobial action, providing effective inactivation of viruses, vegetative bacteria, bacterial spores, yeasts, conidia, and parasites. UV-C light potential in obliterating bacteria, viruses and molds has been documented by many researchers (Table 3). However, the effect of UV-C radiation on microorganisms varies from inter-species, intra-species, strain, medium, density and even their size. Furthermore, the ability of UV-C inhibiting bacteria's replication is due to dimerization of their thymine bases in the DNA strands [48] which is limited to the ability of the UV-C irradiation to penetrate the liquid food. In fruit juices, 90% of UV-C irradiation is absorbed in the first 1-mm from the surface [49]. Moreover, researchers have reported varied power levels, process times, UV-C light source-product distances, and product thickness to achieve varied inactivation levels in many pathogens, had resulted various effects on the juice quality.

Table 3. Effects of UV-C irradiation on fruit juice microflora.

Juices	Microflora	UV-C Dosage	Log Reduction	References
Mango nectar	Aerobic plate count	45 J cm^{-2}	2.7	[4]
Pineapple juice	Aerobic plate count Yeast and mold	10.76 mJ cm^{-2} 10.76 mJ cm^{-2}	1.9 1.4	[22]
	S. typhimurium	0.000154 L s^{-1}	3.0	[24]
	Aerobic plate count Yeast and mold	1607.0 J L^{-1} 1607.0 J L^{-1}	< 1.0 < 1.0	[50]
Pummelo (*Citrus Grandis* L. Osbeck) juice	*S. typhimurium*	15.45–27.63 mJ cm^{-2}	5.23–9.10	[27]
Starfruit juice	Aerobic plate count	NA	total inactivation	[28]
Lemon-melon juice mix	*E. coli* K12	0.44–2.86 mJ cm^{-2}	0.06–6 log	[31]
Apple cider	*E. coli* O157:H7	4.45, 6.67, 13.34 mJ cm^{-2}	2.85–4.76	[15]
	Aerobic plate count Yeast and mold	14 mJ cm^{-2} 14 mJ cm^{-2}	1.8 1.4	[16]
	E. coli O157:H7 *E. coli* K12 *E. coli* O157:H7 *E. coli* O157:H7 *E. coli* O157:H7	8.77–35.11 mJ cm^{-2} 19.4 mJ cm^{-2} 14.0 mJ cm^{-2} 0.1 mJ cm^{-2} 34.0 J cm^{-2}	>5.0 <2.0 7.2 5.4 4.7	[18] [51] [52] [53] [54]
Apple juice	*L. innocua*	2.7 J cm^{-2}	4.8–5.8	[13]
	E.coli *S. cerevisiae* *L. plantarum* *A. acidoterrestris*	7.7 kJ L^{-1} 9.6 kJ L^{-1} 3.9 kJ L^{-1} 9.6 kJ L^{-1}	6.0 4.0 >5.0 (total inactivation) 4.0	[14]
	E. coli K12	24.9 mJ cm^{-2}	>5.0	[51]
	E. coli O157:H7	5, 25 and 75 mJ cm^{-2}	2.81 (at 222 nm) 1.95 (at 254 nm) 1.83 (at 282 nm)	[55]
	A. acidoterrestris *E.coli* O157:H7	0.38–1.31 mW cm^{-2} NA	2.3 2.76	[56] [57]
	E.coli STCC 4201 *E. coli* STCC 471 *E. coli* STCC 27325 *E. coli* O157:H7 *E. coli* ATCC 25922	2.66 mJ cm^{-2} 2.66 mJ cm^{-2} 2.66 mJ cm^{-2} 2.66 mJ cm^{-2} 2.66 mJ cm^{-2}	1.23 1.64 2.36 4.01 6.22	[58]
	Zygosaccharomyces bailii	26.4 kJ m^{-2}	5.0	[59]
	E. coli *L. brevis* *S. cerevisiae*	6–24 mJ cm^{-2} 6–24 mJ cm^{-2} 6–24 mJ cm^{-2}	6.0 5.75 4.0	[60]
	E. coli	NA	>5.0	[61]

Table 3. *Cont.*

Juices	Microflora	UV-C Dosage	Log Reduction	References
Apple juice	Aerobic plate count Yeast and mold *E. coli* K12	230.0 J L^{-1} 230.0 J L^{-1} 1377.0 J L^{-1}	3.5 (total inactivation) 3.0 (total inactivation) >7.0	[50]
	S. cerevisiae *L. monocytogenes*	1100 µW cm^{-2}	5.0 4.0	[62]
	E. coli O157:H7	300.0 mJ cm^{-2}	4.5	[63]
Apple and cranberry juice	*P. fermentans* *E. coli*	5.3 J cm^{-2} 5.3 J cm^{-2}	<2.0 6.0	[64]
Grape juice	*S. cerevisiae* Yeasts Lactic acid bacteria	138 mJ cm^{-2}, 9 min 280 mJ cm^{-2}, 24 min 280 mJ cm^{-2}, 24 min	5 3 4.3	[20]
Grape juice (White)	*E. coli* K12 *A. acidoterrestris*	0.90 mL s^{-1} 0.38–1.31 mW cm^{-2}	5.2 5.8	[21] [56]
	B. bruxellensis *S. cerevisiae*	1377.0 J L^{-1} 3672.0 J L^{-1}	>5.0 >5.0	[65]
Grapefruit juice	*E.coli* *S. cerevisiae*	19.0 mJ cm^{-2} 14.0 mJ cm^{-2}	5.1 6.0	[66]
Grape juice (Red)	*B. bruxellensis* *S. cerevisiae* *L. plantarum*	3672.0 J L^{-1} 3672.0 J L^{-1} 3672.0 J L^{-1}	2.0 >5.0 >5.0	[65]
Pomegranate juice	*E. coli* Aerobic plate count Yeast and mold Yeast and mold	62.4 J mL^{-1} 62.4 J mL^{-1} 62.4 J mL^{-1} NA	6.2 1.8 1.5 4.0	[32]
Watermelon juice	Aerobic plate count	2.7–37.5 J m L^{-1}	1.5	[30]
Passion fruit	Aerobic plate count Yeast and mold	NA NA	0.53 total inactivation	[47]
Guava nectar	Aerobic plate count Yeast and mold	NA NA	0.51 1.36	[47]
Guava-and-pineapple juice	Yeast and mold Aerobic plate count	918.0 J L^{-1} 1377.0 J L^{-1}	4.5 (total inactivation) 3.3	[50]
Orange juice	*L. plantarum* *E. coli* O157:H7	9.6 kJ L^{-1} 36.1 kJ L^{-1}	5.0 5.7	[14] [10]
	Aerobic plate count Yeast and mold	1607.0 J L^{-1} 1607.0 J L^{-1}	<1.0 <1.0	[50]
	E. coli O157:H7	2.2 J cm^{-2}	>5.0	[67]
Pitaya juice	*Z. bailii*	1.0 kJ m^{-2}	1.8	[68]

UV-C light acts as the oxidizing agent inducing the formation of highly reactive hydroxyl radicals [69]. This radical formation and subsequent reaction on cell components is positively influenced by temperature and the optimal temperature is 50 °C [70]. DNA (deoxyribonucleic acid) consists of a sequence of four constituent bases known as purines (adenine and guanine) and pyrimidines (thymine and cytosine). They are linked together in a double-stranded helix. When UV-C radiation is absorbed by the pyrimidine bases, it permits a unique photochemical reaction, which leads to dimerization of adjacent pyrimidines (formation of chemical bond between the pyrimidines). Most of the time, the dimerization happens with thymines but cytosine dimmers and thymine-cytosine heterodimers can also be formed. This disruption in the structure of the DNA makes it unable to replicate when the cell undergoes mitosis [71]. At higher doses (>1000 mJ/cm^2) UV-C light can also affect the capsid proteins. The combined effect of size/type of the virion and nucleic acids are thought to be factors determining the resistance/sensitivity of viruses towards UV-C [72].

UV-C fluency is dictated by the absorption coefficient and path length of the specific fruit juice. These parameters can be influenced by two main factors; (1) the liquid food characteristics, where turbidity, particle size, viscosity, total soluble solids, suspended solids, and—sometimes—pH. These characteristics play an important role in dictating the amount of UV-C light to be absorbed. Compared to water, liquid foods have a range of optical and physical properties as well as diverse

chemical compositions [12]; Whereas factor (2) involves the type of UV-C reactor used to photosensitize the juice, which subsequently will influence UV-C light transmittance, dose delivery, momentum transfer, and—consequently—microbial inactivation [33]. These factors will subsequently influence the amount of photo-oxidation incident within the treated juice.

Foremost, a clear understanding of UV-C influence rate on the relationship between absorption coefficient of liquid food, interference from particulates and soluble and suspended solid, is critical to produce effective UV-C pasteurization. This theory was also reported by Guerrero-Beltran and Barbosa-Canovas [4] and Koutchma et al. [2] where, product composition, solid contents, color and overall chemistry of the food product were found to have a major impact on both the absorption coefficient and UV-C inactivation effectiveness. Fruit juices with different turbidity, total soluble solids, and pH levels as well as varying viscosities significantly distinguish the approaches to treat them successfully using UV-C light. Suspended solids cannot only attenuate the UV-C dose via light scattering, but may also provide a site for the aggregation of bacteria to the particle's surface [2]. Hence, the variations and combinations of physical properties of juice such as turbidity and particle size, cannot be overlooked.

Absorption coefficients of juices are highly dictated by the component inside the juice. Shah et al. [27] in her study observed that absorption coefficient of juice is correlated to the turbidity and total soluble solids, which further affect the particle size distribution in the juice. Juice particle size made up of soluble and suspended solids have high light absorbance and have an opaque characteristic to light unless they have high porosity. However, porosity can harbor microorganisms, allowing them to survive or partially injured during UV-C processing. Whereas, turbidity of juice is determined by the content of suspended solid (or juice matters and pulp), will highly influence the viscosity attributes of the juice. The increment of viscosity or flowability of the juice will subsequently increase the flow rate of the juice inside the UV-C reactor. Higher flow rates resulted in increased mixing and more sufficient irradiation of juice. Decreasing the turbidity of juice will positively influence the effectiveness of UV-C inactivation, resulting in a higher inactivation rate.

On the contrary, Muller et al. [14] had reported that blood orange juice with the highest turbidity (9986 NTU), viscosity (2.74 mPa.s) and linearly correlated to absorption coefficient of 194.3 cm^{-1} had higher inactivation rate of *L. plantarum* in blood orange juice than in naturally cloudy apple juice with absorption coefficient of 48.4 cm^{-1}. In another study done by Koutchma [73], using a coiled UV-C module, the absorption coefficient of juices seems to have a significant effects towards *E. coli* K12 inactivation. However, with value of absorption coefficient of more than 48 cm^{-1}, the inactivation was reported to have less than 1 $\log_{10}$ reduction with one pass through the UV-C reactor. The $\log_{10}$ reduction can be increased if the passes are to be increased, exposing the juice to higher UV-C light energy to inactivate the pathogens. *E. coli* K12 inactivation in apple cider (α = 57 cm^{-1}, turbidity = 1383 NTU) confirmed this observation when only 1 $\log_{10}$ reduction was obtained after six passes through the reactor at a flow rate of 75 L/min.

Pass length and the amount of UV-C absorbed by the fruit juice can maximized the UV-C lethality towards microorganisms. The latest development on dean vortex had proven that inactivation of pertinent microbes can be done even with the most opaque liquid foods. Choudhary et al. [74] in his works had proven to successfully inactivate 5 $\log_{10}$ count of *E. coli* and *B. cereus* in raw and skimmed cow milk. The effectiveness of the reactor was due to high and rapid turbulent (high Reynolds number) formed within the coiled tube reactor while minimizing the path length (or the gap width) of the liquid food sample and UV-C emission. The same technology was replicated by Muller et al. [14] and Shah et al. [27] where it was also proven that the coiled reactor managed to inactivate up to 5 $\log_{10}$ bacterial count of *A. acidoterretris*, *E. coli*, *L. plantarum*, and *S. cerevisiae* and *S. typhimurium*.

4.2. Chemical Safety

Recently, furan was highlighted as one of the main concern in utilizing UV-C irradiation on fruit juice [75]. Furan is a heterocyclic aromatic compound containing one oxygen atom and a suspected

carcinogenic by IARC with Group 2B classification, which is stated as "possibly carcinogenic to humans" [76]. Furan does not have a practical application as a final product. However, it plays a role in the production of (co)polymers and furan has been identified in a number of food that have been heat treated [77] and recently, in UV-C-treated fruit juice [11]. Literatures containing furan as part of the safety analysis involving UV-C irradiation is very limited to the ones reported in Table 4.

Table 4. Effect of UV-C irradiation on furan content in fruit juice.

Medium	Variables	Effects	References
Apple juice	UV-C dose = 10 mW/cm^2	Minimal of furan at dose less than 3.5 J/cm^2. At 8.8 J/cm^2, ~14 ppb furan was formed. Furan formation increased at a rate of 11 ppb per J/cm^2	[11]
Pummelo (*Citrus Grandis* L. Osbeck) juice	UV-C dose = 15.45, 18.18 and 27.63 mJ/cm^2	Furan development depended on UV-C dose (0.66–2.4 ppb/mL) and inversely proportional towards the sugar content of the juice. Furan was also seen to decrease as the storage weeks increased.	[27]
Apple juice	UV-C dose = 39–245 mJ/cm^2	Furan increased from 2.3 to 3.7 µg/kg proportional to increment of UV-C dose. No significant increase was found when freshly squeezed and commercial apple juices were compared.	[14]
Apple juice and cider	UV-C dose = 3.1–6.3 mJ/cm^2	Content of fructose and malic acid in the juice was shown to have induced the furan formation. Apple juice was found to have high furan content in comparison to apple cider.	[78]

In addition to that, furan was found to form from carbohydrates, ascorbic acid, fatty acids, and a mixture of all three [79,80]. Both literatures have claimed that furan formation is highly associated with the physicochemical properties of fruit juice, where fructose was found to be the main cause. The simple sugars can be grouped into two types according to the ring structures: five-member furanoses (furan like) and six-member pyranoses (such as glucose). The furanoses are less stable upon heating than pyranoses. For example, glucose can be heated up to 100 °C, but sucrose and fructose decomposes at a temperature as low as 60 °C [81]. It was also found that the reduction rate of furan during storage, is slower as the UV-C fluence decreased [27]. The same observation was found in a study of furan formation upon gamma irradiation during 14-day storage at 5 °C [80]. The rapid destruction by high-dose of UV-C may also contribute to the initial boost in the accumulation of furan occurring in the tested samples, mostly due to the high amount of sugar. Hence, cautions should be made when fruit juice with a high content of fructose being treated with UV-C irradiation to avoid excessive formation of furan.

The finding of Shah et al. [27], however, was found to be unexpectedly higher than the results reported by Fan and Geveke [11], where it was shown that 8.8 J/cm^2 (equivalent to 8800 mJ/cm^2) would produce 14 ppb/mL of furan in commercial fresh apple cider, at a rate of 11 ppb per J/cm^2. The authors also claimed that significant amount of furan could be accumulated if the fruit juice was over-treated [11]. Comparing to the results of Bule et al. [81], the amount of furan found in apple juice treated with UV-C fluence rate of 5.94 mJ/cm^2 was 1648 ppb/mL. Both literatures have claimed that furan formation is highly associated with the physicochemical properties of fruit juice, where fructose was found to be the main cause.

Temperature of UV-C reactor was also found to be one of the main causes of furan formation. As the results of Shah et al. [27] were considered highest in comparison to the other researchers (Table 4), where the rate furan formation was found to be 1 ppb to every 20 °C increment, whereas, Fan and Geveke [11] reported a furan formation rate of 1 ppb to every 28 °C increment. Nevertheless, the FDA [82] survey reported that furan levels in some thermally processed juices were in the range of 2.5–8.4 ppb/mL and furan formation in UV-C irradiated juices are well below the thermally processed juice.

5. Hurdle Technology of UV-C-Irradiated Fruit Juices

Due to certain limitations that the UV-C technology possesses, the application is often combined with other processing techniques to achieve maximal benefits in microbial reduction and retention of juice quality. There is much to be explored with regards to the use of hurdle technology in UV-C processing of juices. The combination could be between UV-C technology and heat or it could be between UV-C and other nonthermal methods (nonthermal technologies or application of chemicals and preservatives). Juices tested using the hurdle technology includes apple, pineapple, guava, orange, pitaya, mango, watermelon, and mixed juices. Several combinations which have been explored for ultraviolet irradiation of juices includes sonication, mild heat, dimethyl dicarbonate, acids, membrane filtration, TiO_2–UVC (TUVP) photocatalysis, preservatives, and pulsed electric field (Table 5). Some combinations were able to achieve the required 5-log reduction of microorganisms and some failed to do so. Some combined treatments has the potential to significantly reduce a variety of pathogens, spores, yeasts, molds, and protozoa. The combined membrane filtration and UV achieved more than a 5-log reduction of *E. coli*, *C. parvum*, and *A. acidoterrestris* [83]. Gram-negative bacteria, *E. coli* O157:H7, *S. typhimurium*, and *S. cerevisiae* counts were significantly reduced after a combined treatment using TUVP and high pressure [84]. Combined treatment extended the shelf life of juices [64,85]. In some cases, synergistic microbial inactivation effects of the combined treatments were observed [85–88] while in other cases, undesirable flavor of the end products were reported [13,42].

Table 5. Effect of UV-C irradiation and hurdle technology on juice.

Juice Type	Combined Treatments	Irradiation Effect on Juice Properties	References
Apple (Jonagold Red) juice	UV-C treatment (for 30 min) and pulsed electric field treatment at 40 kV/cm for 100 pulses	Obtained satisfactory total microbial inactivation and improved product quality compared to heat pasteurization.	[5]
Mango juice	(i) Combined sonication, 15 min and UV-C treatment, 15 min (ii) Combined sonication, 30 min and UV-C treatment, 15 min (iii) Combined sonication, 15 min and UV-C treatment, 30 min (iv) Combined sonication, 30 min and UV-C treatment, 30 min	Support the use of nonthermal treatments (ultrasound and UV-C) for better retention of quality and prolonged shelf life in Chokanan mango juice processing.	[42]
Orange and carrot mix juice	UV-C treatment (10.6 J/cm^2) or high intensity light pulses (HILP) (3.3 J/cm^2 combined with manothermosonication technology (400 kPa, 35 °C, 1000 W, 20 kHz)	Panelists did not perceive differences in the odor, sweetness, or acidity of the product.	[46]
Apple juice	UV-C treatment (NA) and radio frequency electric field (RFEF) (20 kHz)	Highly depended on the temperature increment (25, 30 and 40 °C) during UV-C and RFEF-treatment which reduced the *E. coli* log count to 4, 3.3, and 1.5 respectively. However, the injured population of *E. coli* was seen the lowest with UV-C treatment (4%) alone in comparison to RFEF treatment (84%).	[61]
	UV-C treatment (13.81–5.20 J/mL) at mild heat (45–60°C)	*S. cerevisiae* showed the highest resistance towards UV-C + heat treatment. As the inactivation of *S. cerevisiae* was limited due to its relatively high absorption coefficient. The combination of UV-C treatment and heat between 52.5 and 57.5 °C led to a synergistic effect of inactivating *S. cerevisae*.	[86]

Table 5. *Cont.*

Juice Type	Combined Treatments	Irradiation Effect on Juice Properties	References
Apple juice	UV-C treatment (for 1.8 s) and pulsed electric fields (PEF) (60 kV/cm)	Additive effect of PEF and UV-C treatment on *E. coli* microbial population. No significant effect was found on the physicochemical characteristics of apple juice treated with HILP and PEF.	[89]
	Pulsed light (2.4–71.6 J/cm^2) and ultrasound (20 kHz, 95.2 µm)	The application of 30 min of ultrasound followed by 60 s of pulsed light with the final temperature of 56 °C was the most effective, with reduction of 6.4 and 5.8 log$_{10}$ of *S. cerevisiae* in commercial and natural squeezed apple juice.	[90]
	High intensity light pulses (HILP) (4–5.1 J/cm^2) and pulsed electric fields (PEF) (130–262 J/mL)	The combination of PEF and HILP resulted in 7 log$_{10}$ reduction of *E. coli* while the reversed of HILP and PEF only resulted in 5 log$_{10}$ reduction of *E. coli.*	[91]
	UV-C treatment (UV-C; 30 min, 20 °C) pre-heating and pulsed electric fields (PEF)	Reduced *S. aureus* in apple juice by up to 9.5 log10. Preheating temperatures had non-significant effects on reduction of *S. aureus*, while treatment time and electric field strength significantly affected bacterial reduction in apple juice.	[92]
Apple (Fuji) juice	UV-C treatment (27.10 J/mL) and heat (55.0 °C, and 3.58 min)	Bactericidal effect of UV-C light on *E. coli* suspended in apple juice synergistically increases with temperature and achieved 5 log$_{10}$ reductions without affecting pH, total soluble solids, and acidity of freshly squeezed apple juice.	[87]
Pineapple juice	UV-C treatment (10.76 mJ/cm^2) and dimethyl dicarbonate (DMDC 250 ppm)	Turbidity, vitamin C, and phenolic content were found to have significant changes—the decrements were considerable in comparison to repetitive UV-C-treatment. The order of DMDC addition to the sample was shown to have significant effect towards total plate count (TPC) and yeast and mold (YMC).	[22]
	Mild heat (55 °C, 10 min) followed by UV-C treatment (5.61 mJ/cm^2)	Effectively inactivate the pectin methylesterase in pineapple juice, preserved relatively high amount of bromelain and total phenol content.	[85]
Peach nectar	UV-C treatment and Potassium Sorbate (250, 500, 1000, and 2000 ppm) UV-C treatment and Sodium Benzoate (250, 500, 1000, and 2000 ppm)	Potassium sorbate absorbs light close to the shortwave ultraviolet germicidal wavelength, thus, it can only be added after the UV-C treatment. The synergistic effect of UV-C and sodium benzoate was shown to have up to 3.5 log$_{10}$ reduction of *A. niger* and *A. flavus*.	[88]
Green guava juice	UV-C treatment (3.47 mJ/cm^2) followed by mild heat (55 °C, 60 s)	Achieved 5 log$_{10}$ reduction of *L. innocua*, retained acceptable physicochemical properties.	[93]
Orange juice	UV-C treatment (23.72 J/mL) and heat (55.0 °C, and 3.6 min)	Achieved more than 5 log$_{10}$ cycles of *E. coli* inactivation without affecting the pH, acidity, total soluble solids, and color. However, ascorbic acid content was decreased by 16.45% and 63.96% of pectinmethylesterase activity.	[94]
	UV-C treatment (0–18.7 kJ/m^2) and ultrasonic (20 kHz, 95.2 µm)	Simultaneous used of both technologies for 20 min yielded the highest reduction of *E. coli* in orange juice (3.4), in comparison to separate treatment of ultrasonic and ultraviolet (2.0).	[95]

Table 5. *Cont.*

Juice Type	Combined Treatments	Irradiation Effect on Juice Properties	References
Red pitaya juice	UV-C treatment, citric acid (1.5%) and dimethyl dicarbonate (15 µL/100 mL)	Addition of 1.5% citric acid and dimethyl dicarbonate into red pitaya juice prior to UV-C treatment achieved significantly higher microbial reduction compared to UV-C alone.	[44]
Apple and cranberry juice	(i) UV-C treatment (5.3 J /cm^2, 30 s) and pulsed electric fields (34 kV/cm, 93 µs); (ii) UV-C treatment (5.3 J/cm^2, 30 s) and manothermosonication (20 kHz, 750 W, 400 kPa)	More than 6 $\log_{10}$ reduction of *E. coli* K12 and *Pichia fermentans* in fresh blend of apple cranberry juice was found for both combinations of ultraviolet and PEF/MTS. Storage time was extended to 15 days for the juice sample after treated with UV-C and PEF.	[64]
	(i) UV-C treatment (5.3 J /cm^2) and pulsed electric fields (34 kV/cm, 93 µs); (ii) UV-C treatment (5.3 J/cm^2) and manothermosonication (20 kHz, 750 W, 400 kPa)	The combination of UV-C and PEF did not cause considerable changes in *Lab** color and total phenolics content in comparison to the combination treatment of UV-C and manothermosonication (MTS) with exception towards non-enzymatic browning index, where non-significant effect detected. The overall acceptability of UV-C and PEF was the highest among other non-thermal combinations. UV-C and MTS was ranked the lowest for the unfavorable flavor of the sample.	[91]
Red and yellow Watermelon juice	UV-C treatment and citric acid (1.5%)	Did not achieve 5 $\log_{10}$ reduction	[96]

Physico-chemical and functional properties of juices treated with a combination of UV-C and other microbial reducing methods were not significantly affected [13,22,88,93]. Shelf life of the juice was also extended and in treatments where mild heat was involved enzyme activity were mostly halted [84]. In one instance UV-C and mild heat combination effectively inactivated the pectin methylesterase in pineapple juice, but preserved relatively high amount of bromelain and total phenol content [84].

A hurdle technology approach must be an intelligent approach so not to affect quality of the product. The intensity of treatment and order of the combined treatments would affect the end results. Whether to apply UV-C as a pre-treatment process or apply another technique before UV-C exposure that is a question which has varying answers, depending on the combinations applied. For example, the order of dimethyl dicarbonate addition (before or after UV-C exposure) to the sample was shown to have significant effect towards total plate count and yeast and mold count [22]. A combination of UV-C and sonication of mango juice was found to decrease the overall acceptability which could be attributed to the formation of free radicals induced by sonication, thus causing an off-flavor of the juices [42].

6. Market Potential and Cost Implications

Juices treated with UV-C when compared with thermally treated juice, has relatively better taste, color profile, and ascorbic acid content, similar to that of the freshly pressed juice [17,43]. A good product can only be launched to reach its target consumers with the aid of a suitable and fitting marketing strategy [97]. When a product produced is of premium quality (better color and flavor profile, higher nutrient retention, and fresh-like characteristics) the selling price could be set at a relatively higher value. Through a survey done, it was reported that consumers especially those who are health conscious will be willing to spend money for premium products thus creating better profitability value [98]. UV-C irradiated juice is perceived as a premium product due to its proven superior quality [97]. UV-C irradiated juice obtained a considerably higher perceived positioning compared to the different commercialized brands, which were largely thermally treated. UV-C pasteurization is a low-cost alternative to thermal pasteurization for small processing operations [17,18,98–100].

The estimated cost of an ultraviolet irradiation equipment is only USD 10,000 to USD 15,000 compared to USD 20,000 to USD 30,000 for thermal pasteurization equipment [100,101]. Energy requirement for UV-C pasteurization is cheaper than thermal pasteurization energy requirement for both technologies and this has been pointed out by several researchers [9,98,99]. The variable cost for UV-C treated pineapple juice is RM 0.895 per can (320 mL) while thermally treated pineapple juice is RM 0.900 per can (320 mL). These results indicate that UV-C pasteurization could produce juice at a lower production cost than thermal pasteurization [98]. Similar observations were reported for apple cider where UV-C pasteurization costs are approximately RM 1.60 per 100 liters [102] and thermal pasteurization costs is approximately RM 4.00 per 100 liters [101].

The fact that consumers are willing to pay more for UV-C treated juices is good news for small scale manufacturers. The fact that implementation of UV-C technology can be more profitable than heat treatment when applied in a small-to-medium scale pineapple juice processing plant is more good news for small scale manufacturers. The profitability index for both investments predicts high profitability, but UV-C technology offers excellent investment potential and shorter payback period. A profitability index of 21.56 and payback period of four months for UV-C treated pineapple juice can be considered attractive in comparison to thermally treated pineapple juice, where the profitability index is only 17.10 and the payback period is 30 days longer [98]. However, despite the market potential for UV-C treated fruit juice, it should be reiterated that UV-C does impart a negative effect towards fruit juice, as such mentioned in Section 4.2 on the furan development of fruit juice, especially on citrus juice. It is therefore recommended that fruit manufacturers establish the correct UV dose and control it during juice exposure to UV-C and regularly test that the amount of furan developed to be within the limits allowed by USFDA [8,75].

7. Summary

Fruit juices treated with UV-C (253.7 nm) have potential and demand in the industry. Although UV-C is still an unfamiliar process to the industry, it is of significance in the production of safe, fresh-like, minimally-altered juice products that are easily degraded by conventional heat treatments. Due to certain limitations of the UV technology, attempts have been made to combine ultraviolet with other processes at low intensities. This is an alternative which could lead to significant benefits in maintaining juice quality. However, it must be done correctly to ensure the required safe limit and quality preferences are met, through appropriate control the dosage and exposure of UV-C to the fruit juice. Positioning of UV-C treated juices as a premium product with relatively lower investment costs and a quicker payback period could be attractive for small scale manufacturers. It is clear that UV-C technology has its place in the juice industry and is definitely an option for juice manufacturers. However, it is important to note that this paper did not cover the aspect of UV-C equipment design and cost implications of combining UV-C technology with other methods. It is also recommended that the current status of regulation in various countries pertaining to the use of UV-C technology for juice production is reviewed and documented.

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