CHAPTER

24 SHORT-WAVE ULTRAVIOLET LIGHT INACTIVATION OF PATHOGENS IN FRUIT JUICES

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24.1 INTRODUCTION

Nonthermal technologies are an alternative to thermal technologies, which are the most widely applied methods for extending food shelf life and ensuring food safety. In other words nonthermal technologies are studied and developed in order to obtain a better final product sensory quality, but without neglecting microbial safety. In this way, these alternatives to thermal technologies can produce food products without enzymes and harmful microorganisms, while maintaining nutritional characteristics and minimizing the loss of quality in terms of flavor, color, and nutritional value. Excessive application of thermal treatment or thermal pasteurization used to cope with this fact has detrimental effects on organoleptic and nutritional qualities of juices. Many researchers have shown that nonthermal processing technologies are able to increasing the shelf life of liquid foods (Bintsis et al., 2000; Koutchma, 2008; Quintero-Ramos et al., 2004; Rodrigo et al., 2001). The advantage of nonthermal processing methods is the minimal processing of foods with reduced loss of nutrients, as well as fewer changes in physical and chemical properties (Quintero-Ramos et al., 2004).

One of these innovative technologies is ultraviolet (UV) irradiation (Butz and Tauscher, 2002; Noci et al., 2008). In contrast to thermal processing, short-wave ultraviolet (UV-C) technologies improve the safety of food products and maintain their proper nutrient content and appearance, involve minimal food processing, thus as well as prolonging their shelf life.

UV-C light treatment for water sterilization and wastewater disinfection, decontamination of air, surfaces, and packaging in food manufacturing is well known and has been used for a number of years (Bachmann, 1975; Bintsis et al., 2000; Brickner et al., 2003; Demirci and Ngadi, 2012; Hassen et al., 2000; Yip and Konasewich, 1972; Koutchma et al., 2009; Koutchma, 2014; Kowalski et al., 2000; McDonald et al., 2000; Qualls et al., 1983; Riley et al., 1971; Shama, 1992; Whitby and Palmateer, 1993). Beside these applications and treatments, scientifically or industrially new applications and innovative treatments (hurdles or combined treatments) have been studied and developed continuously (Hadjok et al., 2008; Hamanaka et al., 2011; Koutchma, 2008, 2014; Koutchma et al., 2009; Taghipour, 2004).

Foodborne diseases are encountered frequently worldwide. In particular, the risk of foodborne illness from minimally or unprocessed fresh food is much greater than from other foods. To reduce this risk, manufacturers in the food industry pay great attention to sterilization technologies, of

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which there are many kinds. Typically, most foods are thermally processed at temperatures between 60°C and 100°C for a few seconds or minutes (Oms-Oliu et al., 2010). However, this preservation processing involves the transfer of a huge amount of energy to these foods, leading to unpredictable changes in their physical, chemical, and organoleptic properties, such as negative effects on certain components of the food itself, reduction in its vitamin content and other nutrients, as well as sensory features that make them less attractive in terms of color and textural properties (Barbosa-Canovas, 1998).

The increased resistance of newly emerged pathogens such as some strains of *Escherichia coli* O157:H7 and acid-adapted and/or resistant strains of enteric pathogens (especially *Salmonella* spp.) has led to foodborne outbreaks even in pasteurized fruit juices, acidic fruit juices (pH 3.3−4.1) have not been considered as vectors for foodborne pathogens (CDC, 2007; Danyluk et al., 2012; Quintero-Ramos et al., 2004). Quintero-Ramos et al. (2004) has shown that outbreaks involving fruit juices have increased consumers' concerns related to the safety of fruit juices. One case of particular interest is the acid resistance of *E. coli* O157:H7 and *Salmonella* spp., which are able to survive in highly acidic liquids (Parish et al., 1997; Quintero-Ramos et al., 2004; Teo et al., 2001).

In 1997, the US Food and Drug Administration (USFDA) regulated that juice producers should achieve a minimum 5-log reduction of pathogen for any juice they produce, which has increased the interest in evaluating the factors that influence pathogenic microorganisms' reduction (USFDA, 1997a,b). Later, the use of UV light as an alternative treatment to thermal pasteurization of fresh juices has been approved (USFDA, 2000a,b). The Report of the Institute of Food Technologists (IFT) written for the FDA stipulated that, to achieve microbial inactivation, the UV-C ($\lambda = 254$ nm) radiant exposure must be at least 400 J/m^2 in all parts of the product (USFDA, 2000a,b). Extensive research over recent years on the use of UV light in food processing has shown that this technology is suitable for the preservation of fruit juices and related products (Keyser et al., 2008; Koutchma et al., 2004). UV light treatment can combine the advantage of preserving the fresh-like characteristics of food quality and the effective inactivation of spoilage and pathogenic microorganisms (Koutchma, 2008; Noci et al., 2008). For instance, UV light technology has been shown to be effective against bacterial pathogens in fruit juices and apple cider, and it neither increases the temperature of the product nor produces undesirable organoleptic changes (Duffy et al., 2000; Gabriel, 2012; Koutchma et al., 2004; Ngadi et al., 2003; Oteiza et al., 2005; Quintero-Ramos et al., 2004; Siobain et al., 2000; Wright et al., 2000).

24.2 UV-C LIGHT

In the electromagnetic spectrum, UV light occupies a wide band of wavelengths in the nonionizing region, including the ones between 200 nm (X-rays) and 400 nm (visible light). According to ISO 21348 (2007) standard, on determining solar irradiances, the range of UV wavelengths used in experiments is situated between 200 and 400 nm and is divided into three parts: full-length UV light (UV-A), medium-length UV light (UV-B), and short-length UV light (UV-C) division of electromagnetic spectrum of experimental UV light. The UV-C (short wave or germicidal UV) has wavelengths in the range of 200−280 nm (4.42−12.40 eV/photon), UV-B has wavelengths in the

range of 280−320 nm (3.94−4.43 eV/photon), UV-A has wavelengths in the range of 320−400 nm (3.10−3.94 eV/photon) with energies in eV/photon (ISO 21348-2007).

In order to carry out a photochemical change, the light radiation has to be absorbed; therefore, the kind of light source to be used is determined by the absorption spectrum of the material to be irradiated. The effect of radiation on a compound can be evaluated by the knowledge of its specific absorption spectrum at different wavelengths. This spectrum can be determined by irradiating a solution with a well-known concentration of the compound at different wavelengths, and measuring its absorbance values at these wavelengths. This absorption spectrum usually determines the optimum area of working wavelengths presenting maximum absorbance peaks (Ibarz and Esplugas, 1989; Ibarz et al., 1985a,b).

Industrial-scale irradiations are often carried out and controlled by means of catalysis or addition of energy. The energy can be supplied in the form of radiant energy, with a special interest in the area of the electromagnetic spectrum that includes the UV (200−400 nm) and the visible (400−700 nm) regions, in which the addition of this energy produces electronically excited molecules, which can lead to chemical reactions (Ibarz and Esplugas, 1989; Ibarz et al., 1985a,b). Besides having a great emission power in the desired wavelengths, the main characteristics which must have a radiation source for an industrial use are: emission stability, long life, good physical dimensions, ease of operation, and low cost.

24.2.1 NATURAL SOURCES

The most important natural radiation source, the Sun, includes wavelengths from 250 to 1200 nm. Solar radiation includes a wide range of wavelengths, whose spectral distribution varies depending on the longitude, latitude, height, weather conditions, etc. of considered area.

For most of the possible photochemical reactions, the energy flow that reaches sea level is very small (nearly 0.1 W/cm^2) and has a spectral distribution with too much infrared radiation, which only has a heating effect and is not able to produce chemical changes. At sea level, approximately 9% of the radiation corresponds to the UV region, 42% to the visible one and 49% to the infrared one. Therefore, it may be noted that there is a large amount of infrared radiation ("useless") that reaches sea level, in comparison with the low amount of UV radiation ("useful"). The Sun is the first UV radiation source that can be considered, since it emits over a wide range of wavelengths. Nevertheless, the fraction corresponding to UV radiation that reaches the Earth's surface depends largely on its attenuation through the atmosphere. The UV-C fraction is completely absorbed in the upper and middle parts of the atmosphere, due to the presence of ozone and molecular oxygen. With the middle wavelength region (UV-B), almost the same happens, although a small fraction of it reaches the Earth's surface. However, UV-A light is hardly affected. Some authors consider that the flux reaching sea level is in a range from 35 to 50 W/m^2 (Bintsis et al., 2000; Kramer and Ames, 1987).

24.2.2 ARTIFICIAL SOURCES

Artificial sources of UV-C light are arches of carbon and plasma, incandescent, fluorescent, and high-intensity discharge lamps (Falguera et al., 2011a,b; Rabek, 1982). High-intensity discharge lamps that produce high-intensity light by passing an electric current through metal in a gaseous

state are commercially available as mercury, sodium, and xenon lamps for industrial use. These lamps are classified according to this emission spectrum and whether the predominating wavelengths are short, medium, or long. The emission spectrum of these lamps is improved by the addition of metal halides. As pressure increases, the emission spectrum becomes more complex, and for low pressure the emission of radiation is almost exclusively at 254 nm (Falguera et al., 2011a).

Mercury lamps classified as high, medium (1−6 bar), or low (typically 0.01 mbar, ∼1 Pa) pressure arches, are similar to fluorescent lamps, and require an electrical device for their ignition and continuous operation. Mercury is the optimum metal for use in gas discharge tubes due to its inert characteristics, relatively low ionization energy, and sufficient vapor pressure at moderate temperatures. On the other hand, the power that high-pressure lamps may have (2500 W) is much greater than the power that low-pressure lamps may achieve (30 W), making them more effective. Sodium lamps consist of a tube made of ceramic material (translucent aluminum oxide) to prevent chemical attack of sodium vapor at high pressure and temperature. Their spectrum is very rich in visible wavelengths, therefore they are useful in outdoor lighting (roads, highways, etc.). High-pressure sodium lamps are quite different from other high-intensity discharge lamps in construction, operation, and emitted radiation. Xenon lamps operate at a very high voltage, making the electrical equipment and maintenance expensive. They have almost continuous spectral distribution, similar to the Sun, and can have high power (2000 W); the system must operate in a vertical position. However, these lamps require more care than mercury lamps and good control of the cooling (Bolton, 2004; Schalk et al., 2006).

Manufacturers usually provide UV-C lamp emission spectra and their nominal power. However, nominal power does not usually coincide with the real power emitted by the lamp, since its power decreases in time. In any quantitative study of UV-C treatment it is necessary to know the real power using UV sensors that provide this magnitude in W/m^2 (Guerrero-Beltrán and Barbosa-Cánovas, 2004). To perform actinometric reactions or simply actinometries is another method.

An actinometric reaction is a standard UV-C reaction (decomposition of oxalic acid in the presence of uranyl cation or decomposition of ferrioxalate), with well-known absorption and kinetic characteristics, which easily allows the measurement of changes in the concentration of some of the species involved in the reaction. The best method for finding the radiation flow that enters the UV-C system is the actinometry due to the presence of a radiation-emitting source, which makes it possible to calibrate this source (Calvert and Pitts, 1967; Rabek, 1982).

24.3 UV-C LIGHT TREATMENT SYSTEMS

Practically, there are different types of UV-C treatment systems that are used in processes, classified as continuous and discontinuous according to their mode of operation.

24.3.1 NONCONTINUOUS UV-C SYSTEMS

Noncontinuous UV-C systems are used to perform reactions with low quantum yield, which need high irradiation times. These are also used if the reactants have a high viscosity. The most frequently used system is designed as a stirring tank, which consists of a perfect mixing tank and a set

of lamps immersed inside to permit radiation to reach any point. An elliptical UV-C system, operating as a batch, is another system used. The system consists of a cylindrical shell with an elliptical cross-section, constructed from a material that is reflective to radiation, in which the lamp is placed in a focal axis and the system in the other one. In this system, high radiation intensities are obtained in the reaction zone because all radiant energy emitted by the lamp theoretically strikes in the system, either in a direct way or through the reflection in the cylindrical shell.

24.3.2 CONTINUOUS UV-C SYSTEMS

A continuous UV-C system, that is a continuous-flow system, is used in reactions with large quantum yields, achieving small irradiation times of the material. Therefore, in reactions with high rates of radiation absorption, continuous UV-C systems are commonly used. Tubular annular, elliptical, parallel flat-plate, descendent film continuous UV-C systems are some examples of these systems. A tubular annular system consists of a cylinder with an annular section, with the lamp placed in this central annulus space. Cylindrical stirred-tank-type UV-C systems, similar to that operating in a noncontinuous mode, consist of a perfectly stirred tank with one or more immersed lamps. Continuous elliptical UV-C systems are identical to the noncontinuous system, but operate continuously. The elliptical thin-film version of this system developed by Lu et al. (2010a,b) with enhanced efficiency is composed of two UV mercury vapor lamps located inside elliptical reflectors. In this system UV rays were reflected in such a way that they could converge at a light point (the focus), and at this UV light point, the radiant energy was transmitted into quartz optical fibers bound by the fiber cluster. The elliptical thin-film UV-C system has a stainless steel body which is studded with optical fibers. The parallel flat-plate UV-C system consists of two parallel plates placed very close to each other, with the materials circulating between them. The radiant energy comes through one side from the outside made of a material transparent to radiation. Material comes either directly from the exterior lamp or by reflection from a parabolic envelope constructed with a reflective material. Because the distance between the plates is very short and the fluid flows with a very low thickness, radiation reaches every point of the fluid, and the parallel flat-plate UV-C system is suitable for materials having high optical density. The descendent film UV-C system is a tubular system in which the lamp is placed in the central axis, and the fluid flows in the form of film down the inner face of the tube.

Shama et al. (1996) developed a thin-film UV-C system that permits liquids to be irradiated without making contact with either the UV sources or any solid walls. The system is based on a nozzle of special design which generates an unsupported thin liquid film, commonly referred to as a liquid "bell." Milly et al. (2007) developed a novel UV-C system consisting of an inner rotating rotor and a stationary quartz housing in order to induce controlled cavitation for ensuring a homogeneous UV-C exposure. The particle bed UV-C system consists of a bed of glass particles with a radioisotope-attached surface layer covered by a fluorescent material. High-energy radiation emitted by the radioisotope interacts with the fluorescent material to produce visible or UV radiation energy. In conclusion, although there are many different kinds of UV-C system designs, to achieve high radiation doses, multilamp UV-C systems consisting of a single UV-C system like the ones described above with several lamps are often used.

24.3.3 UV-C SYSTEMS USED IN FRUIT JUICE APPLICATION

In fruit juice applications of UV-C treatment, both batch collimated beam units and continuous systems (lab-scale and commercial systems) are used.

Batch UV-C systems used for fruit juice application are collimated beam systems with narrow and focused bands of UV-C light in a cylindrical tube, which extends from the light source (i.e., the lamp) to the sample, and direct overhead exposure with an uncontained light source, which is simply located above the sample (Koutchma et al., 2016). Direct overhead exposure systems including the systems with one lamp, as in dark chambers and in thermostated cells, were used for the processing of apple, coconut, grape, grapefruit, mango, orange, pear, and starfruit juices (Augusto et al., 2015; Bhat et al., 2011; Corrales et al., 2012; Falguera et al., 2011a,b, 2012, 2013; La Cava and Sgroppo, 2015; Manzocco et al., 2009; Noci et al., 2008; Sampedro et al., 2014; Santhirasegaram et al., 2015a,b; Zhu et al., 2014). Collimated beam systems consisting mostly of one lamp at 254 nm were used for treatments of the apple and grape juices (Baysal et al., 2013; Orlowska et al., 2013; Tikekar et al., 2011; Taze et al., 2015).

Annular (with laminar and turbulent flow) and coiled-tube systems (Dean-Flow and Taylor−Couette) were the continuous lab-scale UV-C systems used for fruit juices. Annular continuous lab-scale UV-C systems were used for the treatment of apple, coconut, grape, lemon−melon, pitaya juices, and mango nectar (Caminiti et al., 2012a; Guerrero-Beltrán and Barbosa-Cánovas, 2006; Kaya et al., 2015; Ochoa-Velasco and Guerrero Beltrán, 2013). Laminar (vertical thin film) was used by Torkamani and Niakousari (2011) and Tran and Farid (2004) for the treatment of orange juice. Thin film in series was used by Gayán et al. (2013) for apple juice, and a tubular rising film lab-scale continuous UV-C system was used by Caminiti et al. (2012b) for orange−carrot blend juice. A coiled tube continuous lab-scale UV-C system was used for processing the apple white and red grape, orange, pomegranate, watermelon (Müller et al., 2014; Pala and Toklucu, 2011, 2013a,b; Zhang et al., 2011). Although the Taylor−Couette coiled-tube UV-C system was the only continuous lab-scale UV-C system, used only for apple cider (Orlowska et al., 2014), Dean-Flow coiled-tube continuous UV-C system was used for the Guava nectar, orange, watermelon, pineapple, and pummelo juices (Feng et al., 2013; Koutchma 2009; Mansor et al., 2014; Shah et al., 2014).

CiderSure 3500-B (FPE Inc., Macedon, NY, United States), which is a laminar thin-flow commercial continuous UV-C system, was used for pineapple juice (Chia et al., 2012; Goh et al., 2012; Sew et al., 2014). SurePure/PureUV (SurePure Inc., Zug, Switzerland) thin-film turbulent lab-scale continuous commercial UV-C system was used by Keyser et al. (2008) for the treatment of apple juice, guava-and-pineapple juice, mango nectar, strawberry nectar, and two different orange and tropical juices. The same system (SurePure, Cape Town, South Africa), on a pilot scale, was also used for the processing of grape juice (Fredericks et al., 2011).

In the UV-C system UVivatec Lab (Bayer Technology Services GmbH, BTS), which utilizes a teflon tube that is helically coiled around a mercury lamp, which itself is contained in a quartz glass tube, was used for apple juice (Franz et al., 2009). In this system, flow leads to secondary vortices, known as "Dean vortices" that allow radial mixing of the fluid even in a laminar flow field and homogenous UV-penetration into cloudy juices.

Koutchma et al. (2016) stated that a well-defined UV-C treatment system should include information about the lamp characteristics, lamp power (W), lamp wavelength (nm), description of the

reactor for continuous-flow conditions or batch systems; additionally the number of lamps used for a continuous system and the number of passes through the reactor should be described.

24.4 FRUIT JUICE AS VEHICLES OF FOODBORNE PATHOGENS

As can be seen in Table 24.1, there has been a tremendous increase in the number of outbreaks associated with the consumption of fruit juices. The largest reported fruit juice outbreak of salmonellosis has been associated with unpasteurized orange juice (Table 24.1). Orange juice was first reported as a vehicle of transmission in an outbreak of typhoid fever at a hotel in Cleveland, Ohio, in 1944 (Duncan et al., 1946). From 1922 through 2010, 14 outbreaks associated with consumption of orange juice were reported worldwide (Duncan et al., 1946; Danyluk et al., 2012). Of these, nine (64%) were from unpasteurized orange juice, four (29%) from frozen from concentrate, and one (7%) was unspecified. All reported outbreaks linked with unpasteurized orange juice were associated with either retail or food service establishments, whereas outbreaks associated with the consumption of frozen from concentrate orange juice were in hospitals (2, 50%), a hotel (1, 25%), and at a sporting event (1, 25%). Pathogens identified in unpasteurized orange juice outbreaks were predominately *Salmonella* (*S*. Typhimurium, *S*. Saintpaul, *S*. Enteritidis, *S*. Anatum, *S*. Muenchen, *S*. Gaminara, *S*. Hartford, *S*. Rubislaw), but also included enterotoxigenic *E. coli*, *Shigella flexneri*, and a suspected virus. Frozen from concentrate orange juice contaminates identified in outbreaks include *S*. Typhi (Cook et al., 1998).

Salmonellae are found in a broad variety of hosts, including animals (insects, reptiles, amphibians, birds, and mammals), and may survive for long periods in soil or water contaminated with animal feces. Fruits can be contaminated with *Salmonella* directly from animals or indirectly from soil, surface water used for irrigation, or improperly prepared manure used as fertilizer. Regardless of the environmental source and means of contamination, once *Salmonella* had entered into the processing plant, inadequate cleaning and sanitization of processing equipment probably contributed to production of contaminated juice. The presence of a specific fecal indicator organism in all samples of orange juice tested from these outbreaks indicates improper sanitation in the processing plant.

Orange juice manufacturing provides more opportunity for a single contaminated orange to cause an outbreak, compared to oranges consumed fresh, as the juice from thousands of oranges is combined before the distribution and there are more steps in the manufacturing process. Due to climatic variations that affect the fruit or manufacturer processing techniques, the pH of orange juice may rise above the normally observed range (3.6−4.3), which can permit pathogen growth (Eisenstein et al., 1963) and also, some pathogens inhibited from reproductive growth will remain infectious in orange juice. Studies performed on a laboratory scale about the survival of *Salmonella* and other bacterial pathogens in fruit juices also supported the hypothesis that acidic juices can be vehicles of pathogen transmission. Survival studies of salmonellae in orange juice using, in part, strains isolated from case patients and orange juice described in the outbreak investigation showed that salmonellae survived in detectable numbers up to 27, 46, 60, and 73 days at pH 3.5, 3.8, 4.1 and 4.4, respectively (Parish et al., 1997). In another, study orange juice (pH 3.0−3.1) samples were inoculated with viable cells of *Salmonella* species, *Shigella sonnei*, and *E. coli* (each 10^6/mL) and held at 5°C. In this study, the four decimal reduction (4 log) in number of viable *Salmonella*

Table 24.1 Fruit-Juice-Borne Outbreaks Caused by Bacterial Pathogens

Causative Bacterial Agent	Year	Fruit Juice	Cases (Death)	Place	Country
E. coli O111	2015	Apple juice	13		USA (CA)
E. coli O157	2014	Apple juice	3		Canada (ON)
E. coli O157:H7	2010	Apple juice unpasteurized	7	Retail	USA (MD)
Salmonella Typhi	2010	Mamey juice unpasteurized	9	Retail	USA
Salmonella ser. Panama	2008	Orange juice unpasteurized	33	–	Netherlands
E. coli O157:H7	2008	Apple juice unpasteurized	7	Fair	USA (IA)
E. coli O157:H7	2007	Apple juice unpasteurized	9		USA (MA)
Clostridium botulinum	2006	Carrot juice homemade	4	Retail	USA
Clostridium botulinum	2006	Carrot juice commercially canned	3	Retail	Canada (TO)
Salmonella ser. Typhimurium *Salmonella* ser. Saintpaul	2005	Orange juice unpasteurized	157	Restaurant, deli, private home	USA (23 States)
E. coli O157:H7	2005	Apple juice unpasteurized	4		Canada (ON)
E. coli O111	2004	Apple juice unpasteurized	212	Farm, home	USA (NY)
Shigella sonnei	2002	Mixed fruit	78	Resort	Canada, USA, UK
Salmonella ser. Enteritidis	2000	Orange, grapefruit, lemonade juice	74	Multiple places	USA (6 States)
Salmonella ser. Muenchen	1999	Orange juice unpasteurized	398 (1)	Restaurant	Canada, USA
Salmonella ser. Typhimurium	1999	Orange juice	427	Retail	Australia
Salmonella ser. Anatum	1999	Orange juice unpasteurized	10	Other	USA (FL)
Salmonella ser. Typhimurium	1999	Mamey juice unpasteurized	13	–	USA
E. coli O157:H7	1999	Apple cider unpasteurized	5	Private home	USA
E. coli O157:H7	1999	Apple juice unpasteurized	25	–	USA (OK)
E. coli O157:H7	1998	Apple juice	14	Farm, home	Canada (ON)
E. coli O157:H7	1997	Apple cider unpasteurized	6	Farm	USA (IN)
E. coli O157:H7	1996	Apple cider unpasteurized	56	Multiple	USA
E. coli O157:H7	1996	Apple juice unpasteurized	71(1); 14 HUS[a]	Community	Canada, USA
E. coli O157:H7	1996	Apple cider unpasteurized	14(3)	Small cider mill	USA (CT)
E. coli O157:H7	1996	Apple cider unpasteurized	6	Small cider mill	USA (WA)

Table 24.1 Fruit-Juice-Borne Outbreaks Caused by Bacterial Pathogens *Continued*

Causative Bacterial Agent	Year	Fruit Juice	Cases (Death)	Place	Country
Shigella flexneri	1995	Orange juice unpasteurized	14	Restaurant	South Africa
Salmonella ser. Hartford, *Salmonella* ser. Gaminara *Salmonella* ser. Rubislaw	1995	Orange juice	62	Theme park	USA (FL)
Salmonella spp.	1993	Watermelon homemade	18	Home	USA (FL)
Clostridium botulinum	1993	Carrot juice homemade	1	Home	USA (WA)
E. coli O157:H7	1992	Orange juice	6	Roadside vendor	India
E. coli O157:H7	1991	Apple cider	23; 4 HUS[a]	Community	USA (MA)
Salmonella ser. Javiana	1991	Watermelon juice	39	Indoor picnic, school party	
Salmonella ser. Enteritidis	1991	Orange juice	600	–	
Vibrio cholerae	1991	Coconut milk (squeezed from coconut meat)	4	Home, picnic	USA (MD)
Salmonella Typhi	1989	Orange juice reconstituted	69	Hotel	USA (NY)
E. coli O157:H7	1980	Apple juice unpasteurized	14(1); 14 HUS[a]	Local market	Canada (ON)
Salmonella ser. Typhimurium	1974	Apple cider	296	Farm and small retail outlets	USA (NJ)

[a]*HUS, people with hemolytic uremic syndrome.*
Adapted from Powell, D., Luedtke, A., 2000. Fact sheet: a timeline of fresh juice outbreaks. University of Guelph. Available from: <http://www.plant.uoguelph.ca/safefood/micro-haz/juiceoutbreaks.htm> (Powell and Luedtke, 2000); Harris, L.J., Farber, J.N., Beuchat, L.R., Parish, M.E., Suslow, T.V., Garrett, E.H., et al., 2003. Outbreaks associated with fresh produce: incidence, growth, and survival of pathogens in fresh and fresh-cut produce. Compr. Rev. Food Sci. Food Safety 2 (1), 78–141 (Harris et al., 2003); CDC (Centers for Disease Control and Prevention), 2007 (CDC, 2007); and Danyluk, D., Goodrich-Schneider, R. M., Schneider, K.R., Harris, L.J., Worobo, R.W., 2012. Outbreaks of Foodborne Disease Associated with Fruit and Vegetable Juices, 1922–2010. Food Science and Human Nutrition Department (FSHN), FSHN12-04 (Danyluk et al., 2012).

species and *E. coli* was obtained in 27 days, while for *S. sonnei* it was obtained in 35 days (Mitscherlich and Marth, 1984). In another study, in one of the aforementioned orange-juice-associated typhoid fever outbreaks, inoculated orange juice with the outbreak strains and the pathogen was recovered viable up to 6 days later (Birkhead et al., 1993). *Salmonella enterica* serotype Typhi has survived on the surface of cut and whole oranges for 6 and 14 days, respectively (Mitscherlich and Marth 1984).

Therefore, a risk of illness from unpasteurized orange juice persists. Pasteurization of the juice has made fresh and frozen from concentrate orange juice safe to consume, but in drinking unpasteurized orange juice a risk remains because contamination can still occur via food handlers. Moreover, varying by season, the average pH level of Florida orange juice is 3.7 (range: 3.4−4.0) (Attaway et al., 1972). While the pH of orange juice implicated in some outbreaks was less acidic than expected (mean pH 4.3), the FDA does not consider foods with a pH level of 4.6 or less to be "potentially hazardous" (USFDA, 1997a,b). After these orange-juice-borne outbreaks, the governmental agencies regulated the production of fresh-squeezed unpasteurized orange juice by introducing control measures such as banning the use of oranges picked from the ground for the production of juice, washing fruit with an acid wash or other equivalent cleaning method, rinsing fruit with hypochlorite or other equivalent bactericide, completely enclosing the juice-processing area, conducting routine microbiological surveillance of unpasteurized juice, and establishing documented quality control, good manufacturing practices and sanitation standard operating procedures or the Hazard Analysis Critical Control Point (HACCP) program (Anonymous, 1996).

Other acidic fruit juices have also been implicated in outbreaks of gastroenteritis. Unpasteurized apple cider and apple juice were associated with outbreaks of *S.* Typhimurium infection (CDC, 1975), *E. coli* O157:H7 infection (CDC, 1996, 1997; Besser et al., 1993), postdiarrheal hemolytic uremic syndrome (Besser et al., 1993), and cryptosporidiosis (CDC, 1997; Millard et al., 1994). *Clostridium botulinum* was linked with outbreaks associated with both homemade and commercially canned carrot juice. *S. sonnei* and *S. flexneri* were associated with mixed-fruit-juice- and orange-juice-linked outbreaks, respectively. These two species of *Shigella* cause endemic disease and they are either transmitted directly through fecal−oral routes or indirectly through fecal-contaminated food and water. As seen from Table 24.1 outbreaks, associated with the consumption of fruit juices were reported to be at their maximum in 1996 and 1999. Besides *E. coli* O157, in 2004 and 2015 *E. coli* O111 was also associated with apple-juice-associated outbreaks. *E. coli* O111 is an enteropathogenic strain of *E. coli* causing hemorrhagic diarrhea and is mostly transmitted directly or indirectly through human carriers. Animals, particularly dairy and beef cattle, are thought to be carriers. Ingestion of as few as 10−100 cells can produce the disease, especially in sensitive individuals.

As a consequence of outbreaks associated with juices, the USFDA proposed new rules to improve the safety of fresh and processed fruit and vegetable juices and juice products (USFDA, 1997a,b, 2000a,b). The USFDA's proposal mandated the application of HACCP principles to the processing of the juices to prevent bacterial, chemical, and physical contamination mandating that all 100% fruit/vegetable juices sold wholesale be produced under a HACCP plan.

Later, the USFDA (1997a,b) regulated that juice producers should achieve a minimum 5-log reduction in pathogens for any juice they produce and this regulation has increased the interest in studying the factors that influence pathogenic microorganisms' reduction. Currently, *Salmonella* is generally accepted as the pertinent pathogen in citrus juices, whereas *E. coli* O157:H7 as well as *Cryptosporidium parvum* are both considered pertinent for apple juice (USFDA, 2001).

Pasteurization or other risk-management strategies proven to be at least as effective as pasteurization should be used in the production of juices, including those previously thought to be too acidic to transmit infection. Consumers need to be aware that all unpasteurized juices may potentially transmit enteric infections, however their risk for illness can be reduced by drinking only pasteurized juices (both fruit and vegetable). Consequently, there is a demand for developing, evaluating and implementing novel or alternative juice-production methods at least as effective as pasteurization, especially for fresh-like, minimally processed food products and freshly squeezed juices.

24.5 UV-C LIGHT INACTIVATION MODE OF ACTION

Nucleic acids absorb UV light from 200 to 310 nm. Absorbed UV light causes breaking of some bonds and the formation of pyrimidine dimers, which are bonds between adjacent pairs of thymine or cytosine pyrimidines on the same DNA or RNA strand (Fig. 24.1). These dimers prevent cells from replicating, so microorganisms become inactive and unable to proliferate. UV-C photons are absorbed by the nitrogenous bases of microbial DNA causing the formation of cross-linking photoproducts that inhibit transcription and replication, and eventually lead to cell death (López-Malo and Palou, 2005). UV light has been used to reduce the microbial load of several types of microorganisms in some liquid foods. The most studied microorganism is *E. coli*, followed by other bacteria species such as *Listeria innocua*, *Yersinia pseudotuberculosis*, *Bacillus subtilis*, *Staphylococcus aureus*, yeast *Saccharomyces cerevisiae*, undefined molds, and protozoon *C. parvum* (Oguma et al., 2001; Turtoi and Borda, 2013). Several authors have reported the higher UV-C resistance of *Listeria monocytogenes* in comparison to other foodborne pathogens in milk (Lu et al., 2011), fruit juice (Gabriel and Nakano, 2009), and on solid surfaces (Rowan et al., 1999). This fact has been attributed to the thicker peptidoglycan cell wall and higher chromosome condensation of gram-positive bacteria in comparison to gram-negatives (Beauchamp and Lacroix, 2012), as well as to the higher-efficiency DNA repair systems of *L. monocytogenes* in comparison to *E. coli* (Cheigh et al., 2012).

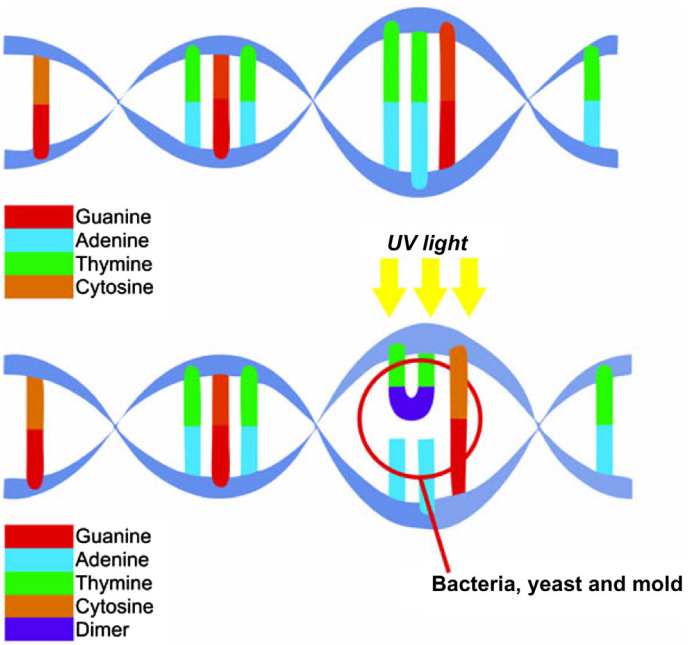

FIGURE 24.1

Effect of UV-C light on DNA in the form of single-strand breaks.

From SurePure™ website, http://www.surepureinc.com/1-sure_pure_science.html.

The antimicrobial effects related to the UV region are attributed to chemical modification and cleavage of DNA, as well as to the production of *cis-syn* cyclobutane pyrimidine dimers (CPDs) and other kinds of DNA lesions (Hallmich and Gehr, 2010; Mitchell et al., 1992; Oguma et al., 2002). If various UV-induced lesions are not repaired, they eventually cause mutagenesis and cell death (Kiyosawa et al., 2001).

In recent years, consumption of several low-pH foods, such as orange and apple juices, and fermented sausages, has been implicated in foodborne diseases caused by *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes*. These pathogens are normally sensitive to low pH (pH ≤ 4.5) and are expected to die off rapidly during storage at refrigerated temperatures. Studies showed that the pathogens isolated from these foods are acid-resistant variants and are thus able to survive well in a low-pH product. A stress response can enable pathogens to survive in food through many processing conditions and make the food potentially hazardous (Ray and Bhunia, 2014). Sublethal injury occurs following exposure of bacterial cells to unfavorable physical and chemical environments (beyond the growth range but not in the lethal range) that cause reversible alterations in the functional and structural organizations of the cells (Ray and Bhunia, 2014). Nonthermal technologies such as UV-C irradiation can lead to the appearance of sublethally injured cells (Gayán et al., 2013). Thus, it is quite likely that the foods and the facilities will harbor injured microorganisms.

Cheigh et al. (2012) performed a study to compare intense pulsed light (IPL, employing a flash lamp filled with inert gas, which emits high-frequency pulses of broad-spectrum radiation containing wavelengths from 180 to 1100 nm) and UV-C-induced cell damage in *L. monocytogenes* and *E. coli* O157:H7. The results demonstrated that the viability of the foodborne pathogens treated with UV-C decreased exponentially with treatment time, and that the death rate was slightly higher for *E. coli* O157:H7 than for *L. monocytogenes* for UV-C irradiation treatments. In the early stages of UV-C irradiation ($0-90$ s), little microorganism inactivation was observed, whereas a 4-log reduction of *L. monocytogenes* and a 5-log reduction of *E. coli* O157:H7 were achieved with 1200 s of UV-C treatment. DNAs from cells irradiated with UV-C accumulated double-strand breaks (DSBs), single-strand breaks, and CPDs, and with a similar pattern; however, more DSBs were detected following UV-C than following IPL in both types of microorganism. Cheigh et al. (2012) compared transmission electron micrographs (TEM) of untreated and continuous UV-C treated *L. monocytogenes* and *E. coli* O157:H7 cells, and found that the membranes of cells untreated or treated with continuous UV-C remained intact. TEM observations clearly indicated that bacterial cell wall or membrane structures were not destroyed by UV treatment (Fig. 24.2). Although the cell walls and membranes of these bacteria were maintained, the shape of UV-C treated *L. monocytogenes* (Fig. 24.2A and B) and *E. coli* O157:H7 (Fig. 24.2C and D) was similar to that of UV-C-untreated control cells, except for a blurry and indistinct cell wall.

TEM images of ultrastructural changes in *S.* Typhimurium and *E. coli* O157:H7 cells induced by UV treatments are shown in Fig. 24.3A and B, respectively. In the case of UV-C-treated cells, morphological changes as well as collapse of internal cellular structures were not observed compared to control cells (Fig. 24.3A and B).

Stress adaptation or stress response has been explained as a situation whereby a brief exposure of a bacterial population to a suboptimal physical or chemical (growth) environment enables the cells to resist subsequent exposure to the same or other types of harsher treatments to which the species is normally susceptible. This phenomenon has been observed among many foodborne pathogens and spoilage bacteria following exposure of cells to various suboptimal physical and chemical

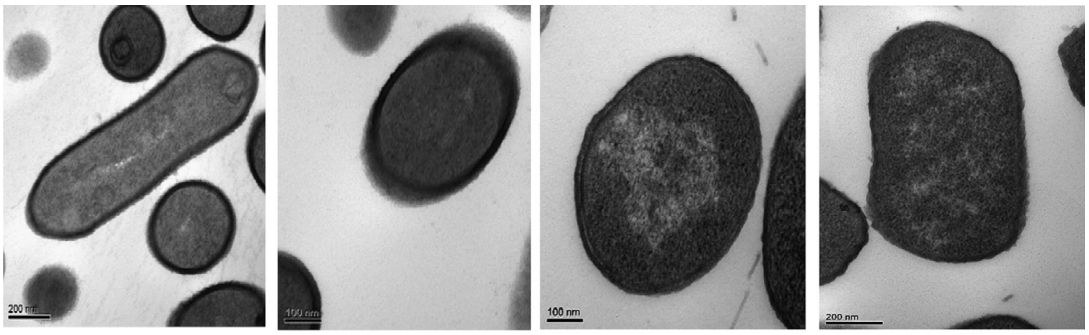

FIGURE 24.2

Transmission electron microscopy of *Listeria monocytogenes* (A, B) and *Escherichia coli* O157:H7 (C, D). Images: (A) and (C) untreated control cells, (B) and (D) UV-C treatment for 600 s, at 376 W/m^2.

From Cheigh C.-I., Park M.-H., Chung M.-S., Shin J.-K., Park Y.-S., 2012. Comparison of intense pulsed light- and ultraviolet (UVC)-induced cell damage in Listeria monocytogenes and Escherichia coli O157:H7. Food Control 25, 654–659.

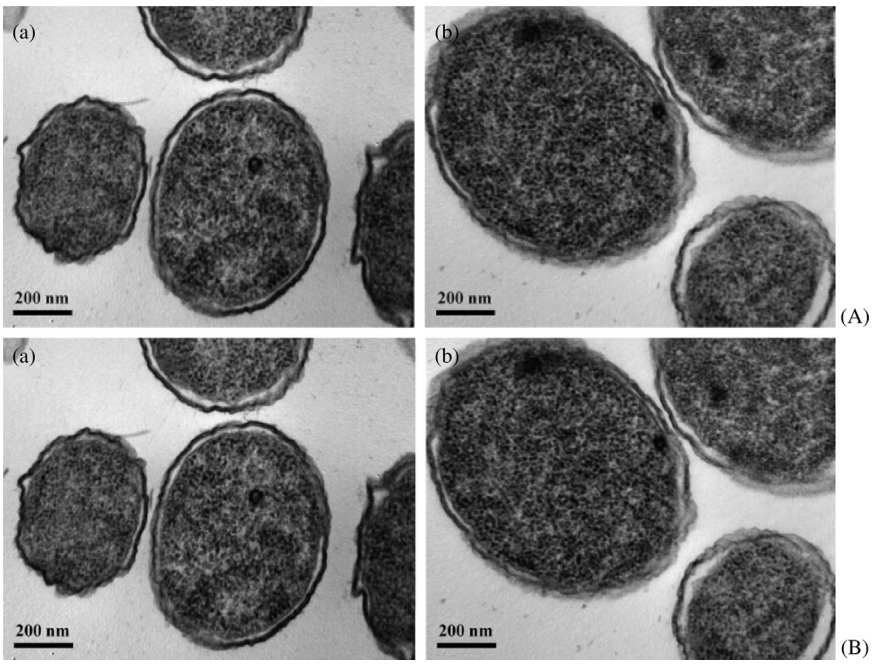

FIGURE 24.3

Comparison of damage induced by UV-C irradiation in *Salmonella* Typhimurium (A) and *Escherichia coli* O157:H7 (B) cells, observed by transmission electron microscopy. (a) Control sample and (b) UV-treated sample.

Taken from Ha J.-W., Kang D.-H., 2013. Simultaneous near-infrared radiant heating and UV radiation for inactivating Escherichia coli O157:H7 and Salmonella enterica serovar Typhimurium in powdered red pepper (Capsicum annuum L.). Appl. Environ. Microbiol. 79, 6568–6575 (Ha and Kang, 2013).

environments, such as cold and warm temperatures, low a_W, low hydrostatic pressure, UV light, high salt concentrations, bacteriocins, preservatives, detergents, several dyes, and antibiotics. It is assumed that a brief exposure to a suboptimal environment triggers some cellular mechanisms that enable them to resist subsequent exposure to harsher treatment (Yousef and Juneja, 2003).

In recent years, stress adaptation by bacterial cells (and other microorganisms) has been viewed to be mediated through the synthesis of many types of shock proteins or stress proteins, some of which are specific for specific stress, whereas others are nonspecific and expressed against more than one stress. Stress proteins provide protection to structures that could be otherwise adversely affected by the stress, such as DNA and many enzymes. Synthesis of stress proteins in large quantities is mediated through the expression of stress-related gene systems, some of which are inducible, whereas others are constitutive but expressed at a low level when cells are not under stress. As some of the gene systems are global, gene expression by one stress can also help cells to adapt to other related stresses (Ray and Bhunia, 2014).

The genome of the *L. monocytogenes* contains a number of stress response genes to allow for its survival under various environmental conditions, including low temperatures (Chan et al., 2007; Helmann et al., 2001), varying pH (Ferreira et al., 2001), and osmolarity (Seeliger and Jones, 1986). In the study performed by Uesugi et al. (2016) in order to determine the gene expression after UV-C treatment, a fluence of 33 mJ/cm^2 (120 s) for UV resulted in reductions of *L. monocytogenes* of 3.14 log CFU. Global gene expression analysis was performed and it was seen that 39 genes from *L. monocytogenes* cells exposed to UV, representing 1.4% of the 2857 ORFs in the array, showed higher transcription levels (>1.5 fold change, adjusted $P<.05$) in early stationary phase cells grown at 37°C. No genes showed decreased transcription levels compared to untreated cells following UV-C treatment. Overall, the results showed that a number of *L. monocytogenes* genes were differentially expressed following exposure to UV. UV-C treated cells showed increased transcription levels of lmo0609 and *sigL* (lmo2461). For UV-C treated cells, lmo0609, whose function is similar to an *E. coli* phage shock protein, showed increased transcription (Uesugi et al., 2016). The phage shock protein operon is usually induced by phage infection, heat, osmotic stress, and ethanol (Model et al., 1997); therefore, its upregulation after exposure to UV-C is expected. The gene *sigL* (lmo2461), which showed increased levels after UV-C exposure, is induced by a variety of stresses, such as low temperatures, organic acids, and high osmolarity (Raimann et al., 2009). The "dark repair" genes, *uvrA* (lmo2488), *uvrB* (lmo2489), and *uvrC* (lmo1234) did not show increased transcription. Also, there was no increase in *recA* (lmo1398), the major regulator of the SOS response involved in DNA repair and the resuming of replications that have stalled (Maul and Sutton, 2005). Expression of photolyase (lmo0588), an indicator for light repair of damaged DNA (Snyder and Champness, 2007), did not increase either, but this was expected because cells were kept under dark conditions following treatment. The mode of action for UV-C light is DNA damage, and thus it would have been expected that the DNA damage and stress-response-related genes would be upregulated and UV fluence used in the study performed by Uesugi et al. (2016) was insufficient to cause the upregulation of these genes in the majority of the microbial population, and therefore in gene expression a significant change could not be detected. The flagellin gene *flaA* (lmo0690) showed upregulation following exposure to UV-C. Flagella production is usually regulated by temperature, and at 37°C there is little motility and flagella in *L. monocytogenes* (Way et al., 2004). *L. monocytogenes* shows maximum transcription of *flaA* when grown at 22°C (Peel et al., 1988). The increased transcription in flaA after 120 s exposure to UV-C was likely in response to the long exposure time in UV-C

(Uesugi et al., 2016). At ambient temperature, the longer time may result in the upregulation of flagellar motility genes that also has been reported by Grundling et al. (2004).

The bacterial cell wall is a complex structure that provides the first defense of the cell to the environment and potential stresses; in the case of pathogens, it also has components that aid in pathogenesis and host cell invasion. UV-C treatments also increased regulation of other cell membrane proteins such as alkaline phosphatase (lmo1870) and a cation efflux transport protein (lmo2575) (Uesugi et al., 2016). These surface-induced proteins are involved in signaling and interacting with the external environment. Efflux pumps often remove toxins from the cell and the other proteins can provide feedback to external factors that *L. monocytogenes* may encounter. An exonuclease (lmo1881) and an RNase (lmo1880) were upregulated following exposure to UV-C, which indicates the need to catabolize the RNA that was generated as a stress response system, or that the single-stranded DNA that was damaged needed to be degraded (Uesugi et al., 2016). Numerous stress response, transcription/translation, motility, cell membrane genes, genes related to carbohydrate, amino acid, and nucleic acid metabolic pathways were upregulated following exposure to UV-C.

In the case of O157:H7, there are only a few studies that evaluate the UV-C effectiveness against this foodborne pathogen (Donahue et al., 2004; Gabriel, 2012; Gabriel and Nakano, 2009; Gayán et al., 2011; Koutchma et al., 2004; Ngadi et al., 2003; Oteiza et al., 2010). The UV-C efficacy for food decontamination was frequently determined against the nonpathogenic *E. coli* strains such as *E. coli* ATCC 25253 (Koutchma and Parisi, 2004), *E. coli* ATCC 25922 (Donahue et al., 2004; Murakami et al., 2006), *E. coli* ATCC 11229 (Schenk et al., 2011), *E. coli* ATCC 8739 (Ngadi et al., 2003), and *E. coli* ATCC 11775 (Guerrero-Beltrán and Barbosa-Cánovas, 2005). However it is necessary to emphasize that UV-C resistance varies among the microorganisms (Chevrefils et al., 2006; Hijnen et al., 2006) and depends on wavelength. Due to the differences in UV-C doses required to achieve 5-$\log_{10}$ reduction of nonpathogenic and pathogenic strains, the safety of food products as well as ensurance of proper safety margins can be affected. Therefore, it is crucial to identify and verify the nonpathogenic surrogate organism whose response to the processing conditions resembles the pathogen of concern.

24.6 UV-C LIGHT DAMAGE REPAIR MECHANISM

To cope with DNA damage, microorganisms have developed different DNA repair mechanisms that include photorepair or photoreactivation and light-independent or dark repair systems (Sinha and Häder, 2002). Photorepair ability, which consists of reversing DNA lesions by photolyase enzymes using the energy of visible light, is the most studied pathway due to its importance in the UV disinfection of water (Hallmich and Gehr, 2010). Microorganisms have evolved with photoreactivation and dark repair mechanisms, when subjected to near UV or visible light wavelength and dark conditions, respectively (Drakopoulou et al., 2009; Hallmich and Gehr 2010; Quek and Hu, 2008; Shang et al., 2009). These repair pathways reverse the UV damage to the DNA by repairing the pyrimidine dimers (Fig. 24.4) (Lindenauer and Darby, 1994; Quek and Hu, 2008). DNA is reactivated by the photolyase enzyme with direct repair of T<>T lesions. It binds to the damaged DNA site, absorbs a (near UV-visible) photon, restores the pyrimidines to their monomeric forms, and dissociates from the substrate. In all three kingdoms of life this repair mechanism is found, but not in humans.

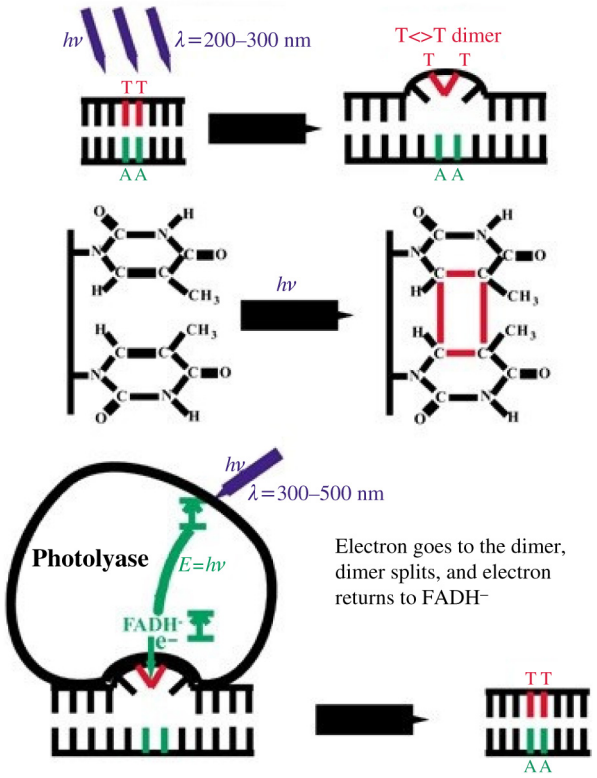

FIGURE 24.4

Photorepair of pyrimidine dimer formed in DNA molecule during UV irradiation.

Source: http://stuchebrukhov.ucdavis.edu/DNA_Repair/photolyase_prior1.html.

Because photoreactivation increases the possibility that microorganisms might regain viability after UV-C light treatment, food safety concerns are raised. Photoreactivation of fecal coliforms and *E. coli* has been reported (Hallmich and Gehr, 2010; Sommer et al., 2000; Tosa and Hirata, 1999; Zimmer and Slawson, 2002). Hu et al. (2012) found that *S.* Typhimurium, *Shigella dysenteriae*, and *E. coli* are able to photoreactivate after UV-C treatment, however Kuo et al. (1997) did not notice photoreactivation of *S.* Typhimurium on shell eggs.

Damage to nucleic acids does not totally kill the cells, which are unable to replicate but they still have metabolism and other cell functions. Some of the damages to nucleic acids can be repaired by enzyme mechanisms within the cell. Therefore, microorganisms can repair themselves using either a light repair mechanism called photoreactivation, or a dark repair mechanism. After reactivation, microorganisms are again able to cause illnesses. Consequently, the UV-C treatment has to provide enough dosage of UV light to ensure that nucleic acids are damaged beyond the stage where they can be repaired (Koutchma et al., 2009; Kim et al., 2002; Turtoi and Borda, 2013).

24.7 UV-C LIGHT APPLICATIONS IN THE FOOD INDUSTRY

The application of UV-C light with germicidal effects has been used in three areas: air disinfection, inactivation or elimination of microorganisms on surfaces (food contact surfaces, sanitization of conveyer surfaces, and packaging materials), and in liquids. In the food industry, UV-C irradiation has been mainly applied in various processes and products to reduce the microbial load such as air disinfection in meat or vegetable processing, on the water that will be used in some stages of the process, on surfaces of fresh products, chicken, fish, eggs, and various liquid foods: milk, fruit juice, or cider (Basaran et al., 2004; Bintsis et al., 2000; Duffy et al., 2000; Guerrero-Beltrán and Barbosa-Cánovas, 2004; Hadjok et al., 2008; Liltved and Landfald, 2000; Matak et al., 2005; Quintero-Ramos et al., 2004; Tran and Farid, 2004; Wong et al., 1998). UV-C light has been approved by the USFDA as an intervention technology to decontaminate food contact surfaces, and surfaces of water and liquid foods (21CFR110.40).

24.7.1 AIR DISINFECTION

UV-C as a germicidal agent for the decontamination of the air is a method that has been known and used for decades. Several studies have been conducted on various microorganisms present in the air, such as bacteria, viruses, bacterial and fungal spores (Bailey et al., 1996; Jensen, 1964; Xu et al., 2003.). The microorganisms are more sensitive to UV-C if they are suspended in the air than in water, and also they are more sensitive to those found in fruit juices (Bintsis et al., 2000). Jensen (1964) irradiated aerosolized viruses by passing them through an aluminum cylindrical tube with a highly reflective inner surface whose center contained a UV lamp, achieving, in the most favorable conditions, of more than 99.9% inactivation for Coxsackie, Influenza, Sindbis, and Vaccinia viruses. Xu et al. (2003) evaluated the effectiveness of UV-C radiation on bacterial spores and vegetative mycobacteria cells. UV-C treatment reduced between 46% and 80% the concentration of *B. subtilis* spores, and between 83% and 98% the *Mycobacterim parafortuitum* spores. Josset et al. (2007) designed a new photoreactor to decontaminate high-speed airflow through UV-A radiation. A 93% inactivation rate was obtained in a single pass through the photoreactor with airflow of 5 m^3/h in air with a concentration of 1.2×10^6 CFU/L of *Legionella pneumophila*.

24.7.2 APPLICATION TO SURFACE DISINFECTION

The main application of UV irradiation in industry is the sterilization of food contact surfaces, packaging materials such as containers, boxes, cartons, wrappers, bottle caps, or bottle tops, and aseptic packaging materials of products treated by ultra-high temperature such as the lids of aluminum bottles and cartons for liquids (e.g., milk) (Bintsis et al., 2000; Cook et al., 2016; Kuse, 1982; Nicolas, 1995; Manzocco and Nicoli, 2015; Otto et al., 2011). Aseptic processing and packaging materials can also be sterilized by combining the treatments with antimicrobials, e.g., hydrogen peroxide (H_2O_2) and UV-C radiation, taking advantage of their synergistic effects on bacterial spore destruction (Marquis and Baldeck, 2007). An ozone and UV-C combination is often used in the treatment of polymer plastics for food packaging (Ozen and Floros, 2001).

UV-C has also been used for the treatment of food surfaces. Thus, there are several papers in the literature demonstrating the effectiveness of UV-C irradiation to reduce the surface population of pathogenic microorganisms in red meat, chicken, fish, fresh-cut or whole fruits and vegetables, and also to increase their shelf life (Baka et al., 1999; Huang and Toledo, 1982; Liu et al., 1993; Marquenie et al., 2002; Mercier et al., 2001; Nigro et al., 2000; Pan et al., 2004; Stermer et al., 1987; Sumner et al., 1995; Artés et al., 2009). In a study conducted on pork skin and muscle, the effectiveness of UV-C light to reduce *E. coli* and *S.* Senftenberg in pig skin and muscle surfaces was evaluated, and UV-C light was found to be more effective on *S.* Senftenberg than on *E. coli*, and its effects were faster on skin than on pork muscle (Wong et al., 1998). Dejenane et al. (2001) found that UV-C treatment of fresh meat may increase commercial shelf life from 12 to 28 days. The application of UV-C light reduced *S.* Typhimurium, *L. monocytogenes*, and *Campylobacter jejuni* in chicken, chicken breast fillets, and ready-to-eat foods such as ham slices, as well as their microbial load (Chun et al., 2009, 2010; Lyon et al., 2007; Wallner-Pendleton et al., 1994).

UV-C light has been proposed for the surface decontamination of fresh-cut fruit and vegetables as a result of some in vivo and in vitro studies performed (Allende and Artés, 2003a,b; Artés et al., 2009; Marquenie et al., 2002). *L. monocytogenes* and *S. enterica* were inhibited with doses of 2.4 kJ/m^2 for a storage time of 13 days at 5°C under in vitro conditions (Artés et al., 2009). Allende et al. (2006) used two-sided UV-C light at 1.18, 2.37, or 7.11 kJ/m^2 and showed that natural microflora of fresh-cut "Red Oak Leaf" lettuce reduced effectively with a 10-day shelf life at 5°C. Similar results have also been found for one-sided UV-C-treated fresh-cut "Red Oak Leaf" and "Lollo rosso" lettuces (Allende and Artés, 2003a,b). However, the studies performed showed that more research is needed to optimize the use of UV-C for surface disinfection or decontamination.

24.7.3 UV-C LIGHT APPLICATION FOR LIQUIDS

In 1910 in Marseille, the first application of UV irradiation for drinking water disinfection was carried out, although at that time its use was limited by its high cost, the low reliability of the equipment, and the advent of chlorination, which was a cheaper, more reliable method, and had the ability to measure the residual disinfectant (Henry et al., 1910; Hoyer, 2004; Wolfe, 1990). Since then, UV irradiation has been gaining interest and since the 1980s, in Europe, it has been widely used to disinfect drinking water, replacing chlorination (Downey et al., 1998; Gibbs, 2000; Lodge et al., 1996; Qualls and Johnson, 1983). The increase in the use of UV light technology is mainly due to the fact that it does not produce oxidation products, as happens with the use of chlorine or ozone. Besides, the high efficacy of UV irradiation against main pathogens affecting drinking water safety namely *Cryptosporidium* and *Giardia* resulted in its use as a primary disinfection process (Clancy et al., 1998). There are several works in the literature that study the disinfection of both drinking and wastewater by UV irradiation (Chang et al., 1985; Hijnen et al., 2006; Liltved and Cripps, 1999; Sommer et al., 2000; Sutton et al., 2000; Whitby and Palmateer, 1993). UV radiation has proved to be effective in treating high-quality secondary and tertiary effluents (Blatchley et al., 1996; Braunstein et al., 1996; Oppenheimer et al., 1997).

In the brewing and beverage industry many producers have adopted UV irradiation as a water-disinfection system, because the treatment does not alter the taste and quality of the final product (Egberts, 1990; Greig and Warne, 1992; Oliver et al., 1990). The radiation dose required for

treatment of water in the brewing industry is much higher than the dose necessary in drinking water treatment, because it should guarantee the absence of any microbial alteration during the early stages of beer production. Lu et al. (2010a,b) applied a thin-film apparatus with quartz optical fibers for UV-C treatment in order to inactivate bacteria in beer. In the study, a 5-log reduction of inoculated *S. cerevisiae* and *Lactobacillus brevis* in beer and from $\sim 10^4$ CFU/mL to nondetectable limits at doses of 16.1 and 9.7 mJ/cm^2, respectively, was obtained. However, the inactivation of *S. cerevisiae* was not so efficient and also, the beneficial yeasts of beer were hardly inactivated.

In liquid egg derivatives, UV-C irradiation may be an alternative treatment to obtain a microbiologically safe and stable product, avoiding alterations of other methods to product properties due to protein denaturation (Bintsis et al., 2000; Donahue et al., 2004; Unluturk et al., 2008). In a study carried out by Ngadi et al. (2003), a decrease from 10^8 to $10^{3.8}$ CFU/mL in microorganisms was demonstrated after an exposure to a UV radiation dose of 300 mJ/cm^2 in liquid egg white (pH 9.1) inoculated with *E. coli* O157:H7. In a study on liquid egg products in which the effect of UV irradiation on nonpathogenic strains of *E. coli* (ATCC 8739) and *S.* Typhimurium, and also the effect of the liquid medium depth, the UV light intensity and the exposure time were investigated, the authors obtained more than 2-log maximum reduction of *E. coli* in liquid egg white with a medium depth of 0.153 cm and a UV intensity of 1314 mW/cm^2 (Unluturk et al., 2008). However, in liquid egg yolk and in liquid whole egg after UV-C treatment under the same conditions, maximum reductions were found to be 0.675 and 0.361 log, respectively.

UV irradiation has also been applied successfully in the pasteurization of liquid foods such as milk and fruit juices (Koutchma et al., 2004; Matak et al., 2005; Milly et al., 2007). Milly et al. (2007) obtained a 3-log reduction of *E. coli* 25922 in skim milk. The total microbial load and coliforms, also *L. monocytogenes* of raw milk, goat milk, and brines used in the production of Mozzarella cheese, was lowered (with a dose of 15.8 mJ/cm^2 more than 5 log units) significantly by using UV-C irradiation (Anonymous, 1994; Lodi et al., 1996; Matak et al., 2007). The effects of UV-C irradiation on quality improvement and shelf life extension of many liquid fruit products have been studied, namely apple, orange, grape (white or red), pineapple, pummelo (*Citrus grandis* (L.) Osbeck), starfruit, watermelon, pomegranate and lemon−melon mix juices, apple cider, mango nectar (Caminiti et al., 2012a,b; Chia et al., 2012; Bhat et al., 2011; Choi and Nielsen, 2005; Donahue et al., 2004; Falguera et al., 2011b; Fan and Geveke, 2007; Feng et al., 2013; Goh et al., 2012; Guerrero-Beltrán et al., 2009; Kaya and Unluturk, 2015; Kaya et al., 2015; Koutchma et al., 2009; Mansor et al., 2014; Müller et al., 2011, 2014; Noci et al., 2008; Orlowska et al., 2014; Pala and Toklucu, 2013a,b; Tandon et al., 2002; Tran and Farid, 2004; Shah et al., 2015; Shamsudin et al., 2013, 2014; Zhang et al., 2011).

24.8 UV-C LIGHT APPLICATION FOR FRUIT JUICES

The germicidal effects of UV-C irradiation on different organisms have also been studied in juices and fruit products (Anonymous, 1999; Basaran et al., 2004; Franz et al., 2009; Gabriel and Nakano, 2009; Guerrero-Beltrán and Barbosa-Cánovas, 2005; Keyser et al., 2008; Baysal et al., 2013; Tran and Farid, 2004; Worobo, 1999). Milly et al. (2007) achieved 4.5-log inactivation of *E. coli* 25922

in apple juice. Worobo (1999) also managed to reduce more than 5 log of the population of *E. coli* in apple cider irradiated with UV light in a CiderSure 3500. UV-C light treatment of fresh apple cider resulted in 5-log inactivation of *E. coli* ATCC, a surrogate for *E. coli* O157:H7, in a CiderSure 3500 system (Duffy et al., 2000). In clarified apple juice, Keyser et al. (2008) were able to reduce by more than 7 log units the population of *E. coli* with a radiation dose of 1377 J/L. As seen in Table 24.2, different strains of bacterial pathogens or their surrogates were used to evaluate the effects of UV-C light treatment inactivation on microorganisms in fruit, mostly in apple juice. In orange juices, when similar experiments were carried out, higher radiation doses were needed to obtain the same reductions due to the large amount of suspended matter (such as orange cells and fiber) serving as a protective barrier to microorganisms against UV-C light (Keyser et al., 2008).

Guerrero-Beltrán and Barbosa-Cánovas (2005) studied the reduction of *S. cerevisiae*, *E. coli*, and *L. innocua* populations after UV-C light treatment in apple juice; their results showed that at the higher treatment time and flow rate, greater damage or inactivation was obtained (Table 24.2). Among the bacterial pathogens, studies performed have shown that *S.* Typhimurium was the most sensitive to UV-C light with a *D*-value of 0.27 min, while *L. monocytogenes* AS-1 serovar 4b was the most resistant one with a *D*-value of 1.26 min (Gabriel and Nakano, 2009).

Guerrero-Beltrán et al. (2009). processed grape, cranberry, and grapefruit pasteurized juices inoculated with *S. cerevisiae*, using a UV-C disinfection unit and working at different flow rates and doses of UV light (75−450 kJ/m^2). The inactivation of *S. cerevisiae* can be described by means of first-order kinetics, obtaining times of decimal reduction ranging from 61.7 to 113.7, 12.2 to 40.7, and 12.5 to 20.7 min for grape, cranberry, and grapefruit juices, respectively. The maximum reductions were 0.53, 2.51 and 2.42 log for yeast count in grape, cranberry, and grapefruit juices, respectively, at a flow rate of 1.02 L/min after 30 min of treatment.

In many studies, scientists used nonpathogenic surrogates (*E. coli* ATCC 25922 and *L. innocua*) with the same UV-C sensitivity or resistance of the pathogens such as *E. coli* O157:H7 and *L. monocytogenes* to determine the effectiveness of UV-C treatments in liquid foods, and also in fruit juices (Table 24.1). However, Guerrero-Beltrán and Barbosa-Cánovas (2005) used *E. coli* ATCC 11775 and *L. innocua* ATCC 51742 as surrogates for *E. coli* O157:H7 and *L. monocytogenes*, respectively. Ye et al. (2007) proposed to measure the inactivation kinetics of *Y. pseudotuberculosis*, a surrogate of *Yersinia pestis* to characterize the resistance of the *Yersinia* species to UV-C treatment using a single-lamp annular UV-C system.

The UV-C efficacy for fruit juice decontamination was frequently determined against the nonpathogenic or non-O157 STEC *E. coli* strains such as ATCC 25922, 25253, 11775, 11229, and 8739 (Char et al., 2010; Donahue et al., 2004; Guerrero-Beltrán and Barbosa-Cánovas, 2005; Koutchma and Parisi, 2004; Milly et al., 2007; Murakami et al., 2006; Ngadi et al., 2003; Oteiza et al., 2005; Schenk et al., 2011). However, there are studies that evaluate the UV-C inactivation efficacies on pathogenic *E. coli* strains (Donahue et al., 2004; Gabriel, 2012; Gabriel and Colambo, 2016; Gabriel and Nakano, 2009; Gayán et al., 2011; Koutchma et al., 2004; Murakami et al., 2006; Ngadi et al., 2003; Orlowska et al., 2015; Oteiza et al., 2005, 2010; Yin et al., 2015; Yoo et al., 2015).

Surrogate organisms are inoculated into or onto food products that are subsequently sent through food processing equipment located in commercial food processing facilities. Because of the risks associated with introducing a pathogen into a food processing facility, it is preferred to

Table 24.2 UV-C Light[a] Inactivation of Microorganisms in Fruit Juices

Fruit Juice	Fruit Juice Properties	UV-C Light Treatment Conditions	Microorganism(s)	Inactivation Results	Reference
Apple juice	Fresh	30 W, 30 min	Natural microbial count	2.2 log	Noci et al. (2008)
Apple juice		1 mm liquid depth 300 mJ/cm^2	*E. coli* O157:H7	4.5 log	Ngadi et al. (2003)
Apple juice			*E. coli* 25922	4.5 log	Milly et al. (2007)
Apple juice	pH 3.47	0−6 J/cm^2 1-mm-thick film 0.1 J/cm^2	*E. coli* O157:H7 (EDL 933) *E. coli* ATCC 25922	5*D* reduction	Oteiza et al. (2005)
Apple juice	Clarified pH 3.68	15 W	*E. coli* K-12 *E. coli* O157:H7 *S.* Enteritidis *S.* Typhimurium *L. monocytogenes* AS-1 *L. monocytogenes* M24-1	$D = 0.55 \pm 0.09$ $D = 0.49 \pm 0.16$ $D = 0.61 \pm 0.04$ $D = 0.27 \pm 0.04$ $D = 1.26 \pm 0.17$ $D = 0.44 \pm 0.07$	Gabriel and Nakano (2009)
Apple juice	pH 3.68 12°Brix	1.5 min	*E. coli* O157:H7	$D = 2.64$−2.76 min	Gabriel (2012)
Apple juice		4−24 mJ/cm^2	*E. coli* O157:H7 (DHS1,ATCC35150, 960218, H3482)	0.406−0.551 log/(mJ/cm^2)	Murakami et al. (2006)
Apple juice	pH 3.5	Distance 13 cm Irradiance 1.26 ± 0.03 mW/cm^2 UV exposure times 0 s, 2 min, 5 min, 7 min, 10 min, 15 min, 20 min UV fluence: 54−514.32 mJ/cm^2	*E. coli* O157:H7 Nonpathogenic *E. coli* ATCC 25253, ATCC 25922, ATCC 11775, ATCC 8739, ATCC 11229, NAR, O157 Dm3Na (surrogate of pathogenic O157:H7) Non-O157 STEC strains (O111:NM, O26:H11, O145:NM, O103:H2)	398.42 ± 2.74 mJ/cm^2 103:H2 348.95 ± 27.18 ATCC 8739 *E. coli* ATCC 8739 recommended as a potential surrogate organism	Orlowska et al. (2015)
Apple juice	pH 3.5	$a = 23.70$ cm^{-1} 0.21 mW/cm^2 UV fluence: 24, 119, 357	*E. coli* O157:H7 EDL 933 (acid-resistant strain)	5, 25, 75 min	Yin et al. (2015)

(*Continued*)

Table 24.2 UV-C Light[a] Inactivation of Microorganisms in Fruit Juices *Continued*

Fruit Juice	Fruit Juice Properties	UV-C Light Treatment Conditions	Microorganism(s)	Inactivation Results	Reference
Apple juice	Pasteurized	8 LP mercury lamps 8×39 W = 312 W	*E. coli* K-12 (ATCC 25253)	3.8 log	Koutchma et al. (2004)
Apple juice		$a = 0.9$ mm^{-1} 12 LP mercury lamps 12×42 W = 504 W Turbulent conditions Flow rates: 32 L/min 75 L/min Almost seven passes	*E. coli* K-12 (ATCC 25253)	> 5 log	Koutchma et al. (2004)
Apple juice		2−100 mJ/cm^2 0.1−1.0 mm	*E. coli* K-12	0.055−0.215 log/(mJ/cm^2)	Murakami et al. (2006)
Apple juice		12, 15.4, 16 mW/cm^2	*E. coli* K-12 (ATCC 25253)	5.3 log	Ye et al. (2007)
Apple juice		1377 J/L	*E. coli* K-12	7.42 log	Keyser et al. (2008)
Apple juice	pH 3.75 Brix: 11.82 Acidity: 0.33	75−450 kJ/m^2 450 kJ/m^2, 30 min 0.548 L/min flow rate	*E. coli* ATTC11775 *Listeria innocua* ATCC 51742 *E. coli* ATTC11775 *Listeria innocua* ATCC 51742	$D = 6.0-17.7$ min $D = 8.2-20.6$ min 5.10 (± 1.12) log 4.29 (± 2.34) log First-order kinetic Log-linear model	Guerrero-Beltrán and Barbosa-Cánovas (2005)
Apple juice	pH 3.1 12°Brix	100 W, 20 min	*E. coli* ATCC 35218		Char et al. (2010)
Apple juice		12, 15.4, 16 mW/cm^2 Annular UV-C system	*Yersinia pseudotuberculosis* *Yersinia pestis* 1122	4.9 log 4.4 log after 6 h	Ye et al. (2007)
Apple juice	Reconstituted from concentrate	4 mm liquid depth 30-W UV light bulb 5−30 min, 20°C	*Staphylococcus aureus* SST 2.4	2.2 log	Walkling-Ribeiro et al. (2008)
Apple juice	pH 3.4 $a_w > 0.99$	$a = 22.1$ cm^{-1}, 5.4 NTU 27.1 J/mL, 8.5 L/h	*Cronobacter sakazakii* Four strains	2 log	Arroyo et al. (2012)

			CECT 858 (ATCC29544)	Linear with shoulder	
			NCTC8155 NCTC9238 NCTC9529	Log-linear regression plus shoulder model	
Apple juice		75−450 kJ/m^2	*Saccharomyces cerevisiae*	D = 23.1−40.5 min	Guerrero-Beltrán and Barbosa-Cánovas (2005)
Apple juice	Clear pH 3.68 12°Brix		Spoilage yeasts *Debaryomyces hansenii* *Clavispora lusitaniae* *Torulaspora delbrueckii* *Pichia fermentans* *Saccharomyces cerevisiae*	8.0 min D = 8.27 min D = 9.78 min D = 9.39 min D = 11.04 min D = 6.38 min	Gabriel (2012)
Apple juice	pH 3.2 10.5°Brix	0.34−13.44 W/m^2	*A. acidoterrestris* CCT 4384 spore	5-log reduction: 11.5 and 13.44 W/m^2, 8 min 0.34 W/m^2, 25 min D = 1.7 min, 13.44 W/m^2 D = 4.9 min, 0.34 W/m^2 First-order kinetics D_{ref}: 2.5 ± 0.5 min z: 30.8 ± 16.0 W/m^2, R^2: 0.86, Bigelow model	Tremarin et al. (2017)
Apple juice	pH 3.8 11°Brix 10 NTU	3.8, 7.1, and 13.1 W/m^2 3−15 min Juice depth: 0.15 cm a = 12 cm^{-1}	*A. acidoterrestris* spore DSM 3922	~2 log reduction 13.1 W/m^2 Log-linear + tail Log-linear plus tail model	Baysal et al. (2013)

(*Continued*)

Table 24.2 UV-C Light[a] Inactivation of Microorganisms in Fruit Juices *Continued*

Fruit Juice	Fruit Juice Properties	UV-C Light Treatment Conditions	Microorganism(s)	Inactivation Results	Reference
Grape juice (white)	pH 3.2	3.8, 7.1, and 13.1 W/m^2	*A. acidoterrestris* spore DSM 3922	5.5-log reduction 13.1 W/m^2	Baysal et al. (2013)
	16.6°Brix	3−15 min		Log-linear + tail	
	5.49 NTU	Juice depth: 0.15 cm		Weibull model	
		$a = 5.82$ cm^{-1}			
Orange juice	pH 3.5	100 W, 20 min	*E. coli* ATCC 35218	3.5 log CFU/mL	Char et al. (2010)
	9°Brix				
Orange juice	pH 3.53	0−6 J/cm^2	*E. coli* ATCC 25922	5*D* reduction	Oteiza et al. (2005)
		0.7-mm-thick film	*E. coli* O157:H7 (EDL 933)	0.55 J/cm^2	
Orange juice	pH 3.64	Absorption coefficient:	*E. coli* O157:H7	First-order kinetic	Oteiza et al. (2010)
	13.1°Brix	0.6371−0.8206		Log-linear model	
		RI: 1.38			
Orange juice	pH 3.64	Absorption coefficient:	Five strains *E. coli* O157:H7	Logistic model	Oteiza et al. (2010)
	13.1°Brix	0.6371−0.8206	Strain cocktail		
		RI: 1.38			
Orange juice	pH 3.58	4.5 log CFU/mL inoculum	*E. coli* O157:H7 NCTC 12079	R^2:0.9347	Yoo et al. (2015)
	14.72°Brix			RMSE: 0.0510	
				Biphasic model	
Orange juice	pH 3.1		*Salmonella enterica*	$D = 12.7$ s	Gabriel et al. (2016)
	11.5°Brix			$D_{UV\text{-}C} = 63.56$ mJ/cm^2	
	0.63 citric acid			First-order kinetic	
				Log-linear model	
Orange juice	pH 3.57	$a = 91.10$ cm^{-1}	*L. monocytogenes*	14.66−21.84 J/mL	Gayán et al. (2015)
		Turbidity: 4460	Five strains (STCC 932, 4301, 4302, 5366, 5672)	Dose needed to inactivate 99.99% of initial population	
Orange juice		1607 J/L	APC, YM	0.3 log, 0.3 log	Keyser et al. (2008)
		1377 J/L	APC, YM	0.89 log, 0.30 log	

Multifruit juice	pH 3.76	0–6 J/cm^2 0.7-mm-thick film	*E. coli* ATCC 25922 *E. coli* O157:H7 (EDL 933)	3 log 0.55 J/cm^2	Oteiza et al. (2005)
Pineapple juice		Dean Vortex UV-C system 13.75 mJ/cm^2 10.37 mJ/cm^2 10.10 mJ/cm^2	*Salmonella* Typhimurium TISTR292	5 $\log_{10}$ CFU/mL 3.99 $\log_{10}$ CFU/mL 3.89 $\log_{10}$ CFU/mL Nonlinear curve	Mansor et al. (2014)
Pummelo fruit juice	pH 3.99 14.17°Brix	Turbidity: 47.73 NTU $a = 17$ cm^{-1} $a = 21$ cm^{-1}	*Salmonella* Typhimurium E292	8.55 $\log_{10}$ 5.64 $\log_{10}$	Shah et al. (2014)
Coconut juice[b]	pH 5.8 6.1°Brix	UV absorbance: 0.9 UV transmittance: 1.08	*L. monocytogenes* *E. coli* O157:H7 *Salmonella enterica*	$D = 3.19–3.76$ s $D_{UV\text{-}C} = 8.28–9.78$ mJ/cm^2	Gabriel and Colambo (2016)
Guava-pineapple juice		1377 J/L	APC YM	3.31 log CFU/mL 4.48 log CFU/mL	Keyser et al. (2008)
Tropical juice		1607 J/L	APC YM	0.59 log 0.72 log	Keyser et al. (2008)
Strawberry nectar		2065.5 J/L	APC YM	1.32 log CFU/ml 2.45 log CFU/mL	Keyser et al. (2008)
Mango nectar		1377 J/L	APC YM	1.4 log CFU/mL 2.8 log CFU/mL	Keyser et al. (2008)
Carrot juice		Flow rates 0.5–7.9 mL/s 5–30 min Dosages of 13.2, 26.4, 39.6, 52.8, and 79.2 J/cm^2	Mesophiles Coliforms	3.2 ± 0.1 log 2.6 ± 0.1 log	Hernández-Carranza et al. (2016)

[a] $\lambda = 254$ nm.
[b] Coconut endosperm liquid.

use a nonpathogenic surrogate organism that has been adequately characterized. Surrogate microorganisms are harmless microorganisms which have similar resistance properties to pathogenic or spoilage organisms and can be used as substitutes for testing (e.g., food process trials, effects of preservatives). Use of surrogates instead of the pathogens is the most scientific means of obtaining data to validate the inactivation efficacy of the UV-C treatments; however, it would be necessary to include additional researches to identify specific pathogen surrogates and indicators for each fruit juice and fruit juice mix.

It has been shown that UV-C treatment efficacy can be increased by the use of a combination of the other methods. Walkling-Ribeiro et al. (2008) treated apple juice inoculated with *S. aureus* TSS 2.4 and obtained 2.2-log reduction by UV-C treatment; however, with a combined method of UV irradiation, preheating, and high-intensity pulsed electric fields, the microbial population was reduced by 9.5 log units. Moreover, Char et al. (2010) reported that application of ultrasound (US) at 20 kHz and 95 μm in combination with UV-C light (253.7 nm, 100 W, 20 min) resulted in 3.5-log reduction of *E. coli* ATCC 35218 in orange juice. This study proved that an additional 1.5 log of reduction followed by US treatment had a synergistic effect, although the mechanism of action of these combined treatment effects is still is unknown.

Studies have shown the advantages of using UV-C light with regard to nutrient retention and storage stability and the many factors for efficient UV-C treatment including: transmissivity of the fruit juice, design of the UV-C light system, power, wavelength and physical arrangement of the UV-C sources, product profile, and radiation path length.

24.9 UV-C INACTIVATION KINETICS OF PATHOGENS

UV-C dose is the product of UV intensity or fluence rate I (e.g., in mW/cm^2) and exposure time t (s). Thus, the microbial reduction rate is related to the applied UV-C dose (in mWs/cm^2 or mJ/cm^2). When any product is irradiated, it is important to define the radiation dose that it receives. This dose depends on the incident radiation, expressed as the amount of radiation received per unit of time and area or flux intensity (Dr, in W/m^2), so that the dose corresponds to the product of this one by exposure time (Bintsis et al., 2000; Guerrero-Beltrán and Barbosa-Cánovas, 2004). In continuous processes, exposure time coincides with the time of residence. From this equation it can be deduced that radiation dose has units of J/m^2. When UV-C irradiation is used to inactivate microorganisms, some authors (Guerrero-Beltrán and Barbosa-Cánovas, 2004; Stermer et al., 1987) consider that the inactivation kinetics is first order. In general, microbial inactivation kinetics obtained can be linear, concave downward (with a shoulder), concave upward (with a tail), and sigmoidal. The UV-C resistance value (death or inactivation kinetics) of bacterial strains is characterized in terms of UV-C decimal reduction dose, D-value, which is equivalent to the UV fluence necessary to reduce the initial population of the challenge test or surrogate bacteria by 1 log unit. The D-value is determined from the negative reciprocal of the slopes of the survivor curves ($\log_{10}$ (N/N_0) vs UV fluence), using the linear portions of the plots. The UV-C decimal reduction dose can be described by the following formula where k is the inactivation rate constant.

$$D = \frac{2.303}{k}$$

24.10 USE OF MATHEMATICAL MODELING FOR ASSESSING UV-C INACTIVATION OF PATHOGENS

First-order kinetics is used to describe the microbial inactivation when heat treatment is applied. The inactivation curve, i.e., survival curve, is linear and the model is based on the first-order kinetics called the first-order or log-linear model. First-order kinetics or log-linear model with the following equation:

$$\log S(t) = -kt = -\frac{t}{D}$$

where k as the rate constant (s or min) and D as the decimal reduction time ($1/k$) are useful in thermal treatment inactivation modeling, but for many inactivation curves which are not nonlinear they become invalid.

Many models have been developed to describe the nonlinear bacterial inactivation curves, of which of the most convenient and flexible is the Weibull distribution (van Boekel, 2002; Peleg, 1999). The model has been successfully used to describe bacterial inactivation kinetics of both thermal and nonthermal treatments (Álvarez et al., 2003; Buzrul et al., 2008; Chen, 2007; Jagannath et al., 2005; San Martin et al., 2007; Ugarte-Romero et al., 2006). The Weibull model equation is as follows:

$$\log S(t) = -\frac{1}{2.303}\left(\frac{t}{\alpha}\right)^{\beta}$$

where α is the scale parameter characteristic time (s), and β is the shape parameter (unitless). β gives the direction of the concavity by indicating whether the death rate is increasing, constant, or decreasing with treatment time. The inactivation curve can be concave downward. A smallerα, at a constant value of β indicates a higher amount of inactivation at a specific treatment time (Keklik et al., 2012). D- and z-values developed by Bigelow, Ball, and Stumbo (Stumbo, 1973) are based on the first-order kinetics. The reliable life (t_R) is analogous to the D-value and defined as the time required to achieve 1 $\log_{10}$ reduction in microbial population (van Boekel, 2002). For the Weibull equation model, the t_R is as follows:

$$t_R = \alpha(2.303)^{1/\beta}$$

Mathematical models can be useful tools to help estimate the UV-C inactivation of bacterial pathogens in fruit juices or nectars. In UV-C inactivation studies, experimental data is fitted with the following nine models: log-linear + shoulder, log-linear + tail, log-linear + shoulder + tail, Weibull, Weibull with fixed parameter p, Weibull + tail, double Weibull, biphasic model, biphasic + shoulder, and biphasic + tail. Shoulder effect suggests initial resistance to stress, while tailing effect can suggest varying levels of resistance, for instance due to mixed populations, clumping, or protective effects of the suspension medium (Albert and Mafart, 2005).

Convex and concave curve shapes are explained as the existence of a (Weibull-type) distribution of sensitivities within the overall population (Van Boekel, 2002). In convex curves, surviving cells become more damaged with increasing exposure time and, as such, the inactivation rate increases. For concave curves, on the other hand, first the most sensitive subpopulation is eliminated followed by increasing weakening and, consequently, elimination of the more resistant subpopulation (Peleg, 2000). Biphasic behavior is (classically) explained as the existence of two subpopulations within the overall *L. innocua* population, of which the first fraction is more sensitive and the second shows more

resistance to the inactivating factor (i.e., the slope of descent phase 1 is higher than the slope of descent phase 2) (Cerf, 1977). Increased variance in the bacterial response to less favorable conditions has been widely reported in the literature (McClure et al., 1994). This nonhomogeneous response of microbial populations to stress conditions is explained by differences in cell age, different states in the cell cycle, or variations in the concentrations of transcription factors (Brul et al., 2003).

The UV inactivation kinetics of bacteria are described using models available in the GInaFiT version 1.6 (Geeraerd and Van Impe Inactivation Model Fitting Tool), a freeware Add-inn for Microsoft Excel 2010 and 2007 (Geeraerd et al., 2005, 2006), downloadable via the KULeuven/BioTeC-homepage (http://cit.kuleuven.be/biotec/) at the topic "Downloads." GInaFiT covers log-linear curves; log-linear curves with an initial shoulder; log-linear curves with a final tailing; curves with both shoulder and tail; concave and convex curves (Weibullian-like functions); convex/concave curves with a final tailing; biphasic inactivation kinetic with and without a shoulder; curves with a double convex/concave shape. The significance of the models and parameters is pointed out by the sum of squared error, the (root) mean sum of squared error (RMSE), R^2, and adjusted R^2. In addition, the software gives the time needed for a 4-$\log_{10}$ reduction (t_{4D}) of the microbial population. The RMSE quantifies the goodness of fit for both linear and nonlinear models via the difference between predicted and observed values. Best fit indicates when this value is close to zero.

Crook et al. (2015) evaluated the effect of UV-C light on the inactivation of seven milkborne pathogens (*L. monocytogenes, Serratia marcescens, S.* Senftenberg*, Yersinia enterocolitica, Aeromonas hydrophila, E. coli*, and *S. aureus*). The pathogens were suspended in ultra-high-temperature whole milk and treated at UV-C doses between 0 and 5000 J/L at a flow rate of 4300 L/h in a thin-film turbulent flow-through pilot system. Of the seven milkborne pathogens tested, *L. monocytogenes* was the most UV-C resistant, requiring 2000 J/L of UV-C exposure to reach a 5-log reduction. The most sensitive bacterium was *S. aureus*, requiring only 1450 J/L to reach a 5-log reduction. This study demonstrated that the survival curves were nonlinear. Sigmoidal inactivation curves were observed for all tested bacterial strains. Nonlinear modeling of the inactivation data was a better fit than the traditional log-linear approach (Crook et al., 2015).

As seen in Table 24.2, the magnitude of microbial inactivation is in line with the findings of the studies working with fruit juices as treatment medium. Different strains of bacterial pathogens have different characteristics, such as *D*-values or inactivation rates. The diversity of these characteristics for strains potentially found in fruit juice or nectars and those used to develop the model must be considered. Models created in broth systems provide an estimate of expected behavior at specified parameters, intrinsic (acidities, pH, °Brix, soluble solid content, color, etc.) and extrinsic (temperature, dosage, etc.) conditions. Models created in broth may not include additional factors relevant to the specific fruit juice of interest. Often models are created using pure cultures; however, competition by the spoilage flora may be an additional factor affecting the inactivation rate or UV-C efficacy.

24.11 FACTORS AFFECTING RESISTANCE OF PATHOGENS TO UV-C LIGHT AND ITS EFFICIENCY

24.11.1 INTRINSIC FACTORS

Intrinsic properties can be classified as treatment medium properties (pH, a_w, °Brix, acidities, soluble solid content, components or composition, suspended particles, opacity, absorptivity,

transmittance, viscosity, turbidity, color, etc.) and level and ratio of indigenous or natural flora of treatment medium in the case of freshly prepared juices and properties of the test microorganisms or surrogates used.

Absorption coefficients of apple juice ($26\ cm^{-1}$), orange ($48\ cm^{-1}$), guava ($46\ cm^{-1}$), carrot ($53\ cm^{-1}$), and pineapple ($73\ cm^{-1}$) for 254 nm UV-C radiation were given by Koutchma et al. (2009), and show that the differences in absorbing properties between the juices affect microbial inactivation by limiting the penetration depth of UV light. Absorbance, transmissivity, turbidity, and particle sizes which are present in the juices can reduce the efficiency of the UV-C light due to shadowing and/or scattering of the UV-C light. One of the main limitations of UV-C treatment of liquids is its low penetration, which is determined by the characteristics of the irradiated liquid. The penetration depth at a given wavelength depends on the absorption spectrum of the UV-C-treated liquid. Thus, in distilled water, the loss of radiation intensity at 40 cm from the surface is up to 30%, while in a 10% sucrose solution the same intensity loss can be achieved at only 5 cm (Snowball and Hornsey, 1988). However, in fruit juices, 90% of UV-C light is absorbed in the first 1 mm from the surface (Sizer and Balasubramaniam, 1999).

The presence of dissolved organic solutes and compounds in liquid foods such as fruit juices or nectars leads to strong UV-C attenuation effects. Fan and Geveke (2007) determined UV-C absorbance of sugars (fructose, sucrose, glucose) and organic acids (mainly malic acid, low amount of ascorbic acid) which are that the major components of apple juice. It was shown that all three sugars had high absorbance around 200 nm and sugars absorbed little UV-C in the range of 240−360 nm. The fructose solution had higher UV-C absorbance at 260−280 nm than glucose and sucrose solutions. Malic acid mainly absorbed UV at wavelengths less than 240 nm, while ascorbic acid had a strong absorbance between 220 and 300 nm even at a very low concentration (0.001%). The presence of suspended particles or solids, which increase the survival probability of microorganisms exposed to UV-C radiation, can attenuate the UV-C dose via light scattering and may also provide a site for the aggregation of bacteria to the particle's surface (Koutchma, 2009). Although the treatment of opaque liquid foods by UV irradiation is an additional problem, transmittivity can be increased by optimizing the number of lamps, residence time in the UV-C system, and the type of the flow. In the studies performed, the effect of fruit juice pH on microbial inactivation resistance was shown using different pathogens or surrogates.

It should be noted that morphological and physiological differences of the bacterial cells could account for the different susceptibilities to UV-C treatments. Also, most of the UV-C treatment systems or equipments and environmental conditions were dissimilar in the studies performed with each bacterial pathogen or pathogen surrogate. Therefore direct comparison of the literature data cannot be made. Models created in broth systems provide an estimate of expected behavior at specified parameters, intrinsic (acidities, pH, °Brix, soluble solid content, color, etc.) and extrinsic (temperature, dosage, etc.) conditions; however, models created in broth may not include additional factors relevant to the specific fruit juice of interest.

24.11.2 EXTRINSIC FACTORS

Extrinsic factors are the environmental factors such as environmental stresses, UV-C treatment parameters, dose (exposure and residence time), photon energy at a given wavelength, UV dose distribution inside the system, temperature (possible increase in temperature), stirring, working volume, thickness of liquid, flow rate, and exposure to dark or light conditions (repair mechanism).

Characteristics (physicochemical) of the UV-C treatment medium also affect the bactericidal efficacy of UV-C treatments, because UV-C transmittance of a liquid mainly depends on the absorptivity of the medium and the present amount of suspended solids which scatter UV photons. Additional critical factors are the reactor and the treatment temperature (Gayán et al., 2015; Koutchma et al., 2004, 2009).

Wright et al. (2000) used an array of 10 chambers at selected flow rate and dose to treat apple cider inoculated with five strains of *E. coli* O157:H7, and obtained only 3-log reduction, which is not enough to achieve the 5-log reduction recommended by the USFDA (1997a,b). Farid et al. (2001) treated orange juice by UV-C and found that the shelf life of treated juice doubled without any change in color or flavor. Also, Guerrero-Beltrán et al. (2009) have treated grape, grapefruit, cranberry juices, and mango nectar inoculated with *S. cerevisiae* and obtained 0.51, 2.42, 2.39 (1.02 L/min; 30 min) and 2.94 (451 mL/min, 30 min) log reductions of the yeast, respectively. However, today there are different types of UV-C systems able to reach higher log reductions (reductions of 4.48 log in Guava pineapple, 5 log in orange juice, 5.3 and 7.42 in apple juice, and 8.5 log in pummelo fruit juice), i.e., USFDA UV-C-light-recommended levels or more of the target microorganisms especially pathogens and surrogates in fruit juices (Keyser et al., 2008; Mansor et al., 2014; Oteiza et al., 2005, 2010; Shah et al., 2014; Ye et al., 2007). Therefore, UV-C light dose is still a prominent factor in the delivery of microbiologically safe fruit juice products with good nutritional, sensorial, and quality characteristics. Composition and color of the fruit juices are critical factors for the lethal effects of UV-C light; also these are important, as fruit juice characteristics determine the odor and flavor of juices after UV-C treatment.

When the fruit juice is transparent and colorless (clear), providing higher penetration or adequate time for exposure in order to expose all parts of the juice, reduced dosages are required than in juices that are thick or have high amounts and types of soluble and/or suspended solids.

Flow rate, flow behavior (laminar or turbulent), path length or flow type (e.g., as a narrow thin-film flow) have more effect on the lethality of UV-C light. UV-C system design and geometric configuration is another critical factor. A UV-C system should be able to create sustainable and uniformly desired turbulence or a very thin film during the process. This issue is also relevant with respect to cleaning and sanitation of the UV-C system, which is not considered in inactivation efficiency studies. Control of the UV-C system, e.g., measuring the lamp's intensity, as well as dosage, is another critical point.

Besides intrinsic and extrinsic factors, microbiological factors have prominent effects on the UV-C resistance of bacterial pathogens. Inactivation efficacy of UV-C light, i.e., is resistance of pathogens to UV-C, can be affected by microbiological factors such as inherent resistance of the species, strains, serotypes, growth culture medium, stage of the growth phase and their concentration/density, previous stresses (specifically sublethal stresses, damages), repair ability (e.g., photoreactivation ability), and UV-C-absorbing properties of cellular components such as proteins (Bachmann, 1975; Morgan, 1989). The mechanism of microbial inactivation at 254 nm was associated with the formation of thymine, cytosine-thymine, and cytosine dimers (Sinha and Häder, 2002). Therefore the effects of UV-C light on DNA structure and also amino acids and their absorption spectrum are the most prominent factors. It was found that amino acids containing an aromatic nucleus, i.e., tryptophan, phenylaniline, tyrosine, and histidine, exhibit strong absorbing properties in the UV-C range and two maxima can be distinguished in the absorption spectrum of the amino acids (Aitken and Learmonth, 1996; Kelly and Price, 2000; Kuipers and Gruppen, 2007).

For UV-C inactivation efficacy, concentration/density and type of microorganisms in fruit juice are important. Yeasts and molds are large microorganisms that UV-C light is likely to reach, but they are less sensitive to UV-C due to their size and shape. Thus, to inactivate large microbial cells, higher doses are needed. In general, spores, yeasts, fungi, and viruses are more resistant than other microorganisms. UV-C light sensitivity differs for each type of microorganism, which may be due to structural differences of the nucleic acids of the cell and the cell wall structure (the thickness and composition of the cell wall and the presence of UV-C-absorbing proteins) (Koutchma et al., 2009). Generally, the resistance of microbial cells to UV-C light from higher resistance to lower follows the pattern: protozoa > viruses > molds > bacterial spores > yeast > gram positives > gram negatives. Gram-negative bacteria are more susceptible than gram-positive bacteria, maybe because of their bigger cell size or cell structure; and bacteria suspended in air are more sensitive than those suspended in liquids (Bachmann, 1975; Bintsis et al., 2000; Koutchma et al., 2009). Pigmented microorganisms (e.g., *Aspergillus niger*, also their spores, some cocci growing as colored colonies) are less susceptible than nonpigmented microorganisms or bacteria.

Higher resistance to the UV-C of rod shaped, gram-positive bacteria *L. monocytogenes* was suggested to be due to the difference in its membrane. However, there are differences between the resistances of the bacteria to UV-C light, although they have the same morphological shape. Gram-negative, coccoid bacillus *Y. pseudotuberculosis* was found to be less resistant to UV-C light than gram-negative bacillus *E. coli* K-12 (Ye et al., 2007). *Lactobacillus plantarum* also was found to be less resistant to UV-C light than *S.* Typhimurium (Condón-Abanto et al., 2016). Coohill and Sagripanti (2008) reported that spores of *Bacillus anthracis*, *B. subtilis*, and *Bacillus megaterium* were 5−10 times more resistant to UV-C than were their corresponding vegetative cells. *Y. enterocolitica* and *Vibrio cholerae* appeared to be more sensitive to UV-C and *S. typhi* slightly more resistant to UV-C than *E. coli*. The sensitivity (at 254 nm) of all vegetative bacteria ranged between 11−80 and 25−200 J/m^2 for a 1-log$_{10}$ and 4-log$_{10}$ kill, respectively.

It was shown that another factor that affects the UV-C light resistance of the bacterial pathogens is the serotype. Specifically, studies performed with *E. coli* showed that, under applied treatment conditions, serotype O103:H2 at 254 nm demonstrated the highest UV-C resistance (2.20 ± 0.09-log$_{10}$ reductions at 254 nm, 190 mJ/cm^2) amongst all tested pathogens. Arroyo et al. (2012) and Gayán et al. (2012) showed the effects of UV-C light on the strains of *S.* Senftenberg (STCC4384 and ATCC43858) and *S.* Typhimurium (STCC878 and STCC443). The 4D (J/mL) for two strains of *S.* Typhimurium (18.03 and 14.94) were found to be different, however, this value was found to be almost the same for the *S.* Senftenberg (15.57 and 15.23) strains (Table 24.3). The dose required to inactivate 99.99% of the initial population of the five strains of *L. monocytogenes* tested ranged from 21.84 (STCC 5672) to 14.66 J/mL (STCC 4031) (Table 24.3).

In general, stationary phase cells of bacteria are more resistant to environmental stresses. In logarithmic growth phase, cells are more sensitive to UV-C light than in the stationary phase (Arroyo et al., 2012; Barbosa-Cánovas et al., 2004). Arroyo et al. (2012) showed that growth temperature (10°C, 37°C), pH (3, 7) and water activity (0.94, 0.99) did not change the UV-C resistance of *Cronobacter sakazakii*, in agreement with others (Basaran et al., 2004; Condón-Abanto et al., 2016; Fine and Gervais, 2004; Gayán et al., 2011). However, cells in the logarithmic phase of growth were found to be more sensitive than those in the stationary phase. Results obtained by Arroyo et al. (2012) showed that *C. sakazakii* cells increase their UV-C light resistance when attaining the stationary phase, which has been related to the expression of the global stress response gene, *rpoS* (Bucheli-Witschel et al., 2010).

Table 24.3 Inactivation Properties of Bacterial Foodborne Pathogens Under UV-C Light Treatment

Pathogen Bacteria	Inactivation Medium	Strain	4*D* (J/mL)	R^2	RMSE	Inactivation Kinetics/ Model Fitted	References
L. monocytogenes[a]	Citrate-phosphate buffer (pH 7.0) $a = 11.04\ cm^{-1}$	STCC 5672	21.84 (± 0.77)	0.983	0.331	Shoulder (initial) plus exponential order	Gayán et al. (2015)
		STCC 4031	14.66 (± 0.10)	0.988	0.355		
		STCC 4032	18.97 (± 0.75)	0.995	0.207		
		STCC 5366	18.86 (± 0.17)	0.993	0.264	Log-linear regression plus shoulder model	
		STCC 932	17.98 (± 0.25)	0.984	0.144		
S. Typhimurium[a]	Citrate-phosphate buffer (pH 7.0) $a = 11.04\ cm^{-1}$	STCC878	18.03	0.994	0.209	Shoulder (initial) plus exponential order	Gayán et al. (2012)
		STCC443	14.94	0.989	0.335	Log-linear regression plus shoulder model	
S. Enteritidis[a]	Citrate-phosphate buffer (pH 7.0) $a = 11.04\ cm^{-1}$	ATCC13076	12.75	0.990	0.310	Shoulder (initial) plus exponential order	Arroyo et al. (2012)
						Log-linear regression plus shoulder model	
S. Senftenberg[a]	Citrate-phosphate buffer (pH 7.0) $a = 11.04\ cm^{-1}$	STCC4384	15.57	0.992	0.264	Shoulder (initial) plus exponential order	Arroyo et al. (2012)
		ATCC43858	15.23	0.992	0.278	Log-linear regression plus shoulder model	
Cronobacter sakazakii	McIlvaine buffer $a = 10.51\ cm^{-1}$ a_w: 0.99	NCTC9238				Linear with shoulder	Arroyo et al. (2012)
						Log-linear regression plus shoulder model	
	pH 3		20.9	0.99	0.218		
	pH 4		21.7	0.99	0.099		
Cronobacter sakazakii	Citrate-phosphate buffer + tartrazine (0.25 g/L) $a = 10.5\ cm^{-1}$	ATCC29544	3-log reduction (13.3 ± 0.78 min) $\alpha = 6.47$ $\beta = 1.53$	0.99	0.214	Nonlinear curve Weibull model	Arroyo et al. (2010)
L. monocytogenes		10493S (serotype 1/2a)	3.14-log CFU reduction 120 s			Shoulder (initial) plus linear curve	Uesugi et al. (2016)
						Log-linear regression plus shoulder model	
Vibrio parahaemolyticus	Luria Bertani medium + 3% NaCl	RIMD2210633	3-log reduction (12 min)			Nonlinear curve	Hamamoto et al. (2010)
Aeromonas hydrophila	0.85% saline solution		7.61-log reduction			Nonlinear curve	Kaur et al. (2015)

[a]*All strains in early stationary growth phase, Recovery medium is tryptic soy agar supplemented with yeast extract (TSAYE).*

L. monocytogenes is more resistant to thermal and nonthermal preservation techniques than exponentially growing cells (Álvarez et al., 2003; Mackey et al., 1995). However, no significant differences were found between the UV-C resistance of exponential- and stationary-phase cells of *L. monocytogenes* STCC 5672. In contrast, others have reported the dependence of the UV-C resistance on the growth phase of *E. coli* (Bucheli-Witschel et al., 2010; Gayán et al., 2011) and *S. enterica* (Child et al., 2002; Gayán et al., 2012). The higher UV-C resistance of the stationary phase cells of gram-negative bacteria has been attributed to the transcription of the general stress sigma factor *RpoS*. Similarly, gram-positive bacteria possess the alternative sigma B factor (σ^B), which is considered by many researchers as functionally homologous to the *RpoS* factor (Gertz et al., 2000). In fact, it has been demonstrated that the enhanced resistance of stationary-phase cells of *L. monocytogenes* to other preservation techniques are induced by the activation of sigma B factor (Becker et al., 1998; Somolinos et al., 2010). The UV-C inactivation of the most resistant strain did not change in different growth phases and after exposure to some stress conditions, e.g., sublethal heat, acid, basic, and oxidative shocks. The pH and water activity of the treatment medium did not affect the UV-C resistance of *L. monocytogenes*, whereas the inactivation rate decreased exponentially with the absorption coefficient (Gayán et al., 2015). The detection of sublethally damaged bacteria following exposure to UV-C radiation is critical because injured cells are able to recover and return to normal physiology and pathogenicity under suitable conditions (Wuytack et al., 2003). However, there is so far little information available on the sublethal damage induced by UV treatment in foodborne pathogens.

Gayán et al. (2015) in model solution apple and orange juices, using selective and nonselective media for recovery of survivors, showed that UV-C treatment did not damage the functionality and integrity of *L. monocytogenes* cytoplasmic membrane in any of the strains investigated. Similarly, Pataro et al. (2011) found no appreciable sublethal damage in *L. innocua* after treatment with pulsed UV light using a selective growth media technique.

The germicidal effect can be achieved by applying either low intensity for long exposure times or high intensity for short times (Bachmann, 1975). UV sensitivity of microorganisms is characterized by the UV-C doses required to reduce microbial populations by 1 log. The sensitivity of a specific microorganism to different UV doses is presented in survival curves, also known as dose−response curves (Koutchma, 2009). A summary of UV-C dose−responses for a wide range of microorganisms, including pathogens, indicators, or organisms encountered in the application, testing of performance, and validation of UV-C disinfection technologies has been provided by Cairns (2006).

Hoyer (1998) has stated that photoreactivated cells showed greater resistance to UV-C light than nonreactivated ones. For example, in order to obtain a 4-log reduction of *E. coli* 50−110 J/m^2 of 254 nm UV-C light was required, however, after photoreactivation the required exposure dose increased up to 188−280 J/m^2. Exposure to visible light of UV-irradiated cells slightly increased the recovery of survivors of the most resistant strain of *L. monocytogenes* and for *L. monocytogenes* STCC 5672 the *4D* value increased from 21.84 ($\pm$ 0.77) to 22.55 ($\pm$ 1.35) J/mL after photoreactivation (Gayán et al., 2015). Moreover, the photoreactivation ability of *L. monocytogenes* was found to be lower than that for *E. coli* under the same experimental conditions (Gayán et al., 2011).

As stated by Koutchma et al. (2009) UV-C light sensitivity of the pathogen of concern is a key factor affecting the efficacy of the treatment of fruit juice. Knowledge of the decimal reduction dose (inactivation kinetics, physicochemical parameters, and inactivation rates) of the target or surrogate bacterium is required in order to design a preservation process with regard to food safety. Therefore, how the variations in product characteristics and process parameters affect the UV-C

light sensitivity of the pathogen of concern should be clearly understood, and then appropriate processes can be developed. Lethal efficacy or germicidal effect of UV-C radiation has been widely studied, however, the UV-C resistance of different species, strains, serotypes of bacterial foodborne pathogens and their biological and intraspecific variability have not been studied systematically. It is difficult to compare the published data on microbial and also bacterial pathogen inactivation in fruit juices by UV-C radiation because of the differences in design (conformation and geometry) of UV-C equipment or systems, juice flow pattern (flow rate, flow type, etc.), optical properties of the juice, knowledge of the effect of physiological state of cells on UV-C resistance, such as growth phase, and environmental stress history prior to treatment.

24.12 CONCLUSION

UV irradiation that is a nonthermal process considered as an alternative to thermal treatment, successfully applied to reduce the microbial load as well as pathogens in different fruit juices and nectars. UV-C light processing systems have low running costs, use less energy than thermal pasteurizers, require little maintenance, contribute to lower capital and running costs, and produce a good-quality and safe product for the consumer. Currently, this technology is not widely used in fruit juice processing, but it could potentially be applied in fruit juices and nectars to obtain a better final product sensory quality without neglecting microbial safety. Therefore, it is very important to consider making critical decisions about UV-C equipment design including radiation source (correct type of lamp), system geometry, and fruit juice properties and optimizing of the parameters and its effects on pathogens besides spoilage microorganisms for fruit juice application. However, to transfer UV technology to the fruit juice industry, it is necessary to improve the knowledge of UV resistance of foodborne pathogens of concern and the effect of different intrinsic and extrinsic factors as well as processing factors on their sensitivity. The combination of UV radiation and milder conventional methods (e.g., milder heat process) or other nonthermal technologies or hurdles should be further investigated.

In order to quantify and predict physical, chemical, nutritional, sensory, and microbiological changes produced by UV light in a fruit juice and to infer essential information for different UV-C system designs, a concrete model is required in each case, since the absorbed amount of radiation has a definitive effect on the inactivation rate of the process at each point of the fruit juice in the process, depending on its location. Although a 5-log reduction was not achieved in all the fruit juice samples used in the literature, higher dose rates can be used, since the dose rates used in this study did not affect the organoleptic properties of the juices and nectars. Increasing the UV-C dosage by increasing the exposure time or lamp intensity as well as increasing the turbulent flow in order to increase the exposure of the fruit juice to the UV-C light can lead to these achievements.

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