UV Processing and Storage of Liquid and Solid Foods: Quality, Microbial, Enzymatic, Nutritional, Organoleptic, Composition and Properties Effects

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Introduction

Non-thermal food processing technologies have been explored extensively in recent years in order to develop food products with extended shelf life as well as preserved nutritional and organoleptic characteristics in accordance with the changing consumer demands (Falguera et al., 2011a; Sanchez-Moreno et al., 2009). Ultraviolet (UV) irradiation is one of the non-thermal processes that can be applied to reduce the microbial load in liquid foods and surfaces, and to sterilize food packages and packaging materials, and environments involved in food processes (Jimenez-Sanchez et al., 2017a; Bintsis et al., 2000).

UV light is subdivided into three regions as short-wave UV (UV-C, 200 and 280 nm), medium-wave UV (UV-B, 280 to 315 nm), and long wave UV (UV-A, 315 to 400 nm). The different types of effects on microorganisms can be caused by UV light of different wavelengths. The effectiveness of UV light on microorganisms results primarily from the fact that DNA molecules absorb UV photons between 200 and 300 nm, with peak absorption around 260–265 nm. This causes DNA damage by altering the nucleotide base pairing, thereby creating new linkages between adjacent nucleotides, particularly between pyrimidine bases, on the same DNA strand and ultimately results in cell death (Zimmer and Slawson, 2002). Peak et al. (1984) proposed that the dimer formation is not the only requirement to damage the DNA. Absorption of different wavelength photons by different molecular groups in the long DNA molecule can damage or destroy these bond groups. Thus, different bonds in the DNA can be affected with photons of different energy (Neister, 2014).

The major drawback of UV technology is associated with leaving no residue in food systems. Therefore, following the UV irradiation, many microorganisms may develop a mechanism to repair DNA damages caused by UV irradiation (Zimmer and Slawson, 2002). Therefore, photo-reactivation and dark repair should be also taken into consideration when the UV injured cells are exposed to wavelengths higher than 330 nm (Guerrero-Beltran and Barbosa-Canovas, 2004).

UV processing can be applied either in continuous or batch photo reactors. The latter is usually preferred when the medium has high viscosity or the need of high irradiation times. Continuous flow systems, on the other hand, can accomplish large quantum yields and short irradiation times (Falguera et al., 2011b). Generally, the low pressure mercury lamps emitting light at 253.7 nm wavelength are used in these systems. Thus, UV-C treatment throughout this document is referred to the process at the germicidal wavelength of 253.7 nm. Factors affecting UV-C processing can be summarized as follows: the type of UV irradiation source, UV dose, flow rate, lamp power, characteristics of liquid, type and number of microorganisms, growth stage of microorganisms, time, and particle content. Regarding the liquid foods, UV transmittance (UVT) is the limiting factor due to the soluble and suspended solids and their absorption result. Therefore, the thin film or turbulent flow reactors have been utilized in order to increase

the efficacy of microbial inactivation in juices with suspended particles or low UVT (Koutchma et al., 2006; Koutchma et al., 2004; Unluturk et al., 2004). More details can be found in several reviews that have been previously focused on the fundamentals of UV irradiation, its applications, and the effects of UV irradiation on many food products including fruit juices, fruits and vegetables, fish, poultry, and meat food products (Koutchma et al., 2016; Gayan, Condon and Alvarez, 2014; Falguera et al., 2011a, 2011b; Koutchma, 2008; Guerrero-Beltran and Barbosa-Canovas, 2004; Bintsis et al., 2000).

Food quality is based on some external and internal characteristics of the products such as shape, size, skin colour, general appearance, taste, smell, flesh firmness, texture, flavour and nutritional values. Hence, it is important to know and assess these parameters both before and after the processing (Abasi et al., 2018). Herein, the current research progresses on the application of UV irradiation (UV-A, UV-B, and UV-C) in food processing are reviewed by putting a special emphasize on the quality effects of UV processing on foods. The results of a number of experimental studies about the effects of UV processing on microbiological, organoleptic, physicochemical quality of foods and as well as on bioactive compounds, quality degrading enzymes, allergens, and toxins are reported. Publications since 2010 are mainly considered with a few exceptions detailed in sections. Pulsed light and UV Light Emitting Diodes (UV-LEDs) were excluded in this chapter.

The Chemistry of Photo-Degradation of Organic Compounds

Photo-degradation is the alteration of materials by light. Photochemical reactions take place in two ways, either directly or through photosensitization. In the direct way, photochemical reaction starts with absorption of a photon by a molecule then a chemical reaction is initiated. The quantum yield and fluence of incident photons determine the extent of the chemical reaction. UV light at 253.7 nm with a radiant energy of 112.8 kcal·Einstein^{-1} (1 E represents 1 mol of photons), theoretically affects directly the O—H, C—C, C—H, C—N, H—N, and S—S bonds if it is absorbed (Koutchma, 2009a, 2009b).

In the second way, the action of a component in the system causes another component to undergo reaction due to light. In the direct photochemical reactions, the types of processes depend on the wavelength (photon energy) of the light and the structure of the absorbing molecule. Following the absorbing a photon, a molecule is raised to a highly excited level and undergoes a photochemical process. This process causes dissociation of molecule into radicals, decomposition into molecular products, isomerization, dimerization and ionization (Spikes, 1981).

Photooxidation is the most common type of photosensitizing reaction. Typically, photosensitizers are excited from the ground state to a short-lived singlet excited state, this undergoes the conversion to a long-lived triplet state that mediates the process. The triplet sensitizer can react by the way of two main pathways as by hydrogen or electron transfer processes (free radical or type I reaction) or by energy transfer (type II) reactions. In general, Photo-degradation of organic compounds is generated by production of hydrogen peroxide or superoxide anion. They react with many kinds of molecules, and undergo to hydrogen or electron transfer processes (free-radical or type I reactions) (Koutchma, 2009b).

The sensitivity of foods to UV light depends on the photosensitivity of the basic nutrients that they contain and the wavelength of light. For example, some nutrients are known as light sensitive, i.e., vitamin A, carotenes, vitamin B12, vitamin D, folic acid, vitamin K, riboflavin (vitamin B2) tocopherols (vitamin E), tryptophan, and unsaturated fatty acid residues in oils, solid fats, and phospholipids (Spikes, 1981).

It is known that vitamin D is photochemically altered to vitamin D2 when subjected to UV-B light especially near around 310–320 nm (Slawinska et al., 2016). Even though, ascorbic acid is a strong absorber of UV light at 254 nm, it does not absorb light significantly above 300 nm (Koutchma, 2009b). The rate of degradation of vitamin A varied with different wavelengths of incident irradiation; the maximum rate of photolysis is observed over the range of 330–350 nm (Allwood and Plane, 1986).

In general, only unsaturated organic molecules absorb light at wavelengths greater than 220 nm. The longer the conjugate chain in the molecule, the maximum absorption wavelength is more prolonged. Aromatic heterocyclic molecules, such as the nucleic acid bases and the aromatic amino acids (phenylalanine, tryptophan, and tyrosine), absorb light strongly at 254 nm. In some cases, the absorption spectrum extends well above 300 nm.

Carbohydrates are quite stable in the absence of photosensitizers. In the presence of photosensitizers such as titanium dioxide, singlet oxygen and hydroxyl radicals can produce some sensitized photoreactions. These reactions can result in photochemical depolymerization of complex heterogeneous polysaccharides such as pectin, amylopectin in foods, leading to softening in fruits and vegetables (Burana-osot. et al., 2010).

Spikes (1981) reported that UV light in the range 265–305 nm causes the stimulation of oxidative changes in fats and oils. Illumination apparently converts fatty acids with a conjugated oxodiene system to radicals that initiate the autoxidation of the methyl linoleate. Especially, the linoleic acid hydroperoxides are decomposed by irradiation at 254 nm. Three essential amino acids for human health such as histidine, phenylalanine, and tryptophan are also degraded by UV light. For example, tryptophan subjected to UV light up to 280 nm is converted to N-formylkynurenine. This product is a photodynamic sensitizer in the irradiation at wavelengths greater than 320 nm. It sensitizes the photo-oxidation of amino acids, nucleic acid bases, and vitamin C. Moreover, UV light causes the degradation of proteins which results in changes in solubility, sensitivity to heat, mechanical properties, and digestion by proteases. Photo-degradation of proteins, for example, can also lead to detectable organoleptic and taste changes in dairy products. Characteristic colors of the foods depend on the presence of a variety of natural pigments, including anthocyanins, betalaines, carotenoids, chlorophylls, flavanoids, heme pigments, leucoanthocyanins, quinones, xanthones, and tannins. A number of these food colorants are altered on subjection to light leading to changes in the color of foods. Some pigments act as the photodynamic

sensitizers and can synthesize various kinds of photo oxidative compounds in foods. On the other hand, some food compounds protect other components against these changes. For example, tocopherols can play a protective role in photo-degradation reactions (Spikes, 1981).

Effects of UV Processing on Microbiological Quality of Foods

Food related microorganisms have different resistivity against UV irradiation. The microbial efficiency of UV irradiation depends on the structure, the wall thickness and the composition of the cell as well as the amount of UV absorbing nucleic acids (Koutchma, 2014). Additionally, food characteristics such as its composition, color, amount of suspended solids, absorptivity and the initial microbial load are important parameters affecting the disinfection efficiency of UV light (Koutchma et al., 2009b; Guerrero-Beltrán and Barbosa-Cánovas, 2004).

Microbial Quality of Liquid Foods Treated With UV Light

There are numerous studies focused on the microbial inactivation aspects of UV processing of liquid foods such as fruit and vegetable juices, juice blends, milk, liquid egg, alcoholic and non-alcoholic beverages etc. Recent studies on UV processing of liquid foods are summarized in Table 1. In these studies, several types of continuous flow UV systems and batch UV devices are utilized depending on the characteristics of liquid foods. Continuous flow UV systems have annular, thin film, dean vortex and coiled type of designs (Rosenthal et al., 2018).

US FDA regulations mandate a minimum pasteurization requirement of 5 log reduction of pathogenic microorganism capable of growing in the product (US FDA, 2001). The studies showed that UV-C irradiation at 253.7 nm was adequate to meet the minimum pasteurization requirement in some products. For example, approximately 5 log reduction was recorded for *Esherichia coli* and *Listeria innocua* in reconstituted clear apple juice ($2.66 \, J \, cm^{-2}$) treated with UV light in an annular flow UV reactor system (Caminiti et al., 2012a). Similarly, the microbial counts of *Salmonella typhimurium* decreased with increasing UV-C dosage. Highest microbial reduction was achieved at dosage of $0.014 \, J \, cm^{-2}$ with reduction of 5-log CFU/mL (Mansor et al., 2014). A 6 log reduction of *E. coli* in cloudy apple juice was achieved at UV dose of $7.7 \, J \, mL^{-1}$ using turbulent Dean Vortex flow UV system (Müller et al., 2011). Higher than 6 log reduction of *E. coli* K12 at UV dose of $2.46 \, J \, mL^{-1}$ was recorded in lemon-melon juice blend treated with the annular flow UV reactor system (Kaya et al., 2015). However, the results of some studies showed that yeasts and moulds are more resistant to ultraviolet light than that of bacteria (Kaya and Unluturk, 2016; Shamsudin et al., 2014; Unluturk and Atilgan, 2014; Pala and Toklucu, 2011, 2013a, 2013b; Müller et al., 2011). For example, Unluturk and Atilgan (2014) reported lower log reduction of spoilage yeasts in white grape juice compared to *E. coli* and lactic acid bacteria (LAB) when they were exposed to the same UV dosage in the annular flow UV reactor system. In addition, it was presented that coliforms had higher UV sensitivity than yeast and moulds in watermelon juice (Feng et al., 2013). Besides, it was determined that the UV inactivation of psychrotrophic bacteria was much higher than that of yeast and moulds when they were exposed to the same UV dose in carrot juice (Riganakos et al., 2017). Other than fruit juices, different types of liquid food products such as vegetable juices, beer, wine, milk, ice tea etc. are also successfully treated with continuous flow UV systems (Biancaniello et al., 2018; Monyethabeng and Krügel, 2016; Fredericks et al., 2011; Lu et al., 2011; Lu et al., 2010).

It was concluded that type of target microorganism is important factor affecting the inactivation efficiency of UV irradiation. Additionally, it was revealed that due to the physicochemical characteristics of fruit juices, application of UV-C irradiation has certain limitations and thus, the equipment design is crucial. The optical juice properties (transparency, suspended solids content, absorption coefficient, turbidity, and color), juice composition and juice physical properties, among other variables, are imperative to produce a safe and wholesome juice using UV technology.

On the other hand, lab scale batch UV systems, which are also called bench scale collimated beam devices, are widely used to determine the reduction equivalent dose (RED) i.e., the minimum UV dose required for inactivation of the target pathogen/s, in the continuous UV processing of liquid foods. The UV dose-response curve is derived through collimated beam testing. The UV dose (RED) is determined from the UV dose-response curve by entering the log inactivation measured during continuous flow UV reactor testing. It is specific to target microorganism used in the experimental testing and validation conditions for continuous flow systems. In the batch systems, sample characteristics (thickness, color, cloudiness of the liquid), UV lamp characteristics (type, power and number of the lamp) and distance between sample and the lamps are important parameters to take into account during experimental testing (Keyser et al., 2008; Sizer and Balasubramaniam, 1999).

Table 1 lists the studies performed by means of collimated beam devices (batch UV systems). More than 5 log reduction of *E. coli* O157:H7, *Alicyclobacillus acidoterrestris* spores and *Saccharomyces cerevisiae* were achieved when clear juices such as apple juice, white grape juice, orange juice were subjected to UV light in these systems at UV dose of $0.54 \, J \, cm^{-2}$, $0.28 \, J \, cm^{-2}$, and $0.49 \, J \, cm^{-2}$, respectively (Tremarin et al., 2017; Kaya and Unluturk, 2016; Baysal et al., 2013; Oteiza et al., 2010). However, lower level of log reductions of total mesophilic aerobic bacteria, total yeasts and molds counts, and *E. coli* K-12, *E. coli* O157:H7 and *L. innocua* counts were obtained in the more opaque type of liquids, e.g., liquid egg white, tomato juice, onion juice, etc (Demir et al., 2019; Unluturk et al., 2010).

Table 1 Processing of liquid foods with continuous flow and batch UV systems

Liquid food	UV processing conditions	Target microorganism	Log reduction/UV dosage	Reference
Apple juice	Annular reactor UV-C lamp (30 W) 352 mL·min^{-1} 1.26 mm path length	E. coli K12 L. innocua	4.83 log E.coli 4.59 log L. innocua (2.66 J cm^{-2})	Caminiti et al. (2012a)
Orange Juice	Annular reactor 9 UV-C lamps (28 W) 20 mL s^{-1}	Aerobic Plate Count (AC) Yeasts- Molds (YM) E. coli (acid adapted)	2.96 log AC 0.52 log YM 5.72 log E.coli (36.09 J mL^{-1})	Pala and Toklucu (2013b)
Lemon-Melon Juice Blend	Annular reactor 4 UV-C lamps (15 W) 3.80 mL s^{-1} 5 mm path length	E.coli K-12	>6 log (2.46 J mL^{-1})	Kaya et al. (2015)
White grape juice Red grape juice	Annular reactor 9 UV-C lamps (28 W) 20 mL s^{-1}	Aerobic Plate Count (AC) Yeasts-Molds (YM)	3.51 log AC 2.71 log YM (12.6 J mL^{-1}) in white GJ 3.59 log AC 2.89 log YM (12.6 J mL^{-1}) in red GJ	Pala and Toklucu (2013a)
Pitaya juice	Annular reactor UV-C lamp (17 W) 30.33 mL s^{-1} 20 mm path length	Aerobic mesophilic bacteria Yeasts-molds	2.11 log aerobic bacteria 1.14 log yeasts-molds (860 J cm^{-2})	Ochoa-Velasco and Guerrero-Beltrán (2012)
Coconut milk	Annular reactor UV-C lamp (17 W) 30.33 mL s^{-1} 20 mm path length	Escherichia coli S. typhimurium Mesophiles Yeasts-molds	4.1 log E.coli 4.1 log S. typhimurium 2.0 log mesophiles 1.3 log molds-yeasts (0.103 J cm^{-2})	Ochoa-Velasco, Cruz-González, and Guerrero- Beltrán (2014)
Cloudy apple juice (CAJ) Blood orange juice (BOJ) Elderberry nectar (EN)	Dean vortex system UV-C lamp (9 W) 16.8 L h^{-1}	Spoilage microorganisms (L. plantarum E. coli DH5a S. cerevisiae A.acidoterrestris)	CAJ: 5 log L.plantarum (1.9 J mL^{-1}) 6 log E.coli (7.7 J mL^{-1}) 4 log S. cerevisiae & 4 log A. acidoterrestris (9.6 kJ L^{-1}) L. plantarum (9.6 J mL^{-1}): >6 log (BAJ) 1 log (EN) >4 log (CAJ)	Müller et al. (2011)
Apple juice Grape juice	Coiled tube reactor UV-C lamp (36 W) 30 L h^{-1}	Aerobic plate count Yeasts and molds	0.50 log total aerobic count 1.56 log yeasts-molds (100.47 J mL^{-1}, apple juice) >2 log in total aerobic & yeasts-molds (100.47 J mL^{-1}, grape juice)	Müller et al. (2014)
Clear white grape juice (CGJ) Freshly squeezed white grape juice (FSGJ)	Pilot scale reactor 6 UV-C lamps (30 W) 5.08 cm path length 820 mL·min^{-1} (CGJ) 774 mL·min^{-1} (FSGJ)	S. cerevisiae Spoilage microflora (Yeasts LAB)	CGJ: 3.39 log S. cerevisiae (0.07 J cm^{-2}) FSGJ: 1.54 log yeasts (0.08 J cm^{-2}) 1.64 log LAB (0.07 J cm^{-2})	Kaya and Unluturk (2016)
Freshly squeezed white grape juice (FSGJ)	Annular reactor 7 UV-C lamps (15 W) 0.90 mL s^{-1} 5 mm path length	E.coli K12 Spoilage microflora (Yeasts LAB)	3.76 log E.coli K12 4.13 log LAB 1.6 log yeasts (116.7 J mL^{-1})	Unluturk and Atilgan (2014)
Pineapple juice	Dean vortex system 2 UV-C lamps (55 W) 7.8, 102, 121 mL·min^{-1}	Salmonella typhimurium	5 log (7.8 mL·min^{-1}, 0.014 J cm^{-2}) 3.89 log (102 mL·min^{-1}, 0.01 J cm^{-2}) 3.99 log (121 mL·min^{-1}, 0.01 J cm^{-2})	Mansor et al. (2014)

Table 1 Processing of liquid foods with continuous flow and batch UV systems—cont'd

Liquid food	UV processing conditions	Target microorganism	Log reduction/UV dosage	Reference
Pineapple juice	CiderSure 3500-B laboratory unit 8 UV-C lamps 0.21–0.48 mm film thickness Automatic flow rate	Natural microflora (total plate count yeasts-molds)	1.91 log total plate count 1.4 log yeasts-moulds (0.22 J cm^{-2})	Shamsudin et al. (2014)
Pomegranate juice	Annular reactor 9 UV-C lamps (28 W) 20.21 mL s^{-1}	Natural microflora (total plate count yeasts-molds) E.coli	1.8 log total plate count 1.45 log yeasts-molds (62.4 J mL^{-1}) 6.15 log E.coli (34.4 J mL^{-1})	Pala and Toklucu (2011)
Watermelon juice	The Teflon®-coil reactor UV-C lamp (75 W) 2.0 mL s^{-1}	Coliforms Aerobic plate count Yeasts-molds	2.6 log coliforms 1.47 log aerobic counts 0.99 log yeasts-molds (37.5 J mL^{-1})	Feng et al. (2013)
Carrot juice	The coiled tube reactor UV-C lamp (30 W) 20 L/h	Total mesophilic count Psychrotrophic bacteria, LAB, Enterobacteriaceae Yeasts-moulds	4.6 log mesophilic count 4.9 log psychrotrophic count >5 log enterobacteriaceae >4 log LAB (totally inact.) >1.8 log yeasts -molds (completely inactivation) (5.76 J/mL)	Riganakos et al. (2017)
Peach nectar	Commercial UV water disinfection system 2 UV-C lamps (40 W) 60 min 1.8 L·min^{-1}	Aspergillus flavus Aspergillus niger spores	4 log A. flavus 3 log A. niger (20.3 J cm^{-2})	Flores-Cervante, Palou, and López-Malo (2013)
Green juice blend (kale, romaine, celery, and apple)	Dean vortex system 6 UV-C lamps (320 W) 27s 980–1000 L h^{-1}	Aciduric bacteria Aerobic count LAB Coliforms Yeasts-molds	3.7 log aciduric bacteria 3.9 log aerobic count >3 log LAB >2 log coliforms 2.1 log yeasts 2.1 log molds (2.93 J mL^{-1})	Biancaniello et al. (2018)
Beer	Thin film flow UV apparatus 3 UV lamp (250 W) 178 mW/cm^2 2.5 mm thickness 5 L h^{-1}	E. coli, L. brevis, S. cerevisiae	>5 log E.coli >4 log L. brevis >2 log S. cerevisiae (9700 J cm^{-2})	Lu et al. (2010)
White wine (Chardonnay) Red wine (Pinotage)	Turbulent SurePure™ pilot-scale UV-C system 1 UV lamp (30 W) 4000 L h^{-1}	Yeasts LAB Acetic acid bacteria	4.97 log in white wine 4.89 log in red wine (3.672 J mL^{-1})	Fredericks et al. (2011)
Cow Milk	Dean vortex UV apparatus UV-C lamps (80 W) 28.8 L h^{-1} 1.5 mm thickness	L. monocytogenes M. tuberculosis E. coli S. aureus S. Typhimurium Shigella flexneri Pseudomonas aeruginosa L. lactis	3.9 log L. monocytogenes 3.7 log M. tuberculosis 4.3 log E. coli 4.5 log S. aureus 3.8 log S. Typhimurium 5.1 log S. flexneri 4.5 log P. aeruginosa 3.0 log L. lactis (0.021 J cm^{-2})	Lu et al. (2011)
Rooibos İce tea	Turbulent SurePure™ pilot-scale UV-C system 4 UV lamp (30 W) 4000 L h^{-1}	E. coli K12, S. aureus, Salmonella, S. cerevisiae Cladosporium spores	4.37 log E. coli K12, 4.31 log S. aureus, 4.57 log Salmonella, 5.19 log S. cerevisiae 3.58 log Cladosporium sp. (3.672 J mL^{-1})	Monyethabeng and Krügel (2016)

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Table 1   Processing of liquid foods with continuous flow and batch UV systems—cont'd

Liquid food	UV processing conditions	Target microorganism	Log reduction/UV dosage	Reference
White grape juice Apple juice (commercial)	Collimated Beam Apparatus 2 UV lamp (15 W) 15 min 0.15 cm depth	*Alicyclobacillus acidoterrestris* spores	5.5 log in white grape juice (0.489 J cm^{-2}) 2.1 log in apple juice (0.539 J cm^{-2})	Baysal et al. (2013)
Orange juice (fresh)	Bench top UV chamber 4 UV-C lamps (30 W) 15 cm distance 0.7 mm thickness	*E. coli* O157: H7	5 log (juice containing 1.0–2.69 log yeasts) (1.48 J cm^{-2} at 20 °C)	Oteiza et al. (2010)
Starfruit juice	Bench top UV system 1 UV lamp 60 min 30 cm distance 10 mm depth	Natural microflora (Aerobic plate count Yeasts-molds)	1.3 log aerobic plate count 1 log yeasts-molds (0.002 J cm^{-2})	Bhat et al. (2011)
Strawberry juice	Bench top UV system 1 UV lamp 60 min 30 cm distance 10 mm depth	Natural microflora (Aerobic plate count Yeasts-molds)	1.1 log aerobic plate count 2.1 log yeasts-molds (0.002 J cm^{-2})	Bhat and Stamminger (2015)
Tomato juice	Bench top UV system 1 UV lamp 60 min 30 cm distance 10 mm depth	Natural microflora (Aerobic plate count Yeasts-molds)	0.34 log aerobic plate count 0.21 log yeasts-molds (0.002 J cm^{-2})	Bhat (2016)
Freshly squeezed mango juice	Batch UV system 1 UV lamp (30 W) 60 min 35 cm distance 0.5 cm depth	Aerobic plate count Yeasts-molds Coliforms	1.2 log aerobic count 0.8 log yeasts-molds 1 log coliform (Completely inactivated) (0.0036 J cm^{-2})	Santhirasegaram et al. (2015)
Apple juice	Bench top UV system 4 UV lamps (15 W) 30 cm distance 4 mm thickness 13.44 W m^{-2}, 8 min	*A.acidoterrestris* spores	5 log (13.44 W m^{-2})	Tremarin et al. (2017)
Pre-Pasteurized white grape juice (PGJ) & Freshly squeezed white grape juice (FSGJ)	Collimated Beam Apparatus 2 UV lamp (15 W) 0–24 min 0.15 cm depth 0–282.24 mJ cm^{-2}	*S. cerevisiae* Spoilage yeasts LAB	5.47 log *S. cerevisiae* (PGJ) (136.08 mJ cm^{-2}, 9 min) 3.0 log yeasts (FSGJ) 4.32 log LAB (FSGJ) (0.282 J cm^{-2}, 24 min)	Kaya and Unluturk (2016)
Onion juice	Bench Top UV irradiation device 2 UV-C lamps (20 W) 0.5 mm depth 30 min 7.5 mW cm^{-2}	Total aerophilic mesophilic count	1.65 log (7500 W cm^{-2}, 30 min)	Demir and Oral (2018)
Liquid egg white	Collimated Beam Apparatus 2 UV lamp (15 W) 0.153 cm thickness 0–20 min 1.314 mW cm^{-2}	*E. coli* K-12 *E. coli* O157:H7 *L. innocua*	0.896 log *E.coli* K12 1.403 log *E. coli* O157:H7 0.960 log *L. innocua* (20 min, 0.026 J cm^{-2})	Unluturk et al. (2010)

Microbial Quality of Solid Food Surfaces Treated With UV Light

UV light has been widely used for the surface decontamination of fresh cut and whole fruits, vegetables, and meat products (Table 2). Significant decontamination levels have been recorded in the target microorganisms present on solid food surfaces after UV treatment. It was found that the number and power of the UV lamps, type of microorganisms, exposure time, sample distance from the lamps and as well as the level of UV dose applied to the food surfaces are very important to achieve the desired level of

Table 2   Surface decontamination of solid foods by UV light

Food	UV processing conditions	Target microorganism	Log reduction/UV dosage	Reference
Fresh cut Broccoli	Bench top UV system 15 UV-C lamps (36 W) 17.5 cm distance	*E. coli* *S. enterica serovar Enteritidis* *L.monocytogenes*	1.2 log *E.coli* 3.29 log *Salmonella* 1.14 log *L.monocytogenes* (1.5 J cm^{-2})	Martínez-Hernández et al. (2015)
Lettuce Strawberry	UV cabinet 4 UV-C lamps 8 cm distance 60 min	cocktail of: *E. coli*, *L. innocua*, *S. Enteritidis* *S. aureus*	1.75 log *E. coli* 1.27 log *L. innocua* 1.39 log *S. Enteritidis* 1.21 log *S. aureus* (In lettuce, 7.2 J cm^{-2}) 1–1.4 log *Cocktail microorganisms* (In strawberry, 7.2 J cm^{-2})	Birmpa et al. (2013)
Blueberries	Portable UV-C device 1 UV-C lamp (95 W) 120 s	hepatitis A virus (HAV) murine norovirus (MNV)	>1 log MNV >1 log HAV (1.331 J cm^{-2})	Butot et al. (2018)
Apricot	UV treatment chamber 2 UV-C lamps (55 W) 12.5 cm distance 10 s 7.4 mW cm^{-2} intensity	*Salmonella* *E. coli* O157:H7	1.2 log *E.coli* 1.5 log *Salmonella* (0.074 J cm^{-2},10s)	Yun et al. (2013)
Pear	UV-C EmitterTM table-top System 2 UV-C lamps 10 cm distance 90s	*Penicillium expansum conidia*	2.8 log 0.17 J cm^{-2}	Syamaladevi et al. (2014)
Apple	UV-C light apparatus 2 UV-C lamps (15 W) 20 W·m^{-2} (each side) 20 min	Total viable counts	>1.5 log 2.4 J cm^{-2}	Manzocco et al. (2011)
Watermelon	The UV-C equipment 2 UV lamps (36 W) 15 cm distance 1.6, 0.72 J cm^{-2}	Background flora: Mesophilic Psycrophilic *Enterobacteria*	2 log (0.72 J cm^{-2})	Artés-Hernández et al. (2010)
Chicken breast	Collimated beam UV reactor 3 UV-C lamps (10, 15, 30 W) 40 min	*L. monocytogenes*	1.58 log (2.4 J cm^{-2})	Yang et al. (2017)
Mushroom cup	UV-C irradiator 4 UV-C lamps 0–0.315 J cm^{-2} (0–105 s)	*E. coli* O157:H7 Total aerobic count (TAC)	0.96 log *E.coli* (0.32 J cm^{-2}) 0.9–0.6 log TAC (0.09 J cm^{-2})	Guan et al. (2012)
Apricot	Bench-top UV system with a rotating roller bearing 4 UV-C lamps (15 W) 10.8 cm distance 0–25 min 0–48.45 kJ m^{-2}	total aerobic plate (TAC), yeasts-moulds total coliform	3 log TAC 2.25 log yeasts-molds (31.01 kJ m^{-2},16 min) complete inactivation of coliforms (0.775 J cm^{-2}, 4 min)	Hakguder Taze and Unluturk (2018)
Iceberg lettuce	The UV radiation apparatus 10 UV-C lamps 6.8 mW cm^{-2} 1min at 4 °C and 25 °C	*E. coli* O157:H7 *S. Typhimurium* *L. monocytogenes*	at 4 °C, 0.31 log *E.coli* 0.57 log *S. typhimurium* 1.16 log *L. monocytogenes* at 25 °C, 1.45 log *E.coli* 1.35 log *S. typhimurium* 2.12 log *L. monocytogenes* (0.408 J cm^{-2})	Kim et al. (2013)

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Table 2   Surface decontamination of solid foods by UV light—cont'd

Food	UV processing conditions	Target microorganism	Log reduction/UV dosage	Reference
Green tomato	The UV radiation apparatus 2 UV lamps 53.3 cm distance 743.6 mW cm^{-2} 240s	*S. enterica* serovars	4.39 log (0.178 J cm^{-2})	Lim and Harrison (2016)

decontamination (Guerrero-Beltrán and Barbosa-Cánovas, 2004). For example, more than 3 log reductions of *Salmonella* spp. were achieved in fresh cut broccoli and green tomato after exposure to 0.0015 J cm^{-2} and 0.178 J cm^{-2} UV dose, respectively (Lim and Harrison, 2016; Martinez-Hernandez et al., 2015). On the other hand, less than 3 log reductions were recorded in apricot (3.1 J cm^{-2}), watermelon (0.72 J cm^{-2}), apple (2.4 J cm^{-2}) and pear (0.17 J cm^{-2}) samples after UV treatment at different UV dose levels (Hakguder and Unluturk, 2018; Syamaladevi et al., 2014; Manzocco et al., 2011; Artés-Hernández et al., 2010). Furthermore, higher than 1 log inactivation of hepatitis A virus (HAV) murine norovirus (MNV) was reported in UV treated blueberries (1331 mJ cm^{-2}) (Butot et al., 2018).

Microbial Quality of UV-Processed Foods During Storage

In recent years, consumer demands have been increased to more fresh-like and healthy foods with a high sensorial and nutritious quality. However, fresh foods are more vulnerable to spoilage as a result of the growth of bacteria, yeasts and moulds.

Recent studies showed that UV light processing successfully inactivates spoilage microorganisms in foods and extended their microbial shelf life compared to untreated samples. Additionally, some of these studies showed that UV processing results in a higher quality characteristics compared to untreated and thermally processed foods during storage period. The most recent studies on the microbial changes occurred during storage of several liquid and solid foods after exposure to UV light are summarized in Table 3. These studies showed that the microbial growth in untreated food samples was faster than that of UV-C treated ones during storage at cold and room temperatures. For example, no microbial growth was detected in UV-C treated lemon-melon juice blend (2.46 J mL^{-1}) after 31 days, whereas untreated blend was spoiled within 2 days at refrigerator temperatures (Kaya et al., 2015). Similarly, untreated orange juice was spoiled in 2–3 days at cold storage conditions, while the microbial growth in UV treated juice was reached to the limits after 9 days at 4 °C and 5 days at 10 °C (Pala and Toklucu, 2013b). The shelf life of UV treated pineapple, watermelon and mango juices was extended from 1–2 to 8–9 weeks, from 14 days to 31 days and from 1 to 5 weeks at 4–5 °C, respectively (Santhirasegaram et al., 2015; Feng et al., 2013; Chia et al., 2012). Besides, it was detected that the shelf life of tiger nuts milk was increased to 4 days at 2 °C storage conditions (Corrales et al., 2012). There are more studies reporting that UV processing technology successfully prolongs the microbial shelf life of fruit and vegetable juices (Riganakos et al., 2017; La Cava and Sgroppo, 2015; Müller et al., 2014; Torkamani and Niakousari, 2011).

Similar findings were reported for the shelf life of UV processed solid foods (Table 3). For example, significantly lower counts of *E. coli* and *Salmonella* were observed in apricots exposed to UV treatment at 0.442 J cm^{-2} and stored at 2 °C and 20 °C for 21 days and 8 days (Yun et al., 2013). Similarly, Manzocco et al. (2011), Gómez et al. (2010) and Artés-Hernández et al. (2010) reported lower level of spoilage bacteria and yeasts and moulds count in apples (1.12 J cm^{-2}) and watermelon (0.72 J cm^{-2}) compared to untreated samples at the end of storage period. Similarly, UV processing has been shown to delay the microbial growth in garlic (0.2 J cm^{-2}) stored at 25 °C and at 0 °C for 15 days and 45 days, respectively (Park and Kim, 2015). Additionally, the number of *Listeria monocytogenes* in chicken breasts (2.4 J cm^{-2}) were lower compared to that of untreated samples stored at 5 °C for 72 days (Yang et al., 2017). On the other hand, Martinez-Hernandez et al. (2015) did not observe any difference in microbial quality of untreated and UV treated fresh cut broccoli samples (1.5 J cm^{-2}) stored at 5, 10 and 15 °C for 13 days. Likewise, no change has been reported for microbial shelf life of untreated and UV treated mushrooms (0.18 J cm^{-2}) stored at 4 °C for 21 days (Guan et al., 2012).

Effect of UV Processing on Organoleptic Properties of Foods

Sensory analysis is important in the field of food processing as it helps to develop new products or to optimize the processing conditions. Sensory characteristics of the foods reflect the consumers' preferences (Palczak et al., 2019). Consumers' demand for a specific food product relies on the quality (Abasi et al., 2018). Therefore, it is essential to preserve quality characteristics of foods after being processed.

Table 3   The effect of UV processing on the microbial shelf life of liquid and solid foods

Product	UV processing conditions	Storage conditions	Main findings	Reference
Apple juice Grape juice	Coiled tube UV reactor 1 UV-C (36 W) 1 UV-B (18 W) lamps UV-C:100.5 J mL^{-1} UV-B:71.5 J mL^{-1}	18 days/4 °C	• In apple juice, total aerobic count reached to 7 log after 15 days in control, 18 days in UV treated one • In grape juice, yeasts-molds reached to 7 log after 18 days in control, 5.27 log after 18 days in UV treated one • No effect of UV-B detected on the microbial count of juices	Müller et al. (2014)
Lemon-Melon juice blend	Annular flow UV reactor 4 UV-C lamps (15 W) 2.46 J mL^{-1}	30 days/4 °C	• Shelf life of the juice increased from 2 to 30 days by UV treatment • No microbial growth observed in UV-treated juice after 30 days	Kaya et al. (2015)
Orange juice	Coiled UV reactor system 9 UV-C lamps (28 W) 48.12 J mL^{-1}	84 days/4 °C 61 days/10 °C	• The rate of microbial growth in control was higher than that of UV-C treated juice at both temperatures • UV-treated juice reached to spoilage limits of yeasts-molds after 9 days at 4 °C and 5 days at 10 °C • Control was spoiled after 2–3 days at both temperatures	Pala and Toklucu (2013b)
Pineapple juice	Thin film UV reactor 8 UV-C lamps 0.053 J cm^{-2}	13 weeks/4 °C	• Shelf life of UV-treated juice was extended from 1–2 weeks to 8–9 weeks (6 log by total aerobic count and yeasts-molds)	Chia et al. (2012)
Water melon juice	Coiled tube UV reactor 1 UV-C lamp (75 W) 37.5 J mL^{-1}	37 days/5 °C	• Control juice reached to the limit (6 log) by spoilage bacteria and yeasts-molds after 14 days • Shelf life of UV-treated juice was 31 days	Feng et al. (2013)
Mango juice	Batch UV system 1 UV lamp (30 W) 3.525*10^{-4} J cm^{-2}	5 weeks/4 °C	• Control juice was spoiled lower than 1 weeks by yeasts and molds (3 log limit) • UV-treated juice shelf life was spoiled at the end of the 5 weeks • Shelf life of mango juice was increased for at least 4 weeks at cold storage	Santhirasegaram et al. (2015)
Carrot juice	The coiled tube UV reactor 1 UV-C lamp (30 W) 5.76 J mL^{-1}	16 days/4 °C	• Shelf life of the juice was extended from 4 days to 12 days by UV treatment (total aerobic bacteria reached up to 7 log)	Riganakos et al. (2017)
Grapefruit juice	UV chamber 3 UV-C lamps (36 W) 3.94 J cm^{-2}	30 days/4 °C 16 days/10 °C	• Shelf life of UV treated juice was extended in the range of 10–15 days at both storage temperature	La Cava and Sgroppo (2015)
Orange juice	Thin film UV reactor UV-C lamp (30 W) 0.125 J cm^{-2}	14 days	• Shelf life of orange juice was prolonged from 2 to 7 days (up to 5 log total aerobic count and yeasts-molds)	Torkamani and Niakousari (2011)

(Continued)

Table 3   The effect of UV processing on the microbial shelf life of liquid and solid foods—cont'd

Product	UV processing conditions	Storage conditions	Main findings	Reference
Onion juice	Coiled tube UV reactor 4 UV-C lamps (20 W) 38.1 J mL^{-1}	6 weeks/22 °C	• Lower TAMC and TYMC in UV-treated samples than those of untreated samples • UV treated juice: 2.72 and 3.85 log total aerobic bacteria and yeasts-molds, respectively • Control: spoiled (5 log counts) in total aerobic bacteria and yeasts-molds	Demir and Oral (2018)
Tiger nuts milk	Batch UV device 1 UV-C lamp (9 W) 4.23 J cm^{-2}	11 days/2 °C	• Shelf life of UV treated milk was extended from 3 days to 7 days (pH below 6.3)	Corrales et al. (2012)
Apricot	2 UV-C lamps (55 W) 0.442 J cm^{-2}	21 days/2 °C 8 days/20 °C	2 °C/21 days; • 3.5 log lower *E. coli* in UV treated fruit than in control • >4 log lower *Salmonella* in UV-treated fruit than in control 20 °C/8 days; • 3.3 log lower *E. coli* in UV-treated fruit than in control • 2 log lower *Salmonella* in UV-treated fruit than in control	Yun et al. (2013)
Apple	2 UV-C lamps (15 W) 0.12 J cm^{-2}	10 days/6 °C	• 2 log lower total counts in UV treated fruit than in control after 8 days • 1 log lower yeasts in UV-treated fruit than in control	Manzocco et al. (2011)
Watermelon	2 UV-C (36 W) 0.72 J cm^{-2}	11 days/5 °C/80% RH	• UV-treated ones significantly lower microbial counts comparing to control • 4–5 log bacteria in control • 3 log bacteria in UV-treated one	Artés-Hernández et al. (2010)
Fresh cut Broccoli	15 UV-C lamps (36 W) 1.5 J cm^{-2}	13 days/5, 10 and 15 °C	• No differences in the microbial counts between control and UV-treated samples at all temperatures	Martínez-Hernández et al. (2015)
Chicken breast	3 UV-C lamps (10, 15, 30 W) 2.4 J cm^{-2}	72 days/5 °C	• *L. monocytogenes* counts 3.7 log in UV-treated samples • 4.5 log in control	Yang et al. (2017)
Apple	2 UV lamps (15 W) 1.12 J cm^{-2}	7 days/5 °C	• Lower bacteria count natural microflora in UV-treated sample than in control • total bacteria: 1.85 log in UV-treated sample, 3 log in control • yeasts-molds: 4.62 log in UV-treated sample, 2.61 log in control	Gómez et al. (2010)
Mushroom	4 UV-C lamps 0.09 J cm^{-2}/each side	21 days/4 °C	• No difference between control and UV treated samples • up to 8.1–8.3 log in UV treated one, 8.6 log CFU/g in control	Guan et al. (2012)
Garlic	1 UV-C lamp (15 W) 0.2 J cm^{-2}	15 days/25 °C 45 days/0 °C	• Significant difference between UV-treated sample and control • 2 kJ·m^{-2} is an ideal UV dosage to retard microbial growth of garlic • 5.21 and 4.59 log in control and UV-treated garlic at cold storage • 6.78 and 6.10 log in control and UV-treated garlic at 25 °C	Park and Kim (2015)

UV light processing is a physical method which avoids the detrimental effects of heat. Thereby, it has a positive impact on consumers. Taste, smell, texture, appearance is evaluated in order to determine the sensorial quality of food products irradiated by UV light (Koutchma, 2009a, 2009b).

In literature, there are many studies about the effect of UV irradiation on sensorial quality of different food products such as lettuce, mushroom, many fruits, seafood, fruit juice, tomato, cheese, milk, poultry etc (Ferrario et al., 2018; McLeod et al., 2017; Hernández-Carranza et al., 2016; Lee et al., 2015; Cilliers et al., 2014; Tiecher et al., 2013; Jiang et al., 2010; Allende et al., 2006; González-Aguilar et al., 2001). Influence of UV-A, UV-B and UV-C light on the quality characteristics of various products were investigated by different researchers. For instance, Sun et al. (2014) examined the effect of UV-B light (280–315 nm) on the firmness of 'Mantianhong' pears. Light treatment was found to have insignificant effect on the softening of the fruit. In another study, it was reported that firmness of tomato fruit treated at different doses of UV-B light (2 and 4 J cm^{-2}) could be better preserved during 14–37 days of storage (Liu et al., 2011a). This was explained by the phenomenon that UV irradiation could reduce the activity of cell wall degrading enzymes. However, higher dose of UV-B irradiation (8 J cm^{-2}) was indicated to be deleterious on the sensorial quality of the fruit. Castagna et al. (2013) also studied the effect of UV-B irradiation on firmness of tomato samples. Nevertheless, firmness of the fruit was reported to be lower after UV-B light processing. This was attributed to the stimulation of enzymes by UV-B irradiation in favour of fruit softening. Mariz-Ponte et al. (2019) treated tomatoes by both UV-A and UV-B light at the pre-harvest stage. Consumer acceptance of treated tomatoes was investigated by conducting a sensory panel. Results showed that consumers preferred control samples with respect to its appearance and surface characteristics. However, UV-A light treated tomatoes were highly appreciated due to their taste and aroma (Mariz-Ponte et al., 2019).

There are also other studies on the processing of tomatoes by UV-C light. Liu et al. (2009) reported that UV-C light treatment (1.37 J cm^{-2}) caused a substantial decrease in firmness of tomatoes after 21 days of storage in comparison to untreated ones. On the contrary, pre-harvest application of UV-C irradiation at a dose of 0.8 J cm^{-2} was found to slow down the softening of tomatoes and yielded higher firmness values considering the control samples and those exposed to lower UV-C dose (0.3 J cm^{-2}) after 12 days (Obande et al., 2011). These findings were in agreement with the results of the study conducted by Mansourbahmani et al. (2017). It was also demonstrated that UV-C treatment did not affect firmness and colour of tomato samples which means sensorial quality of the fruit was preserved during storage (Mukhopadhyay et al., 2014). This might be due to the inhibition of ethylene synthesis, which results in rapid ripening and subsequent quality loss, by UV-C light treatment (Bal and Kok, 2009). Tiecher et al. (2013) suggested a delay in ripening of tomato represented by a greener colour of the fruit after UV-C irradiation. However, UV-C treatment was revealed to be insufficient to preserve fruit firmness by itself (Tiecher et al., 2013).

Bal and Kok (2009) studied the effect of UV-C treatment on some quality parameters of kiwi fruit. They performed a sensory panel in order to evaluate any changes in the taste of kiwi fruit samples treated at different light intensities for different time intervals. Results showed that an increment in the taste scores were obtained as the fruit matured. Fruit maturation brings about an increase in total soluble solid (TSS) content and a decrease in the acidity level. UV-C irradiation was indicated to retard maturation of kiwifruit leading to lower TSS value and consequently lower taste scores (Bal and Kok, 2009). Sensory characteristics of tomato and strawberry were investigated by consumer preference test after the products were treated by UV-C light at two different light intensities (0.0003 J cm^{-2} s^{-1} and 0.0033 J cm^{-2} s^{-1}) (Cote et al., 2013). According to the results, fruits treated at high intensity values were highly preferred by the consumers due to delayed softening and reduced darkening of fruit surfaces.

UV light is commonly administered as a decontamination method in many different industries to disinfect such products as dairy products, seafood and poultry. In a study conducted by Lacivita et al. (2016), Fiordilatte cheese samples were treated by UV-C light at 0.002 J cm^{-2} s^{-1} for different exposure times ranging from 5 to 750 s. Sensory evaluation pointed out that samples treated by the highest UV dose value (1.5 J cm^{-2}) resulted in the lowest scores with respect to overall acceptance. They reported that it was due to the formation of off-odour arisen from the reaction of UV light with proteins. These photo-activated proteins may cause oxidation and modification of the protein structure which leads to non-enzymatic browning and disulphide/thiol exchange reactions. Consequently, some evaporative compounds can be formed (Lacivita et al., 2016). Cilliers et al. (2014) examined the effect of UV light application on sensorial properties of milk used for Cheddar cheese making. According to the results, UV treated milk samples had a creamy flavour and aroma which was attributed to the oxidation of sulphur containing amino acids after the light exposure. On the other hand, UV-C treatment resulted in negligible changes in sensorial quality of chicken breasts when it was used at lower doses (0.1, 0.3, 0.6 and 3 J cm^{-2}) (McLeod et al., 2017). Likewise, sensory panel results indicated no observable alterations in the organoleptic characteristics of smoked salmon after UV-C treatments at 0.0075 J cm^{-2} and 0.05 J cm^{-2} (Holck et al., 2018). On the other hand, Yang et al. (2017) found that higher UV-C doses (more than 1.8 J cm^{-2}) generated undesirable changes in overall acceptability of raw chicken breast samples.

In conclusion, UV light treatment can preserve sensorial characteristics of foods in addition to its beneficial effects on microbial quality and shelf life. However, treatment conditions (light intensity and exposure time) play a significant role in organoleptic properties of the treated products. Foods with high lipid contents, such as dairy products, poultry and seafood, are susceptible to oxidative changes caused by UV light irradiation. Therefore, selection of the processing conditions requires attention in accordance with the product to be irradiated.

Table 4   Physicochemical quality of liquid and solid foods subjected to UV treatment

Product	UV processing conditions	Quality parameter	Main findings	Reference
Apple & cranberry juice blend	Continuous flow 1 UV-C lamp (30 W) 5.3 J cm^{-2}	pH TSS Color	• No change in pH, TSS and color • No difference in color of UV-treated and thermal pasteurized samples	Caminiti et al. (2011)
Green juice blend (kale, romaine, celery, and apple)	Continuous flow 6 UV-C lamps (320 W) 2.93 J mL^{-1}	pH TSS TA Absorption coefficient Viscosity Color	• No change in pH, TSS, acidity, viscosity and absorption coefficient • Important decrease in b* value • Noticeable color change in comparing to control	Biancaniello et al. (2018)
Lemon-melon juice blend	Continuous flow 4 UV-C lamps (15 W) 2.461 J mL^{-1}	TSS pH TA Color Turbidity Absorption coefficient	• No change in pH and acidity • TSS slightly decreased • Turbidity increased, absorption coef. decreased • No change in a* and L*, lower b* value • Slightly noticeable color change	Kaya et al. (2015)
Coconut milk	Continuous flow 1 UV-C lamp (17 W) 0.07–0.10 J cm^{-2}	pH TSS TA Color	• No change in TSS, pH, and TA • 0.342 and 0.684 kJ·m^{-2} did not significantly affect color • Noticeable color change and darkening after 1.026 kJ m^{-2} (less L*, higher a* and b*)	Ochoa-Velasco et al. (2014)
Pomegranate juice	Continuous flow 9 UV-C lamps (28 W) 62.4 J mL^{-1}	pH TSS TA	• No significant changes in pH, TSS and TA	Pala and Toklucu (2011)
Orange juice	Continuous flow 9 UV-C lamps (28 W) 48.12 J mL^{-1}	pH TSS TA	• No significant changes in pH, TSS and TA	Pala and Toklucu (2013a, 2013b)
Apple juice	Continuous flow 1 UV-C lamp (30 W) 2.66–53.10 J cm^{-2}	pH TSS Color	• No significant changes in pH, TSS • Color lightning effect was observed by increasing UV dosage • Slightly noticeable color change up to 26.55 J cm^{-2} • a* value significantly decreased	Caminiti et al. (2012a)
Milk	Batch 1 UV-C (20 W) 1 MPM (UV-C & UV-B) (2660 W) lamps 0.01 J cm^{-2}	pH Viscosity TSS Color	• No change in pH, TSS and viscosity at both lamps • No noticeable color changes at both lamps • More undesirable changes in MPM lamps than LMP lamps	Orlowska et al. (2013)
Pineapple-mango juice blend	Continuous flow 6 UV-C lamps	pH, TA TSS Turbidity Colour	• Minimally change in physicochemical properties of juice blends	Kamarul Zaman et al. (2017)
Tamarind juice	Continuous flow 5 UV-C lamps 0.036 J cm^{-2}	pH TA TSS Turbidity Colour	• No change in pH, acidity, turbidity and color • Reduction of TSS in UV-treated juice • Color and turbidity protected better in UV-treated juice than in thermal pasteurized one	Mohd-Hanif et al. (2016)
Lettuce Strawberry	Batch 4 UV-C lamps 0–7.2 J cm^{-2}	Color	• No change in appearance and texture up to 5.4 J cm^{-2} • Reduction of a*, b* and chroma after 5.4 J cm^{-2}	Birmpa et al. (2013)
Pear	Batch 2 UV-C lamps 0.31 J cm^{-2}	Weight loss TSS Texture Color	• No significant change in weight loss, TSS and texture • Slightly browning of color (less L* value)	Syamaladevi et al. (2014)

Table 4 Physicochemical quality of liquid and solid foods subjected to UV treatment—cont'd

Product	UV processing conditions	Quality parameter	Main findings	Reference
Apple	Batch 2 UV-C lamps (15 W) 2.4 J cm^{-2}	Weight loss Cell structure Color Firmness	• UV treatments resulted in apples much more stable than the untreated sample • Firmness not changes • Weight loss due to rupture of apple cells • Lighter, less red and yellow color of apple	Manzocco et al. (2011)
Chicken breasts	Batch UV-C lamps (10, 15, 30 W) 2.4 J cm^{-2}	pH Color	• Slight reddish and yellowish color of chicken • Insignificant change of color • No difference in pH	Yang et al. (2017)
Mushroom	Batch 4 UV-C lamps 0.09 J cm^{-2}/each side	Color	• Browning occur with less L*, higher a* and b* values	Guan et al. (2012)
Iceberg lettuce	Batch 10 UV-C lamps (6 W) 4.08 J cm^{-2}	Color Texture	• No difference in color up to 20.4 kJ m^{-2} • After this, discoloration and softening occur (L* decreased, b* increased)	Kim et al. (2013)

Effects of UV Processing on Physicochemical Properties of Foods

Changes in Physicochemical Properties of Foods After UV Light Treatment

Physicochemical properties of foods, i.e. pH, total soluble solid content (TSS), titratable acidity (TA), turbidity, absorption coefficient and color are commonly studied in order to assess the final quality of the liquid foods and beverages after UV light processing. These physicochemical quality parameters can be also monitored during storage to give an idea about the quality and shelf life of UV treated products (Kamarul Zaman et al., 2017; Bengtsson, 2009).

The pH and acidity content of foods are very important to select suitable processing conditions of foods (US FDA, 2008). Acidic foods with pH less than 4.5 can be safely processed at 100 °C (pasteurization treatment). Besides, the stability of bioactive compounds in foods is highly dependent on pH (Chia et al., 2012). Turbidity and absorbance is more related to the appearance of liquid foods. Color is an important parameter especially for evaluation of the visual quality of foods by consumer preference (Mohd-Hanif et al., 2016; Cinquanta et al., 2010). These physicochemical properties of foods have been extensively studied before and after UV processing (Table 4). The results of these studies showed that pH, TA and TSS (°Brix) of fruit juice and juice blends, milk, solid foods such as fresh cut fruits and meat did not change significantly immediately after UV treatment (Biancaniello et al., 2018; Yang et al., 2017; Mohd-Hanif et al., 2016; Ochoa-Velasco et al., 2014; Syamaladevi et al., 2014; Orlowska et al., 2013; Caminiti et al., 2011, 2012a; Ochoa-Velasco and Química, 2012; Pala and Toklucu, 2011, 2013a). On the other hand, some studies reported a decrease in TSS of the fruit juices due to photolysis of fructose caused by UV light (Mohd-Hanif et al., 2016; Kaya et al., 2015).

Turbidity and absorption coefficient are the essential optical parameters of liquid foods. The studies showed a slight increase in turbidity of UV treated liquid foods. Absorption coefficient determines how far incident light of a certain wavelength penetrates a material before being absorbed. It is a measure for the rate of decrease in the intensity of light, as it passes through a given substance. For example, UV light treatment did not affect the turbidity of tamarind juice (Mohd-Hanif et al., 2016). However, an increase in turbidity of UV treated lemon-melon juice was reported by Kaya et al. (2015). This was attributed to the suspended particles comprised from degradation of the pectin and formation of pectin complex with other compounds in the fruit juice such as proteins, phenolic matters etc (Yen and Lin, 1998). In contrast, a decrease in turbidity was reported resulted from inactivation of large microbial cells such as yeasts and moulds (Shamsudin et al., 2014). Although, in most of the studies, no significant change was observed in the absorption coefficient of fruit juices after UV process (Biancaniello et al., 2018; Müller et al., 2014), a decrease in absorption coefficient of lemon-melon juice blend was detected by Kaya et al. (2015). It was correlated with the breakdown of ascorbic acid by UV light (Koutchma, 2008).

Color is an important parameter of UV processed foods and one of the first characteristics to be evaluated by the consumers, closely associated with the food quality. It is highly influenced by the level of UV dose used for foods. Most of the studies cited in the literature reported no significant color change after UV treatment in fruit juices (Kamarul Zaman et al., 2017; Mohd-Hanif

Table 5   Changes in the physicochemical properties of UV treated liquid and solid foods during shelf life period

Product	UV processing conditions	Storage conditions	Quality parameter	Main findings	Reference
Grapefruit juice	Batch 3 UV-C lamps (36W) 3.94 J cm^{-2}	30 days/4 °C 16 days/10 °C	pH TA TSS	• No change in pH, TSS and TA of UV treated juice at both temperatures • Slightly noticeable change in color of UV treated juice • Increase of L* value • No browning occurred	La Cava and Sgroppo (2015)
Pineapple juice	Continuous flow 8 UV-C lamps 53.42 mJ cm^{-2}	13 weeks/4 °C	pH TSS Turbidity	• pH, acidity and TSS better protected in UV treated juice • UV treatment was more efficient in maintaining of lightness of juice • Juice became redder, less yellow, less saturated • UV-treated juice and control had lower turbidity than thermal treated one	Chia et al. (2012)
Apple juice Grape juice	Continuous flow 1 UV-C (36W) 1 UV-B (18W) lamps UV-C: 100.5 kJ L^{-1} UV-B: 71.5 kJ L^{-1}	18 days/4 °C	Color	In apple juice: • No color change in UV treated juice • Browning occurred in control juice • In grape juice: • Increase a* and b* values in control and UV-treated juice	Müller et al. (2014)
Onion juice	Continuous flow 4 UV-C lamps (20W) 38.1 J mL^{-1}	6 weeks/22 °C	pH TA TSS Turbidity Color	• Lower pH and higher turbidity both UV-treated and control samples • Less TSS obtained in UV-treated juice than in control • Relatively higher b* value in UV-treated juice resulted in more noticeable total color change than control	Demir and Oral (2018)
Lemon-melon juice blend	Continuous flow 4 UV-C lamps (15W) 2.461 J mL^{-1}	30 days/4 °C	TSS pH TA color turbidity Absorbance	• No change in pH and TA, turbidity increased • No change absorption coefficient after 16 days • Higher L* and b*, lower a* value • No noticeable total color difference • Different physicochemical properties of control and UV-treated sample	Kaya et al. (2015)
White grape juice	Continuous flow 7 UV-C lamps (15W) 9.92 J cm^{-2}	14 days/4 °C	TSS pH TA color Turbidity Absorbance	• No change in pH, TSS and TA of UV treated juice • Increase in turbidity less in UV treated juice than control • Non-enzymatic browning increased absorption coef. of UV treated one • Total color change much higher in control than UV treated one • Noticeable color change in UV treated one	Unluturk and Atilgan (2015)
Watermelon	Batch 30 UV-C lamps (36W) 7.2 kJ m^{-2}	11 days/5 °C	Color	• Slight chroma decrease, increase hue angle of control and UV-treated watermelon (UV-treated less change) • No change in lightness in UV treated one	Artés-Hernández et al. (2010)
Mushroom	Batch 4 UV-C lamps 0.90 kJ m^{-2}/each side	21 days/4 °C	Color	• Less color changes for the UV-C treated samples compared to the control	Guan et al. (2012)

Table 5   Changes in the physicochemical properties of UV treated liquid and solid foods during shelf life period—cont'd

Product	UV processing conditions	Storage conditions	Quality parameter	Main findings	Reference
Iceberg lettuce	Batch 10 UV-C lamps (6W) 20.4 kJ m^{-2}	7 days/4 °C	Color Texture	• Change in color and at both control and UV treated samples during 7 days • Less L*, higher a* and b* obtained • No significant different between control and UV treated sample at the end of the storage	Kim et al. (2013)
Apple	Batch UV-C lamps (15W) 5.6 kJ m^{-2}	7 days/5 °C	Color	• L* value decreased, darker surface occur in UV treated samples • a* value significantly increased • No change in b* value in UV treated one, higher b* value in control	Gómez et al. (2010)
Pear	Batch 2 UV-C lamps 3.1 kJ m^{-2}	8 weeks/4 °C	Weight loss TSS Texture Color	• No difference between weight of control and UV treated samples • Higher TSS in UV treated one, lower TSS in control • Increase of yellow color (b*) were less in UV-treated pears comparing to control • L*, a*, b* increase in control (ripening) • Browning occurred (less L*) in UV treated pears	Syamaladevi et al. (2014)

et al., 2016; Kaya et al., 2015; Caminiti et al., 2011), milk (Orlowska et al., 2013), lettuce (Kim et al., 2013) and chicken (Yang et al., 2017). However, UV light application has resulted in a noticeable color change in green juice blend (Biancaniello et al., 2018), coconut milk (Ochoa-Velasco et al., 2014), apple juice (Caminiti et al., 2012a), lettuce and strawberry (Birmpa et al., 2013), pear (Syamaladevi et al., 2014) and apple (Manzocco et al., 2011) (Table 4). The change of color in UV treated foods was attributed to the discoloration of the products by degradation of color pigments, or browning of foods by the formation of dark colored pigments from enzymatic and non-enzymatic browning (Maillard) reactions (Krokida et al., 2001). To overcome color degradation of foods, appropriate UV system with a minimal UV dose and time exposure should be designed in terms of food characteristics.

Changes in Physicochemical Properties of UV-Processed Foods During Shelf Storage

The impacts of UV treatment on foods during shelf storage were investigated in different studies (Table 5). The majority of the authors did not observe any significant change in the pH, acidity and TSS content of UV treated foods during storage (Kaya et al., 2015; La Cava and Sgroppo, 2015; Chia et al., 2012). On the other hand, the changes in the pH, acidity and TSS content of the foods observed in some studies have been associated with microbial spoilage (Demir and Oral, 2018; Mansor et al., 2017). Turbidity and UV absorbance of the liquid foods, critical factors for UV processing, are closely related to the growth of microorganisms during storage period and also associated with the color degradation and darkening of samples (Chia et al., 2012; Tandon et al., 2003; Kaya et al., 2015; Unluturk and Atilgan, 2015). For example, Unluturk and Atilgan (2015) observed an increase in the absorption coefficient of UV treated white grape juice during 14 days of refrigerated storage.

The color characteristics (lightness, redness, and yellowness) of foods, especially fruit juices, have been extensively investigated by many researchers (Table 5). They reported stable or unstable color changes during storage period. The stability of color was attributed to the metabolic reactions take place in food samples due to the effect of UV light. For example, Müller et al. (2014) indicated no color change in UV treated apple juice stored for 18 days at 4 °C. The majority of studies concluded that UV treatment retained the color attributes of the juices much more so than untreated ones during storage period (La Cava and Sgroppo, 2015; Unluturk and Atilgan, 2015; Syamaladevi et al., 2014; Chia et al., 2012; Guan et al., 2012; Artés-Hernández et al., 2010; Gómez et al., 2010). Additionally, Kim et al. (2013) did not observe significant difference in the color of untreated and UV treated iceberg lettuce stored at 4 °C for 7 days. On the other hand, Demir and Oral (2018) reported more

Table 6   Effect of UV irradiation on bioactive compounds of fresh produce after harvest

Product	UV processing conditions	Bioactive content	Main findings	Reference
Apple	UV-B irradiation (36 h, 21.9 J cm^{-2}) 3 UV-B lamps (20 W) Storage at 20 °C and 85% relative humidity)	Total phenolics Total flavonoids Antioxidant activity	• Significant reduction in total phenolics and flavonoids after 36 h UV-B irradiation. • However, the content of total phenolics and flavonoids as well as antioxidant activity increased during storage.	Assumpcao et al. (2018)
Tomato	UV-C irradiation (0.2–1.6 J cm^{-2}) storage at 14 °C and 95% relative humidity for 35 days	Total phenolics Total flavonoid Antioxidant activity	• UV-C irradiation at 0.4 and 0.8 J cm^{-2} increased total phenolic and flavonoid contents as well as the antioxidant activity.	Liu et al. (2012)
Tomato	UV-C irradiation (0.4 J cm^{-2}) Storage at 13 °C and 95% relative humidity for 35 days	Total phenolic content Phenolic acids Flavonoids	• UV-C irradiation increased TPC by 12.82% compared to control fruit. UV-C treated fruit had the highest total phenolics content (246.42 mg kg^{-1}).	Liu et al. (2018)
Fresh-cut carrot	single and combined effects of UV-B (0.15 J cm^{-2}) and UV-C (0.40 J cm^{-2}) at 15 °C	Phenolics	• Highest phenolic accumulation (498%) was observed after 72 h of UV-B treatment. • Single and combined UV-C treatments achieved a phenolic accumulation of 440%.	Formica-Oliveira et al. (2017)
Peach	UV-B irradiation (0–10–60 min at 2.31 W·m^{-2} UV intensity)	Alkylphenols Hydroxycoumarins Hydroxyphenilacetic acids Anthocyanins Dihydroflavonols Flavones	• 10 min of UV irradiation followed by 24 h recovery increased alkylphenols (1.40-fold), hydroxycoumarins (1.42-fold) and hydroxyphenilacetic acids (1.30-fold), and decreased anthocyanins (0.46-fold), dihydroflavonols (0.50-fold) and flavones (0.60-fold). • After 36 h, dihydroflavonols, anthocyanins and flavones showed major increase.	Santin et al. (2018)

noticeable color changes in UV treated onion juice compared to those of untreated one after 6 weeks storage at room temperature.

It is concluded that the color stability of foods can be ensured by the more efficient application of UV light to foods, inactivating enzymes that are responsible for browning reactions and using suitable storage conditions.

Effects of UV Processing on Bioactive Compounds of Foods

Consumption of food products with rich micronutrients (e.g., vitamins) and phytochemicals (e.g., phenolic compounds and carotenoids) is highly appreciated due to their health-promoting effects (Koutchma et al., 2016). Especially the consumption of fruits and vegetables has been linked to lower risks of neurodegeneration diseases, cardiovascular diseases, cancer as a result of their antioxidant, antiinflammatory, and antitumoral effects of bioactive constituents (Cassidy, 2018; Camara et al., 2013). The antioxidative phytochemicals are classified as carotenoids, phenolics, alkaloids, nitrogen-containing, and organosulfur compounds. The dietary phenolic compounds naturally present in plant foods are categorized into different subclasses such as flavonols, flavones, flavanones, flavan-3-ols, isoflavones, and anthocyanins depending on the structural differences (Nayak et al., 2015). Carotenoids (i.e. lycopene, β-caroten) are known as the antioxidative compounds that can reduce the oxidative damage to lipids, proteins, and deoxyribonucleic acid (DNA) with their anticarcinogenic and antiatherogenic effect (Camara et al., 2013). Vitamin C, on the other hand, has been commonly considered as an indicator of nutritional quality of processed fruits and vegetables (Dewanto et al., 2002).

Different products can be introduced into one's diet to support the daily intake of antioxidative compounds. However, these constituents may be exposed to some alterations during processing and storage of the food. It has been previously reported that thermal processing may cause some degradation and losses in nutritional, organoleptic, physicochemical and rheological properties of foods (Jimenez-Sanchez et al., 2017b; Rawson et al., 2011). Moreover, consumer expectations and preferences have shifted towards fresh like food products with natural flavour and taste (Rastogi et al., 2007). Therefore, it is of great interest to optimize the processing and storage conditions for the retention and preservation of bioactive compounds that have influence on human

health and product marketability. For this purpose, nonthermal food processing technologies have been considered as advanced alternative methods to satisfy the expectations of fresh-like product quality with respect to nutritive and health benefits of the food as Koutchma et al. (2016) stated.

Ultraviolet light irradiation is one of the promising nonthermal processing technologies. In this section, recent researches on the effect of UV-C irradiation on bioactive compounds have been discussed taking into account different types of food products such as fresh products, fruit and vegetable juices, milk and dairy products, meat and meat products, poultry and seafood.

Fresh Produce

Phenolic compounds are involved in plant defense mechanisms and play an important role in increasing the resistance of plants to biotic and abiotic stress factors. They contribute to the appealing color and taste of the fresh produce (Boudet, 2007). Biosynthesis of these compounds in plants varies depending on the developmental stage, genotype, and environmental factors (Assumpcao et al., 2018). Recent studies have focused on the biosynthesis of phenolic compounds by putting special emphasis on the regulation of gene expression by environmental factors (Boudet, 2007). Because the environmental stress factors can induce the gene expression for the key enzymes of primary (shikimate) and secondary (phenylpropanoid) pathways involved in the biosynthesis of polyphenolic compounds (Dixon and Paiva, 1995). Some of the enzymes acting in the biosynthesis of phenolic compounds are phenylalanine ammonia lyase (PAL), chalcone synthase (CHS), stilbene synthase (STS), anthocyanidin synthase (ANS), 4-coumarate:coenzyme A ligase (4CL), cinnamic acid 4-hydroxylase (C4H), chalcone isomerase (CHI), flavanone 3-hydroxylase (F3H) and flavonol synthase (FLS) (Pinto et al., 2016; Dixon and Paiva, 1995). Particularly, phenylalanine ammonia lyase (PAL) is an important enzyme induced by several factors such as wounding, water stress, chilling injury, low minerals, hormones, pathogen attack, and radiation exposure (Formica-Oliveira et al., 2017; Alegria et al., 2016; Avena-Bustillos et al., 2012; Becerra-Moreno et al., 2012; Jacobo-Velazquez et al., 2011).

UV irradiation can be used as a stress factor on fresh-cut or whole fruits and vegetables. It induces the enzymes that are responsible for the biosynthesis of secondary metabolites (Alegria et al., 2012; Cantos et al., 2000).

Recent studies focus on the use of UV irradiation as a pre-harvest or post-harvest treatment to stimulate the synthesis of bioactive compounds in the fresh produce (Table 6). The results showed that total phenolic content, total flavonoid, and the antioxidant activity of tomato have been promoted by UV-C irradiation at 0.4 or 0.8 J cm^{-2} and subsequent storage in the dark at 14 °C and 95% relative humidity for 35 days (Liu et al., 2012). UV-C irradiation, used as a post-harvest treatment, stimulated the accumulation of individual phenolic acids and flavonoids after 21 days of storage of tomato fruit. It was shown that chlorogenic acid has been claimed as the most abundant phenolic compound followed by p-coumaric acid, caffeic acid, protocatechuic acid and gallic acid after 21 days of storage. This finding has been attributed to the significantly increased PAL activity in tomato fruit exposed to UV-C irradiation (Liu et al., 2018). Additionally, the authors reported that the CHI activity in UV-C irradiated fruit increased rapidly and significantly compared to that of untreated fruit (p < 0.01) from the day 14 to 28 during storage. Furthermore, the molecular mechanism that is responsible from the accumulation of phenolic compounds in UV-C treated tomato fruits during storage has been associated with the enhancement of different types of enzymes (PAL, C4H, 4CL, CHS and CHI) by induction of gene expression involved in the phenylpropanoid pathway (Liu et al., 2018). These findings imply that UV-C irradiation increases the total phenolic content in fresh produce by stimulating the phenylpropanoid pathway. Similarly, the enhancement of secondary metabolites in conventional and organic grapes by post-harvest UV-C irradiation has been attributed to the stimulation of gene expression and accumulation of transcripts of PAL, CHS, STS and ANS genes (Pinto et al., 2016). Since the skin color of the fruit is an important parameter for the consumer perception and marketability, post-harvest light irradiation results in the accumulation of bioactive constituents in the fruit skin by inducing biosynthesis–related genes (Azuma et al., 2019).

It has been demonstrated that UV-B irradiation also stimulates the secondary metabolism of phytochemicals and thereby influences the nutraceutical value of the fruit (Castagna et al., 2013). This can be related to the stimulation of protection mechanisms or activation of repair mechanisms in plants by UV-B irradiation (Frohnmeyer and Staiger, 2003). The biosynthesis of phenolic compounds has been reported to be the consequence of PAL activation after application of abiotic stress (Jacobo-Velazquez et al., 2011).

In contrast, PAL activity of shredded carrots did not change significantly after UV-B and UV-C treatments on the processing day, but increased throughout storage (Formica-Oliveira et al., 2017). The authors divided the incremental stages of PAL activity and the accumulation of phenolics in stressed carrots into three phases during storage at 15 °C: (i) < 24h, early PAL activity increments; (ii) 24–48 h, moderate phenolic increments concurring with the highest increase of PAL activity, (iii) 48–72 h, high phenolic increments while a moderate increment of PAL activity. On the other hand, UV-C irradiation showed an inhibiting effect on PAL activity of shredded carrots which could arouse from the partial denaturation of PAL due to the higher photon energy compared to UV-B (Formica-Oliveira et al., 2016, 2017). In accordance with the PAL activity, it has been reported that UV-B treatment (1.5 kJ m^{-2}) achieved the highest phenolic accumulation with 498% after 72 h storage at 15 °C while UV-C treatment UV-C (4.0 kJ m^{-2}) showed an accumulation of 440% (Formica-Oliveira et al., 2017). On the contrary, another study compares the effect of UV-B and UV-C irradiation on the bioactive compounds of table grapes followed by subsequent storage at 4 °C for 28 days. In this case, the phenolic content, antioxidant activities as well as individual phenolics have been reported to be higher in UV-C irradiated grapes compared to untreated and UV-B irradiated grapes. This finding has been linked to the expression of several important genes involving in phenylpropanoid, flavonoid and stilbenoid pathways (i.e. PAL, CHS, F3H, ANS, STS) as a response mainly to UV-C irradiation (Sheng et al., 2018).

Table 7   Changes in the bioactive constituents of some fruit juices as effected by UV-C irradiation

Product	UV processing conditions	Bioactive content	Main findings	Reference
Grapefruit juice	UV-C irradiation (0–2.36 J cm^{-2}) Batch Lamp distance 17 cm (36 W) Temperature 25 °C Exposure time: up to 9 min Film thickness 5–7 mm	Total phenolics Individual flavonoids Antioxidant activity	• TPC and individual flavonoids showed no significant change, • AA decreased significantly as the UV-C dose increased.	La Cava and Sgroppo (2018)
Cranberry flavored water	UV-C irradiation (0.015–0.24 J cm^{-2}) Continuous flow	Individual anthocyanins, Ascorbic acid	• At 0.04 J cm^{-2}, ASC of UV-C treated juice was 82% of that in the untreated beverage. • At 0.06 J cm^{-2}, ASC decreased by 20%. • The concentrations of individual anthocyanins (Cy3Ar, Cy3Ga, Pe3Ar, Pe3Ga) were not significantly affected.	Gopisetty et al. (2018)
Tomato juice	UV-C irradiation (2.16 J m^{-2}) Batch Lamp distance 30 cm Room temperature Exposure time: up to 60 min	Total phenolics Total lycopene Antioxidant activity Ascorbic acid	• TPC increased significantly (27.8–36.2 mgGAE·g^{-1}). • TLC decreased non-significantly (31.2–28.3 g·g^{-1}). • AA increased significantly (50.3%–60.5%). • ASC reduced significantly (9.07–3.86 mg·100 mL^{-1}).	Bhat (2016)
Carrot juice	UV-C irradiation (13.2–79.2 J cm^{-2}) Continuous, 12 W UV-C lamps Flow rate 0.5–7.9 mL s^{-1} Exposure time 5–30 min	Total phenolics Antioxidant capacity	No significant change was observed for • TPC (4.1–8.6 mg GAE·100 mL^{-1}), • AA (6.1–9.4 mg Trolox·100 mL^{-1}).	Hernández-Carranza et al. (2016)
Apple juice	UV-C irradiation (0–0.24 J cm^{-2}) Collimated Beam	Total phenolics Antioxidant activity	• Significant changes in AA were observed after UV-C exposure of 0.04 J cm^{-2}. • No change in TPC of irradiated apple juice was found.	Islam et al. (2016)
Grapefruit juice	UV-C irradiation Batch 36 W UV-C lamps UV dose 0–3.94 J cm^{-2} Lamp distance 17 cm Temperature 25 °C Film thickness 5–7 mm Storage during 30 days at 4 °C and 16 days at 10 °C	Total phenolics Individual flavonoids Antioxidant activity Ascorbic acid	• ASC significantly decreased by 15%–30%. • AA significantly decreased by 10%–27%. • No significant changes in total phenolics and individual flavonoids were reported after UV-C treatment.	La Cava and Sgroppo (2015)
Mango juice	UV-C irradiation Batch 30 W UV-C lamps Lamp distance 35 cm Exposure time 15–60 min Temperature 25 °C Storage for 5 weeks at 4 °C	Polyphenols Flavonoids Carotenoids	Significant increases were reported when UV-C light applied for 15 and 30 min as below • polyphenols (31%), • flavonoids (3%), • carotenoids (6%). Besides, antioxidant activity was enhanced after UV-C treatment.	Santhirasegaram et al. (2015)
Strawberry juice	UV-C irradiation (2.158 J m^{-2}) Batch Lamp distance 30 cm Temperature 25 °C Exposure time 15–60 min	Total phenolics Total anthocyanins Ascorbic acid Antioxidant activity	UV-C irradiation significantly reduced • TPC after 15 min, • TAC after 15 min, • ASC after 30 min, • AA after 60 min of exposure.	Bhat and Stamminger (2015)
Watermelon juice	UV-C irradiation Dean vortex (teflon coil), 75 W UV-C lamps Temperature 10 °C Storage during 37 days at 5 °C	Total phenolics Total lycopene	• No significant change in TPC (15–21 mg GAE·mL^{-1}). • TLC (35–39 mg L^{-1}) until 25th day of storage.	Feng et al. (2013)

Table 7   Changes in the bioactive constituents of some fruit juices as effected by UV-C irradiation—cont'd

Product	UV processing conditions	Bioactive content	Main findings	Reference
White and red grape juice	UV-C irradiation, Continuous, 28 W UV-C lamps Flow rate 20 mL s^{-1} Time for one pass 150 s UV intensity per single pass 12.6 J mL^{-1}	total phenolics, antioxidant capacity, total anthocyanins	• No significant changes in antioxidant capacity, total phenolics. • The losses in TAC were not significant and reported as 6.1% and 8.7% after UV-C treatment of 12.6 and 25.2 J·mL^{-1} doses, respectively.	Pala and Toklucu (2013a)
Orange juice	UV-C irradiation (2.03, 24.06, 36.09, 48.12 J mL^{-1}) Continuous, Flow rate 0.02 L s^{-1} 28 W UV-C lamps	Total phenolics Ascorbic acid Antioxidant capacity	• No significant changes were reported for TPC and AA. • Losses in ASC increased with the rising UV-C doses. Significant reduction (9.25%) was reported for ASC after the 48.12 J mL^{-1} of UV-C dose.	Pala and Toklucu (2013b)
Apple juice	UV-C irradiation (2.66 to 53.10 J cm^{-2}) Flow rate 22–352 mL·min^{-1} Exposure time 15–300 s	Total phenolics Antioxidant activity	• TPC showed no significant change • Significant reductions in AA were reported at the UV doses higher than 5.31 J cm^{-2}. The maximum decrease in AA (11%) was found when UV dose was 53.10 J cm^{-2}.	Caminiti et al. (2012a, 2012b)
Pomegranate juice	UV-C irradiation (12.47, 37.41, 62.35 J mL^{-1}) Continuous, Flow rate 20.21 mL s^{-1} 28 W UV-C lamps	Total phenolics Total anthocyanins Antioxidant activity	• TPC and AA showed no significant change. • The losses in TAC were 3.89% and 8.4% after 37.41 and 62.35 J·mL^{-1} doses of UV-C treatments, respectively.	Pala and Toklucu (2011)

TPC: total phenolic content, TLC: total lycopene content, ASC: ascorbic acid content, AA: antioxidant activity.

The major challenge of applying UV-B irradiation to fresh produce is attributed to the generation of reactive oxygen species (ROS) (Hideg et al., 2013). Significant reductions in total phenol and flavonol contents immediately after UV-B irradiation have been associated with the increased generation of stable carbon radicals in the skin of apples (Assumpcao et al., 2018). The different phenolic compounds can respond differently to UV-B irradiation. For instance, it has been reported that hydroxycinnamic acids have been increased while flavonols have been decreased in apple skin as a consequence of exposure to UV-B irradiation. But the hydroxycinnamic acid, anthocyanin and flavonol contents as well as antioxidant activity showed a further increase in all UV treated apples during 21 day of storage (Assumpcao et al., 2018). The initial reduction in bioactive constituents immediately after processing and the subsequent enhancement during storage could be attributed to the increased expression of biosynthetic genes, and the time that the crops needs to adapt the applied UV-B stress (Assumpcao et al., 2018; Du et al., 2014). Similarly, Santin et al. (2018) observed that a wide range of metabolites in peach fruit reacted differently to UV-B irradiation. For instance, the highest accumulation was observed for alkylphenols (1.40-fold), hydroxycoumarins (1.42-fold) and hydroxyphenilacetic acids (1.30-fold) in peach skin after 10 min of UV-B irradiation and 24 h of recovery period while reductions were observed for some other subclasses such as anthocyanins (0.46-fold), dihydroflavonols (0.50-fold) and flavones (0.60-fold). Longer UV-B irradiation time (60 min) had negative effect on the accumulation of phenolic compounds after 24 h of recovery period. Interestingly, phenolic compounds from almost all subclasses remarkably increased in UV-B treated peach skin after 36 h of recovery regardless of irradiation time (Santin et al., 2018). Similarly, it has been reported that the concentration of different flavonoid compounds (flavanones, dihydroflavonols, flavones, flavonols and anthocyanins) in lemon skin treated with UV-B light for 3 minutes increased after 48 hours (Ruiz et al., 2016). On the other hand, the concentration of phenolics decreased in the early stage of storage. This was associated with the degradation of phenolics used to detoxify the UV-B-induced reactive oxygen species. Apparently, a significant increase in the accumulation of bioactive components was achieved as the storage time increased (Santin et al., 2018). Additionally, Wang et al. (2018) reported two-fold increase in anthocyanin content of peach fruit after 0.144 J·cm^{-2}d^{-1}) of UV-B irradiation. Castagna et al. (2013) indicated that UV-B treatment increased the concentration of ascorbic acid and carotenoids in 'money maker' genotype of tomato. However, the firmness was negatively influenced by UV-B, since tomatoes were soften after the treatment.

In a recent study, the potential use of UV-A and UV-B lights as a pre-harvest treatment was investigated in order to evaluate the potential improvement in tomato quality in accordance with the consumer preferences. The tomato plants were subjected to two daily doses of UV-A (1 or 4 h) and UV-B (2 or 5 min). The supplementation of UV-A irradiation was suggested as a pre-harvest

treatment because of its efficacy in increasing the ripening synchronization and fruits nutritional properties (Mariz-Ponte et al., 2019).

The findings of these studies imply that pre-harvest and post-harvest UV-C irradiation ($0.15–1.6$ J cm^{-2}) used as an abiotic stress takes advantage of the defense mechanism of the plants and leads to the progressive increase in the levels of bioactive compounds in the fresh produce. Increasing the concentration of bioactive compounds in fresh products by UV irradiation indicates that the amount of antioxidants needed in the human diet can be achieved by consuming these products. Moreover, decay and spoilage in fresh produce can be delayed by the increased phenolic compounds due to their antimicrobial properties. However, further investigations are necessary to gain the understanding of the molecular mechanisms revealing the influence of UV irradiation on various plant metabolites as well as organoleptic quality of the fresh produce.

Fruit and Vegetable Juices

Fruit and vegetable juices are commonly consumed as non-alcoholic beverages that contribute to the recommended intakes of vitamins, minerals and antioxidants. Retention of these bioactive constituents in commercial products influences not only the attractive color and nutritional value but also the health promoting functions that can reduce the oxidative stress and the risk for cancer and cardiovascular diseases (Cassidy, 2018; Camara et al., 2013). UV-C irradiation has been reported as an alternative processing method to thermal treatment due to its efficacy on achieving high quality beverages without significantly decreasing the concentration of bioactive compounds (Gopisetty et al., 2018). Fortunately, UV irradiation has been increasingly applied for different kinds of liquid foods such as apple juice, mango juice, cranberry flavored water, and skim milk (Gopisetty et al., 2018; Gunter-Ward et al., 2018; Santhirasegaram et al., 2015; Islam et al., 2016). The changes caused by UV light on biological active compounds such as anthocyanins, polyphenols, carotenoids and vitamins of fruit juices and beverages are summarized in Table 7.

Anthocyanins are the important groups of colored water soluble pigments. The stability of anthocyanins can be enhanced through the copigmentation with alkaloids, amino acids, benzoic acids, coumarin, cinnamic acids, and many other compounds (Delgado-Vargas et al., 2000). However, anthocyanins can be degraded easily during processing of fruit and vegetable products. Degradation of anthocyanins during processes including clarification, filtration, mashing, enzymatic treatment, thermal and nonthermal processes has been well documented by Weber and Larsen (2017). More details were provided by Patras et al. (2010) for the adverse effects of thermal treatment ($50–140$ °C) on anthocyanin stability. It has been demonstrated that anthocyanins (i.e. pelargonidin-3-glucoside) were degraded by $15\%–82\%$ in strawberry paste depending on the applied temperature between $95–130$ °C (Verbeyst et al., 2010). In order to obtain better retention of bioactive compounds, UV-C irradiation has gained attention as an alternative method (Koutchma et al., 2016). As previously stated, UV irradiation has been reported to enhance the accumulation of anthocyanins in fresh produce during pre- and post-harvest treatments. Nevertheless, the scenario can be different when it is applied to fruit juices and beverages. For instance, it has been reported that the degradation of individual anthocyanins was in the range of $8.1\%–16.3\%$ in pomegranate juice subjected to UV-C irradiation at a dose of 62.35 J mL^{-1}. However, these levels of reductions in anthocyanin content were found to be insignificant compared to untreated pomegranate juice (Pala and Toklucu, 2011). Similarly, no significant differences were observed in the total anthocyanin content of red grape juice treated with UV-C light at UV doses of $12.6–25.2$ J mL^{-1} (Pala and Toklucu, 2013a). Besides, no significant differences have been reported for the individual anthocyanin content (such as cyanidin 3-arabinoside, cyanidin 3-galactoside, peonidin 3-arabinoside, and peonidin 3-galactoside) of cranberry flavored juice subjected to UV-C fluence of 60 mJ cm^{-2} (Gopisetty et al., 2018). However, Bhat and Stamminger (2015) observed statistically significant reduction in total anthocyanin content of strawberry juice after UV-C irradiation (2.158 J m^{-2}) (Bhat and Stamminger, 2015). The degradation of anthocyanins has been associated with the Photo-degradation of conjugated bonds (Koutchma, 2009a).

Pala and Toklucu (2013a, 2013b) reported that the thermal treatment (85 °C for 15 min) resulted in significant degradation of total anthocyanins (11.8%) in red grape juice compared to that of UV-C irradiation. This finding was in line with the study of Szalóki-Dorkó et al. (2016). They observed that the heat treatment at 70, 80 and 90 °C significantly reduced the level of cyanidin-3-glucosyl-rutinoside by 18%, 29% and 38%, respectively (Szalóki-Dorkó et al., 2016). Glycosylation level has been reported to affect the anthocyanin stability. For instance, diglucosides are more stable than monoglucosides. However, browning becomes more likely to occur by the presence of the additional sugar molecule (Delgado-Vargas et al., 2000). Accordingly, color deterioration may appear along with the anthocyanin degradation due to the formation of brown colored polymeric pigments by thermal treatment (Patras et al., 2010). Nevertheless, it is interesting to note that higher anthocyanin retention can be achieved in processing of fruit juices with UV-C irradiation as compared to heat treatment.

Polyphenols are the major contributors to the antioxidant activities of fresh fruits and vegetables. UV-C irradiation is an important nonthermal technology used to maintain or enhance the total phenolic content (TPC) of different types of juices and beverages, e.g., tomato juice (Bhat, 2016), mango juice (Santhirasegaram et al., 2015), apple juice (Caminiti et al., 2012a), grapefruit juice (La Cava and Sgroppo, 2018), watermelon juice (Feng et al., 2013), green tea beverage (Vergne et al., 2018). UV-C irradiation of tomato juice for 15, 30 and 60 min at the same UV dose of 2.16×10^{-4} J cm^{-2} increased the total phenolic content from 27.8 mg to 32.6, 35.4 and 36.2 mg GAE·g^{-1}, respectively (Bhat, 2016). Similarly, Santhirasegaram et al. (2015) observed an increase in the extraction of polyphenols (31%), and flavonoids (3%) in mango juice exposed to UV-C irradiation for 15 and 30 min. Several other studies have reported no significant changes in total phenolic content of fruit juices. As reported by Caminiti et al. (2012a) UV-C irradiation did not have influence on the total phenolic content of apple juice whereas antioxidant activity significantly decreased compared to that of untreated juice under the same conditions (Caminiti et al., 2012a). Likewise, increasing of UV-C irradiation

dose up to 2.36 J cm^{-2}, did not significantly change the total phenolic content of grapefruit juice whereas the antioxidant activity (DPPH) significantly reduced (La Cava and Sgroppo, 2018). The authors also reported no significant change in grape fruit flavonoids (naringin, hesperidin, neohesperidin). In contrast, thermal treatment at 80 °C for 11 s decreased the levels of phenolic compounds by approximately 16% in grapefruit juice (Igual et al., 2010). The total phenolic content of green tea beverage preserved after application of UV-C irradiation at a relevant commercial disinfection dose of 68 mJ cm^{-2}. However, some minor reductions have been reported in the levels of catechin and (−)-epigallocatechin (Vergne et al., 2018). On contrary, it has been demonstrated that UV-C irradiation applied between 20–240 mJ·cm^{-2} significantly decreased the chlorogenic acid and phloridzin in apple juice by 19.3% and 50%, respectively (Islam et al., 2016). The degradation of polyphenolic compounds has been correlated with the photo-oxidation or photo-induced molecular rearrangement depending on the several factors such as pH, the presence of oxygen, wavelength of light, structure and concentration of phytochemicals, and the inter molecular interaction in the treatment medium (Ioannou et al., 2012). However, as compared to heat treatment, processing of fruit and vegetable juices with UV-C irradiation can be beneficial in preservation of the polyphenols.

Lycopene is lipophilic red-colored carotenoid pigment that is naturally present in the fresh produce, primarily in tomato fruits (about 80% of their total carotenoid content). It can be also found in some other fruits such as watermelon, guava, pink grapefruit (Camara et al., 2013). The level of lycopene in fresh produce highly depends on the maturity, cultivar as well as the processing conditions. Total lycopene content in tomato juice subjected to UV-C irradiation (up to 60 min) showed insignificant decrease (31.2–28.3 µg g^{-1}) compared to that of untreated samples (Bhat, 2016). Similarly, no significant change was reported for the total lycopene content of watermelon juice processed by UV-C irradiation at the doses of 2.7 and 37.5 J mL^{-1} (Feng et al., 2013). Furthermore, lycopene content was found to be stable for 25 days at storage temperature of 5 °C. Interestingly, a significant increase was reported for the extractability of carotenoids (6%) in Chokanan mango juice exposed to UV-C light for 15 and 30 min, when compared to freshly squeezed juice (Santhirasegaram et al., 2015). It was concluded that the use of UV-C light could be used to improve the quality of Chokanan mango juice along with safety standards as an alternative to thermal pasteurization.

Numerous publications have reported that the stability of vitamins affected significantly as a function of temperature, moisture, oxygen, light, pH, oxidizing/reducing agents and metallic ions (Ottaway, 1993). Ascorbic acid (vitamin C) is water soluble vitamin that can be naturally present in fruit juices or added to several beverages due to its antioxidant properties. As reported by Santhirasegaram et al. (2015), 65% of ascorbic acid in mango juice was degraded by the thermal treatment. Similarly, a degradation of ascorbic acid was observed to some extent in UV-C irradiated fruit juice and beverages. For instance, a significant loss has been reported for the vitamin-C content of tomato juice subjected to UV-C irradiation for 60 min (Bhat, 2016). Likewise, exposure of cranberry flavored water to UV-C light at the dose of 60 mJ cm^{-2} resulted in 20% reduction in vitamin C content (Gopisetty et al., 2018). This finding is consistent with results of the study conducted by La Cava and Sgroppo (2018). They found that the losses in ascorbic acid content were between 12%–17%, 20%–29% and 25%–35%, when the grapefruit juice was exposed to UV-C irradiation at the dosages of 1.83, 2.84, 3.94 J cm^{-2} (La Cava and Sgroppo, 2018). Bhat (2016) also reported that UV-C irradiation significantly reduced the ascorbic acid from 9.07 to 3.86 mg·100 mL^{-1} in tomato juice. Vitamin C degradation has been attributed to the induced molecular excitation and subsequent photochemical reactions (Tikekar et al., 2011). On the other hand, it has been demonstrated that ascorbic acid content as a major quality parameter of orange juice did not significantly change after applying UV-C treatment (36.09 kJ·L^{-1} dose) (Pala and Toklucu, 2013b).

Overall, it is concluded that bioactive constituents such anthocyanins, polyphenols, carotenoids and vitamins in UV-C irradiated juice samples is well retained compared to heat treated samples.

Effects of UV Processing on Enzymes

The activity of endogenous deteriorative enzymes including polyphenol oxidase (PPO), peroxidase (POD) and pectin methylesterase (PME) considerably shorten the shelf life of fruits and vegetable products. PPO is a copper-containing enzyme, catalyzes the oxidation of several phenolic substrates. The oxidation of o-dihydroxy phenols to o-quinones leads to formation of undesirable brown pigments, cause the enzymatic browning. Thus, it is important to inactivate it to prevent the formation of melanin that causes the color deteriorations. POD is responsible for enzymatic browning like PPO when acting with phenolic compounds. It catalyzes to the oxidation of various compounds in the presence of hydrogen peroxidase. PME is a pectic enzyme, cause the undesirable cloud instability and sedimentation of the suspended solid fractions in juices by catalyzing the hydrolysis of methyl ester groups from the pectin and forming a calcium pectate gel. LOX is responsible for the generation of volatile flavor compounds and free radicals in many juices. It catalyzes the oxidation of polyunsaturated fatty acids into hydroperoxides (Koutchma, 2009b).

The effects of UV light on PPO, POD, PME and LOX have been studied by some researchers. It was reported that the enzyme inactivation using UV light depends on the juice matrix and its composition, applied UV dose and wavelength.

UV light generated by medium pressure mercury (MPM) vapor lamps had significant effect on the enzymes in fruit juice compared to UV light emitted by low pressure mercury vapor (LPM) lamps. For example, Falguera et al. (2011c) reported complete inactivation of enzymes such as PPO and POD in apple juice after 100 min and 15 min of irradiation at the incident energy of 3.88×10^{-7} E min^{-1}. They treated the juice with 400 W high-pressure mercury UV lamp emitting light between 250 and 740 nm. The authors used the same UV system for inactivation of PPO and POD in white grape juice and pink grape juice (Falguera et al., 2013). Polyphenol oxidase was not completely inactivated during 140 min of irradiation, reducing only 80% of its initial activity in juices from white grapes and only 50% in those from pink grapes. On the contrary, peroxidase was completely inactivated.

Aguilar et al. (2018) evaluated the effect of ultraviolet and visible light (UV–Vis) C on the enzymatic activity (polyphenol oxidase and peroxidase) of peach juices from three different varieties at 25 °C and 45 °C. They used a multi-wavelength emission lamp (250–740 nm) which provided a radiation power of 4.49×10^{-2} W cm^{-2} at liquid surface. UV–Vis irradiation was found to be effective at inactivating polyphenol oxidase (PPO) and peroxidase (POD). The effectiveness of the inactivation was enhanced with temperature. PPO was completely inactivated at 45 °C whereas reduction in POD activity was 60%.

Manzocco et al. (2009) studied the effect of UV-C and visible light on the enzyme polyphenoloxidase in model systems and food (clear apple juice and fresh-cut apple slices). They concluded that UV-C light promoted enzyme inactivation in the entire range of irradiance and exposure time tested whilst visible light was effective only at high doses. They stated that polyphenoloxidase inactivation upon UV-C light exposure was due to protein aggregations. According to Manzocco et al. (2009), the exposure of juice to UV and visible light promote the photo oxidation processes by modifying the structure of proteins. Photo oxidation may result in the loss of functional activity of enzymes by means of formation of side-chain oxidation, backbone fragmentation or cross-links and aggregates.

Müller et al. (2013) showed that the PPO activity in cloudy apple juice decreased approximately from 99% to 96% by increasing UV-C (254 nm) doses from 0 to 53 kJ L^{-1}. Müller et al. (2014) investigated the effect of UV-C and UV-B irradiation on PPO activity of cloudy apple and grape juice, respectively. Even though, they did not observe a significant effect on PPO enzyme activity in both juices treated with UV-B irradiation (71.51 kJ L^{-1}), a reduction of PPO activity of more than 40% and 20% was reported in apple and grape juices subjected to UV-C irradiation at UV dose of 100.48 kJ L^{-1}.

Juice matrix is also an important factor influencing the enzyme inhibition by UV irradiation. After UV irradiation, it was observed that PPO inhibition in orange juice was lower than cloudy and clear apple juice (Gayan et al., 2013; Müller et al., 2013). This can be directly attributed to the presence of pigments, sugars, organic acids that affect the absorption and absorption of UV light, and may lead to a decrease in inactivation performance of the UV process.

The cloud stability of juices such as fresh orange and blend of orange and carrot juice, watermelon, pineapple can be affected by the presence of pectin methylesterase (PME). PME is the UV resistant enzyme (Sew et al., 2014). Although, Falguera et al. (2011c) reported that UV light emitted from high pressure mercury lamp totally inactivates PME in apple juice after 40 min of irradiation, UV-C has been reported to be not effective in inactivating PME in pineapple juice (Sew et al., 2014). Caminiti et al. (2012b) evaluated the effect of UV light on PME activity in the blend of fresh orange and carrot juices. They were able to reduce PME activity down to 82% after subjecting the juice to 6.1 kJ L^{-1} UV dose. Contrarily, PME activity in orange juice was not affected by UV-C irradiation at 7.2 J mL^{-1} (Sew et al., 2014; Torkamani and Niakousari, 2011).

Also, the performance of UV light on inactivation of enzyme can improve by the combined approach with milder heat treatment. In this regard, Aguilar et al. (2018), evaluating the effect of UV–Vis processing on PPO activity in peach juices also at 45 °C, showed that the enzyme was almost totally inactivated for all varieties at 45 °C in shorter time than that of UV-Vis treatment at 25 °C. Gayan et al. (2012) and Gayán et al. (2013) reported that the combination of UV-C irradiation with mild heat at 55 °C treatment approximately doubled the inactivation of PPO in apple juice compared to the same UV treatment at room temperature, 63.96% of PME was inactivated in orange juice after the juice was treated with mild heat at 55 °C for 3.6 min and UV at 23.72 J mL^{-1}. Sew et al. (2014) showed that PME activity (54.4%) in freshly made pineapple juice were affected by mild heat treatment but not UV dose of 0.011 J cm^{-2}.

The PPO activity is used for an indicator of browning in whole or cut fruit and vegetable products. Ding and Ling (2014) examined the effect of UV-C irradiation at different doses on the surface colour of Berangan banana fruit during ripening and determined polyphenol oxidase (PPO) activity after irradiated with 0.003 and 0.004 J·cm^{-2} doses of UV-C. They concluded that the lethal dose causing browning for Berangan banana fruit was 0.003 J cm^{-2} and browning index was the most effective to correlate browning with PPO activity.

UV-C treatment has been examined to inhibit the browning of vegetables and fruits including potato slices, fresh-cut apples and fresh cut lotus root (Wang et al., 2019; Chen et al., 2016; Teoh et al., 2016). The studies by Teoh et al. (2016) demonstrated that the application of UV-C irradiation at 13.68 kJ·m^{-2} dosage did not show a significant effect on inhibition PPO and POD activity of potato slices neither immediately after treatment nor during the 10-days of storage period. Contrarily, the UV-C treatments at dose of 1.5–3 kJ·m^{-2} exhibited significant inhibiting effect on PPO, POD, Phenylalanine ammonia lyase (PAL) activities of fresh cut lotus root (Wang et al., 2019). On the other hand, they also reported that a long time of UV-C irradiation caused the enhancement of enzyme activity since prolonging treatment time increased the contact of enzyme and substrate by causing the damage of the cells. Similarly, the increase in PPO activity with storage time has been also reported in fresh cut apples (Chen et al., 2016).

It can be concluded that there is a limited impact of UV treatment on quality related enzymes in fruit and vegetable products. On the other hand, polychromatic light emitted from MPM lamps is shown to be more effective than UV light emitted from LPM lamps at reducing residual enzyme activity of fruit and vegetable products. However, it should be considered that MPM lamps causes significant deterioration of other quality parameters in food products (Orlowska et al., 2013).

Effects of UV Processing on Allergens and Toxins

Allergens

Food allergy is defined as abnormal reaction of the immune system against certain foods when an individual is exposed to relevant food allergens by ingestion, inhalation, skin contact or injection (Chizoba Ekezie et al., 2018; Verhoeckx et al., 2015; Morandini,

2010). It may cause severe health problems related to respiratory tract, skin, cardiovascular system and gastrointestinal tract (Chizoba Ekezie et al., 2018).

It was reported that over 170 foods might cause allergic symptoms (Chizoba Ekezie et al., 2018). However, the number of foods which are most commonly accounted for allergic reactions was reported to be 14 by European Commission (Verhoeckx et al., 2015). These foods are cereals (wheat), milk, eggs, peanuts, tree nuts, seafood (crustaceans, molluscs, fish), legumes (lupin, soybean), celery, seeds (mustard, sesame) and also sulphur dioxide (Chizoba Ekezie et al., 2018; Verhoeckx et al., 2015).

The first step of the development of food allergy is exposure to certain allergenic food proteins. This causes sensitization of the subjects. In the second step, allergic reactions take place if sensitized subjects come across with sufficient amount of allergens in their diet (Verhoeckx et al., 2015). The symptoms may vary from mild effects to life threatening anaphylaxis (Gomaa and Boye, 2015). The only way to prevent food allergy is to avoid relevant food ingredients (Tammineedi and Choudhary, 2014).

Immunological mechanism of allergy development depends on IgE-mediated, non-IgE-mediated and mixed-type cellular responses (Chizoba Ekezie et al., 2018; Verhoeckx et al., 2015). The most common response is the formation of IgE antibodies (Chizoba Ekezie et al., 2018; Verhoeckx et al., 2015). These antibodies are able to bind to allergens (antigens) (Tammineedi and Choudhary, 2014). Antigens are proteins and primary structure of the protein determines the binding sites. These specific sites are called epitopes. Epitopes can be classified as linear epitopes and conformational epitopes. Linear epitopes consist of amino acid chains whereas three dimensional folding of proteins resulted in conformational epitopes. Allergenicity of a protein can be modified by altering or disrupting the epitopes. Alteration of genetic material or fragmentation of the amino acid chain can modify linear epitopes. On the other hand, denaturation, crosslinking and chemical changes are necessary in order to alter the conformational epitopes (Tammineedi and Choudhary, 2014).

Different processing methods including thermal and non-thermal techniques can be applied in order to change the configuration of food allergens (Chizoba Ekezie, Cheng and Sun, 2018; Tammineedi and Choudhary, 2014). Effect of heating on allergenic food proteins has been extensively studied (Bavaro et al., 2018; Long et al., 2016; Cabanillas et al., 2012, 2015; Gomaa and Boye, 2015; Bu et al., 2009). The extent of the treatment greatly varies depending on the heat resistance of the protein and whether the applied heat is dry or moist (Tammineedi and Choudhary, 2014). Moreover, formation of new allergens and enhancement of the allergenicity of existing protein can be observed after the heat treatment (Chizoba Ekezie et al., 2018; Gomaa and Boye, 2015). Hence, non-thermal processing can serve as an alternative in order to overcome these problems.

Formation of free radicals and oxidation occur after UV light exposure. These free radicals cause conformational changes and denaturation of the allergenic proteins (Tammineedi and Choudhary, 2014). Moreover, interaction of food biopolymers with UV light causes photoreactions. Proteins are photoreactive biopolymers due to the existence of photo responsive chromophores in their structure. Chromophores absorb the incident light and subsequently some modifications such as, crosslinking, aggregation, and backbone fragmentation, occur in the protein structure (Chizoba Ekezie et al., 2018; Zhu et al., 2018; Manzocco and Nicoli, 2012a). Hence, alteration of the properties may change the binding ability of food allergens to IgE antibodies (Chizoba Ekezie et al., 2018). Protein structure and its amino acid composition were also reported to influence the effectiveness of UV light treatment on the protein antigenicity (Tammineedi and Choudhary, 2014).

Tammineedi et al. (2013) treated allergenic milk protein samples (casein and whey proteins) with UV-C light for different exposure times ranging between 5 and 15 min. According to their results, the concentrations of α-casein, α-lactalbumin and β-lactoglobulin were reduced after UV-C light treatments at doses between 1.006 and 3.018 J cm^{-2}. On the other hand, bovine serum albumin, lactoferrin and immunoglobulins were totally vanished from SDS-PAGE gel after the same process. Furthermore, IgE binding capacity of α-casein was found to be decreased by 25% whereas the allergenicity of whey proteins was reduced by 27.7% after 15 min of UV-C exposure. Similarly, Hu et al. (2016) stated that application of UV-C light for 15 min at 11.8 W·m^{-2} lower the allergenicity of α-casein solution. However, it was reported that UV-C light treatment was less efficient in reducing the antigenicity of α-casein as compared to pulsed UV light (PUV) treatment since PUV treatment is able to produce higher energy (Hu et al., 2016; Tammineedi et al., 2013; Chung et al., 2008).

In another study, egg white proteins were analyzed for any alterations in their antigenicity after UV-C light irradiation at an intensity of 35.4 W m^{-2} (Manzocco et al., 2012b). Main allergens of egg white (ovalbumin and ovomucoid) were found to be almost insensitive to UV-C light treatment. Nevertheless, Manzocco et al. (2012b) propounded that UV-C light at an intensity ranging from 0.00016 to 0.00291 J cm^{-2} s^{-1} was very effective in reducing the immunoreactivity of egg white proteins of 0.1 g L^{-1} concentrations.

In summary, studies about the use of UV irradiation as a tool to decrease allergenic properties of food proteins are found to be limited. Moreover, there is a lack of information about the effect of UV light treatment on the reduction of allergenicity of food proteins, other than milk and egg proteins. Besides, continuous UV light processing is revealed to be insufficient to obtain hypoallergenic food products when it is used alone. Therefore, application of combined methods such as UV light treatment in combination to mild heat processing or use of cold plasma, high pressure processing, pulsed light and other nonthermal methods in a hurdle strategy is suggested to improve the treatment efficiency.

Toxins

Food safety is of top priority with respect to both food service industry and consumers. Nowadays, consumers tend to prefer prepared foodstuff, which are prone to contamination from various sources (Falguera et al., 2011b). Contamination of food products by mycotoxins is of great concern due to the health problems associated with their consumption and economic loss (Magzoub et al., 2019).

Mycotoxins are known to be toxic, carcinogenic, mutagenic and teratogenic substances produced as secondary metabolites by filamentous fungi (Pankaj et al., 2018; Hojnik et al., 2017; Diao et al., 2015). More than 400 toxins were reported to be mainly produced by species of *Aspergillus, Fusarium, Penicillium, Alternaria, Claviceps* genera (Pankaj et al., 2018; Hojnik et al., 2017; Ghanghrou et al., 2016). The most toxic mycotoxins can be classified as aflatoxin, fumonisin, zearelenone, ochratoxin, patulin, tricothecene and deoxynivalenol (Pankaj et al., 2018; Hassan, 2017; Hojnik et al., 2017). Among all, aflatoxins (AFs) were indicated to be one of the most toxic group produced by *Aspergillus flavus* and *Aspergillus parasiticus* (Magzoub et al., 2019; Pankaj et al., 2018; Hassan, 2017; Ghanghrou et al., 2016; Mao et al., 2016). AFs can be divided into four main compounds namely, B_1, B_2, G_1, G_2. Furthermore, different degradation products also occur after the metabolism of AFB1 by cellular enzymes, such as AFM_1 and AFQ_1 (oxidative derivatives) and DNA adducts with guanine (Jubeen et al., 2012).

AFs can appear in different products such as meat, milk, eggs, and also contaminate fruits, nuts, cereals, spices and oil before and after harvest, during transportation, storage, handling and processing (Magzoub et al., 2019; Hassan, 2017; Hojnik et al., 2017; Ghanghrou et al., 2016). Allowable limits for AFB_1 and total AFs were strictly determined by European Commission (EC) as $2 \, \mu g \, kg^{-1}$ and $4 \, \mu g \, kg^{-1}$, respectively. On the other hand, US Food and Drug Administration) has set the permissible limit as $20 \, \mu g \, kg^{-1}$ for total AFs (Magzoub et al., 2019; Garg et al., 2013).

Pre- and post-harvest strategies need to be applied in order to achieve the desired limit of mycotoxins in foods. Application of HACCP (Hazard Analysis and Critical Control Points) can prevent contamination of food products with aflatoxin-producing fungi (Mao et al., 2016). Various physical (thermal treatments such as heating, roasting, frying, cooking, baking), chemical (ozonation, ammoniation, use of citric acid, lactic acid, hydrogen peroxide etc.) and biological (fermentation, enzymes) methods have been used to reduce the level of AFs (Magzoub et al., 2019; Hassan, 2017; Shen et al., 2014; Garg et al., 2013). However, conventional methods are not sufficient to detoxify already contaminated products (Pankaj et al., 2018). It is known that AFs are very heat stable (Pankaj et al., 2018; Ghanghrou et al., 2016). Therefore, effective processing methods, which can prevent fungal contamination and provide detoxification, need to be developed (Ghanghrou et al., 2016). UV light treatment can be used as an alternative to other physical treatments owing to its ability to inactivate microorganisms and destroy toxins without altering the quality of the product, ease of use, cost-effective and photosensitive properties (Magzoub et al., 2019; Hassan, 2017; Ghanghrou et al., 2016; Mao et al., 2016; Diao et al., 2015; Shen et al., 2014). AFB_1 can absorb UV light at 222, 265 and 362 nm and maximum absorption occurs at 362 nm (Pankaj et al., 2018; Hassan, 2017; Ghanghrou et al., 2016; Jubeen et al., 2012; Falguera et al., 2011a, 2011b, 2011c). When AFB_1 exposed to UV irradiation at 362 nm, the toxin activates and hence, it becomes susceptible to degradation (Falguera et al., 2011a, 2011b, 2011c). Consequently, terminal furan ring of AFB_1 is modified and lactone ring is broken under the effect of UV light (Pankaj et al., 2018; Hassan, 2017). Double bond found in the terminal furan ring of AFB_1 is the active site of the toxin to possess toxic and carcinogenic effects (Mao et al., 2016).

Hassan (2017) used UV lamps emitting light at 365 nm at a distance of 60 cm from the sample in order to reduce the level of AFB_1 in different types of canned foods. It was found that UV treatment could significantly decrease AFB_1 level from 975 ppb to 111 ppb for beef luncheon and from 75 ppb to 8 ppb for tuna flakes after 30 min of exposure (Hassan, 2017). UV intensity is one of the most important factors that affect the treatment efficiency (Diao et al., 2015). It can be increased by reducing the distance between the light source and the food material to be irradiated. As it can be observed from the results of abovementioned study, the treatment could not achieve the strict standards for AFB_1 determined by EC or US FDA. Thereby, intensity needs to be improved so as to enhance detoxification levels. In another study, wavelength of 254 nm was utilized to investigate the effect of light treatment on decontamination of peanuts (Garg et al., 2013). AF level was reduced from 350 ppb to 3 ppb after 10 h at a distance of 15 cm whereas initial AF concentration could be lowered to 25 ppb when the distance was 30 cm under the same treatment conditions (Garg et al., 2013). They also indicated that as the exposure time increased, both the level of fungal contamination and AF concentration decreased. Similarly, Ghanghrou et al. (2016) obtained 80%–90% of reduction in AF concentration of wheat grains after 160 min of UV light exposure ($0.96 \, J \, cm^{-2}$) which is almost 3–4 times higher than that of 5 min of exposure ($0.03 \, J \, cm^{-2}$).

Hussein et al. (2015) studied the effect of UV irradiation on the growth of *A. flavus* in order to restrict the production of AFB_1. It was reported that fungal growth was inhibited by 84.7%, 88.5% and 90.5% after 30, 60 and 120 min of UV light treatment at 220 nm, respectively. Fungal growth was showed to be affected by moisture content of the food (Diao et al., 2015; Jubeen et al., 2012).

On the other hand, Mao et al. (2016) revealed that different levels of AFB_1 ranging from 48 to 128 ppb could be effectively destroyed by UV irradiation at 365 nm. However, initial AFB_1 level was indicated to be insignificant on the treatment efficiency (Mao et al., 2016). Likewise, initial AFB_1 concentration in peanut oil was pointed to be rather less effective than light intensity and exposure time on photo degradation by UV light (Liu et al., 2011b).

In conclusion, UV light treatment is capable of detoxifying AF contaminated food products. Moreover, growth of toxin-producing fungal species can be inhibited by UV irradiation. Best practice to avoid AF contamination of foods is to prevent fungal development. Thereby, UV light irradiation can be used as a non-thermal alternative step to prevention fungi growth.

Conclusions

UV light has been shown to be an effective nonthermal treatment to inactivate microorganisms in liquid and solid food products, apparently without affecting product properties. Compared with conventional thermal processing, it preserves nutritional and

sensory properties of foods better. The use of the UV light process is limited due to the poor penetration power of the light, the need for a transparent product to be treated, effective mixing and the requirement of the smooth food surface.

However, UV light treatment can preserve quality characteristics of foods and enhance contents of some nutrients in addition to its beneficial effects on microbial quality and shelf life. The treatment conditions (light intensity, exposure time, wavelength and design of the treatment chamber) play a significant role in changing quality properties of the treated products. Especially, foods with high lipid contents are susceptible to oxidative changes caused by UV light irradiation. Therefore, selection of the processing conditions requires attention in accordance with the product to be irradiated.

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