Food Bioprocess Technol (2009) 2:138–155
DOI 10.1007/s11947-008-0178-3

REVIEW PAPER

Advances in Ultraviolet Light Technology for Non-thermal Processing of Liquid Foods

Tatiana Koutchma

Received: 18 June 2008 / Accepted: 18 December 2008 / Published online: 20 January 2009
© Springer Science + Business Media, LLC 2009

Abstract A negative, public reaction is growing over the addition of chemical preservatives to liquid foods and beverages to extend their shelf life and to protect against foodborne pathogens. As a physical method, ultraviolet light (UV) irradiation has a positive consumer image and is of interest to the food industry as a low cost non-thermal method of preservation. Recent advances in the science and engineering of UV light irradiation have demonstrated that this technology holds considerable promise as an alternative to traditional thermal pasteurization for liquid foods and ingredients, fresh juices, soft drinks, and beverages. However, its use for treating foods is still limited due to low UV transmittance of liquid foods. The goal of this review is to provide a summary of the basic principles of UV light generation and propagation with emphasis on its applications for liquid food processing. The review includes information on critical product and process factors that affect UV light inactivation and consequently the delivery of a required scheduled process in liquids foods; measuring and modeling of UV inactivation, and the important effects of UV light on overall quality and nutritional value of liquid foods. The commercially available UV light sources and UV reactor designs that were used for liquid foods treatment are reviewed. The research priorities and challenges that need to be addressed for the successful development of UV technology for liquid foods treatment are discussed.

T. Koutchma (✉)
Guelph Food Research Center,
Agriculture and Agri-Food Canada,
93 Stone Road West,
Guelph, ON N1G 5C9, Canada
e-mail: koutchmat@agr.gc.ca

Keywords UV light technology · Low UV transmittance liquids · UV inactivation · Reactor performance

Introduction

Modern consumer demands for tasty, safe, healthier, organic, natural, and fresh foods or "green" foods produced in an environmentally friendly manner with sustainable methods and small carbon footprints. The negative public reaction over chemicals added to foods is growing. To address the challenges and issues facing the food industry, the alternative technologies for modern food processing are being investigated.

Although the use of ultraviolet (UV) light is well established for air and water treatment and surface decontamination, its use for treating liquid foods is still limited. Compared to water, liquid foods have a range of optical and physical properties and diverse chemical compositions that influence UV light transmittance (UVT), dose delivery, momentum transfer, and consequently microbial inactivation. However, as a physical preservation method, UV irradiation has a positive consumer image and is of interest to the food industry as a low cost non-thermal technology. Recent advances in science and engineering of UV irradiation and sufficient evidence in the literature have demonstrated that UV technology holds considerable promise as a viable alternative to thermal pasteurization for a range of liquid foods and ingredients (fresh juices, soft drinks, raw milk, liquid eggs, liquid sugars and sweeteners, etc). In 2004, the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) of the USDA revised the definition of "pasteurization" for foods that now includes any process, treatment, or combination thereof, which is applied to food

to reduce the most microorganism(s) of public health significance. The processes and technologies described in the NACMCF report included UV irradiation as an alternative to heat that can be used for pasteurization purposes (Supplement to JFP 2006).

A systematic approach to evaluating UV light as an alternative pasteurization method entails consideration of the properties and composition of the food product to be treated, source of UV radiation, microbial effects, modeling, commercial, and economical aspects. The goal of this review is (1) to provide a summary of the basic principles of UV light generation and its propagation with emphasis on its applications for liquid food processing; (2) to review critical product and process factors that affect UV light inactivation and delivery of a required scheduled process including quality effects of UV light; and (3) to discuss available UV light sources including advances in their development and designs of UV reactors suitable for liquid foods processing.

Principles of UV Technology

The wavelength range for UV light for food processing varies from 100 to 400 nm. This range may be further subdivided into: UV-A (315 to 400 nm) that is normally responsible for tanning in human skin; UV-B (280 to 315 nm) that causes skin burning and can lead to skin cancer; and UV-C (200 to 280 nm) called the germicidal range since it effectively inactivates bacteria and viruses. Vacuum UV range (100 to 200 nm) can be absorbed by almost all substances and thus can be transmitted only in a vacuum. Radiation from UV light and the adjacent visible spectral range as well as other less energetic types is termed non-ionizing radiation. In contrast, ionizing radiation which includes X-rays, gamma-rays, and ionizing particles (beta-rays, alpha-rays, protons) is capable of ionizing many atoms and molecules. The absorption of non-ionizing radiation, however, leads to electronic excitation of atoms and molecules. Light is emitted from the gas discharge at wavelengths dependent upon its elemental composition and the excitation, ionization, and kinetic energy of those elements. The gas discharges are responsible for the light emitted from UV lamps.

UV Light Sources

The success of UV technology for food treatment depends on the correct matching of the UV source radiating properties to the specific requirements of the UV application. For liquid foods and beverages, UV absorption can be relatively high; therefore, effective UV treatment requires search of alternative approaches and UV sources to those normally employed for water.

The correct UV source can enhance efficiency of inactivation performance by both increasing UV penetration in the liquid as well as employing higher UV intensity from pulsed sources.

Mercury Lamps

The low and medium pressure mercury vapor UV lamp sources have been successfully used in water treatment for nearly 50 years (Masschelein 2002). They are both well understood and reliable sources for most disinfection treatments that benefit from their performance, low cost, and quality. Typically, three general types of mercury UV lamps are used: low pressure mercury lamps (LPM), low pressure high-output (LPMHO), and medium pressure mercury lamps (MPM). These terms are based on the vapor pressure of mercury when the lamps are operating. Vapor discharge lamps consist of a UV-transmitting envelope made from a tube of vitreous silica glass sealed at both ends. An electrode is located at each end of the envelope connected to the outside through a seal. The envelope is filled with mercury and an inert gas. Argon, the most common filler, has an ionization energy of 15.8 eV, whereas the lowest activated metastable state is at 11.6 eV (Masschelein 2002). Recently, amalgam lamp technology was developed and incorporated into disinfection applications.

Low pressure mercury lamps for the generation of UV light are operated at nominal total gas pressures of 10^2 to 10^3 Pa, and the carrier gas is in excess at proportions of 10 to 100. This corresponds to the vapor pressure of liquid mercury at an optimum temperature of 40 °C at the lamp wall. Typically, the specific electrical loading in the glow zone, expressed in watts per centimeter, is between 0.4 and 0.6 W (e)/cm. The linear total UV output of the discharge length for lamps appropriate for use in disinfection is in the range of 0.2 to 0.3 W (UV)/cm. The emission spectrum of LPM is concentrated at a limited number of well-defined lines and the source is called monochromatic. The resonance lines at 253.7 and 185 nm are by far the most important (Masschelein 2002). The 253.7-nm line represents around 85% of the total UV intensity emitted and directly related to the germicidal effect. The wavelength of 253.7 nm is most efficient in terms of germicidal effect since photons are absorbed most by the DNA of microorganisms at this specific wavelength. Light with a wavelength below 230 nm is most effective for the dissociation of chemical compounds. At wavelengths below 200 nm, such as 185 nm, ozone is produced from oxygen and organic compounds can be oxidized (Voronov 2007). The US FDA regulations approved the use of LPM lamps for juice processing, and they have already been successfully commercialized (US FDA 2000)

Medium pressure mercury lamps are operated at a total gas pressure of approximately 10^4 to 10^6 Pa (Masschelein 2002). Compared to the LPM lamps, the coolest possible temperature of the MPM is about 400 °C, whereas it goes up to 600 °C and even 800 °C in a stable operation. Therefore, it is absolutely necessary to use an open (or even vented), quartz enclosure for the lamp to avoid direct contact of the lamp surface with the treated fluid. MPM lamps operate in the potential gradient range of 5 to 30 W/cm. The emission of MPM lamps is polychromatic. The spectrum covers wavelengths from about 250 to almost 600 nm, which results from a series of emissions in the UV region and in the visible range as well. Hence, such lamps are not considered to be useful for targeted germicidal treatment; however, their strong UV radiation flux results in high penetration depth. By varying the gas filling, doping, and the quartz material, the spectrum as well as the radiation flux of the UV lamps can be varied and matched to suit specific food processing applications, especially for oxidation or photodegradation.

LPM and MPM lamps generally contain elemental mercury, while LPMHO lamps generally contain a mercury amalgam. The potential mercury exposure due to lamp sleeve breakage is a health concern. Breakage of lamps can occur when lamps are in operation and during maintenance. The mercury contained within a UV lamp is isolated from exposure by the lamp envelope and surrounding lamp sleeve. For the mercury to be released, both the lamp and lamp sleeve must break. The mercury content in a single UV lamp used for water treatment typically ranges from 0.005 to 0.4 g (5–400 mg). LPM lamps have less mercury (5–50 mg/lamp) compared to LPMHO (26–150 mg/lamp) and MPM lamps (200–400 mg/lamp). Little information exists regarding the fate of mercury released to the water or liquid food product as a result of UV lamp breakage and potential health risks. Clarke (2006) indicated that the breakage of a UV lamp containing 150 mg mercury in a 50-L batch reactor resulted in a concentration of 2.5 μg/L of mercury in the reactor. However, it was not reported whether all 150 mg of mercury was recovered. The EPA established a maximum contaminant level (MCL) for mercury at 0.002 mg/L. The EPA has found mercury to potentially cause kidney damage from short-term exposures at levels above the 0.002 mg/L MCL (EPA 1995). The concern over the impact of mercury release into the food plant environment stimulated the development and validation of mercury-free special technologies lamps.

Special Lamp Technologies

Several alternative UV source types such as excimer lamps (EL) and lamps with pulsed-UV (PUV) technologies have been developed. These lamps show great promise for instant UV emission. They are independent of temperature effects and can be applied to food treatment. However, the efficacy and specific characteristics of these UV light sources that are used today for water treatment have not been evaluated for food applications. Only a few studies have been reported in the literature (Schaefer et al. 2007; Warriner et al. 2002).

Excimer Lamps

Modern excimers lamps or excilamps are based on the formation of rare gas (RG_2*) or halogen excimers (X_2*) or of rare gas halide exciplexes (RgX*) and the efficient fluorescence of these molecules in different types of discharges. Excimer is an abbreviation of “excited dimer”. Noble gases and noble gas/halogen mixtures can form excimers. The excimer state is very short lived. On decomposition of the excimers, a UV photon is emitted in a very tight, quasi-monochromatic spectral range. Depending on the choice of gas, different narrow band UV spectra can be produced, predominantly in a single spectral line. Today, there are several different excimer combinations, which can produce UV radiation in the wavelength range between 120 and 380 nm. ELs also have an advantage of extremely low output and are able to operate at much lower surface temperatures. Thus, they can provide an advantage by avoiding fouling behavior by liquid foods. Warriner et al. (2002) demonstrated that UV-excimer light was effectively used for sterilization of the packaging carton surfaces.

Broadband-Pulsed Lamps

In this technology, alternating current is stored in a capacitor and energy is discharged through a high-speed switch to form a pulse of intense emission of light within about 100 μs. The emission is similar in wavelength composition to solar light. The PUV devices can deliver high intensity UV which can both penetrate opaque liquids better than mercury lamps and provide enhanced treatment rates. The US FDA has approved the use of pulsed UV light in the production, processing, and handling of food (US FDA, Code 21CFR179.41). A few studies recently reported an application of UV-pulsed light for food surface treatment such as corn, fresh produce, meats, and fish (Ozer and Demirci 2006; Woodling and Moraru 2005; Oms-Oliu et al. 2009). This technology is claimed to be promising but not yet thoroughly established in the field of liquid foods processing (Schaefer et al. 2007).

Microwave UV Lamps

A new UV lamp technology that eliminates the need for electrodes is the microwave-powered electrodeless mercury

UV lamp (Meier et al. 2007). Instead of utilizing electrodes, microwave energy is generated by a magnetron and directed through a waveguide into the quartz lamp containing the gas filling. The directed microwave energy excites the argon atoms, which in turn excite the mercury atoms to produce radiation as they return from excited states to states of lower energy as in the case with other mercury lamps. Electrodeless lamps operate at similar pressures and temperatures to typical LPM lamps. The advantages of using microwave-powered lamps over conventional lamps with electrodes include: quick warm up, elimination of the primary deterioration process associated with UV lamps, and a lamp life is approximately three-folds longer than that of lamps with electrodes.

Table 1 provides a summary of some of the basic characteristics of common UV sources. From this summary, it is evident that no single lamp technology will represent the best source for all food applications. However, situation-specific requirements may dictate a clear advantage for a given process technology. For UV reactors containing LPM or LPMHO mercury lamps, UV absorbance and transmittance at 253.7 nm are important design parameters. However, for broadband UV lamps, such as MPM or PL UV lamps, it is important to measure the full scan of absorbance or transmittance in the germicidal region from 200 to 400 nm. In addition, the molar absorption coefficient and its spectra should be collected for a variety of compounds. Special technology lamps as PL UV and EL are promising due to different spectral bands or specific wavelength that they can provide considering the effects on quality attributes. They also have instant start and robust packaging with no mercury in the lamp. However, more research is needed to establish their suitability for food processing applications.

Characterization of Liquid Foods in Relation to UV Treatment

Liquid food products have a diverse range of physical, chemical, and optical properties. Each group of properties needs to be properly assessed in order to design preservation process and optimize performance of the UV reactor. Physical properties (viscosity, density) influence the effectiveness of fluid momentum transfer and flow pattern. Optical properties are the major factors impacting UV light transmission and consequently microbial inactivation in liquid foods. Chemical composition, pH, dissolved solids (°Brix), and water activity are considered as hurdles that can modify UV inactivation efficacy.

Propagation of UV Light

UV light emitted from the atoms and ions within the gas discharge of a UV lamp will propagate away from those atoms and ions. The emitted UV light interacts with the UV reactor components such as the lamp, the lamp sleeve, the reactor walls, as well as the liquid substance being treated. As UV light propagates, it interacts with the materials it encounters through absorption, reflection, refraction, and scattering. Each of these phenomena influences the intensity and wavelength of the UV light reaching the bacteria or chemical compound in the liquid.

Absorption of light is the transformation of energy of light photons to other forms of energy as it travels through a substance. The UV absorbance of the liquid foods strongly influences UV dose delivery. The Lambert–Beers law (Eq. 1) is the linear relationship between absorbance (A), concentration of an absorber of electromagnetic radiation (c, mol/L), and extinction coefficient (ε, L/mol/cm) or molar absorptivity of the absorbing species which is a measure of the amount of light absorbed per unit concentration absorbance or optical density, and path length of light (d, cm)

$$A = \varepsilon \times c \times d \tag{1}$$

The liquid itself and the concentration of the suspended units can be transparent if $A \ll 1$, opaque if $A \gg 2$ or semitransparent if $1<A<2$ for anything in between these extremes. In a majority of cases, liquid foods will absorb UV radiation. For example, clear juices can be considered

Table 1 Summary of UV sources and their basic characteristics

UV radiation source	Electrical efficiency (%)	UV efficiency (%)	UV intensity (W/cm^2)	Lamp surface temperature (°C)	Lifetime (months)	Output spectrum
LPM	50	38	0.01	40	18–24	Monochromatic 253.7 nm
MPM	15–30	12	600	400–1,000	0.5	Polychromatic (200–300 nm)
Pulsed Xenon	15–20	17	30,000	–	1	Polychromatic
Excimer	10–35	10–40	–	Ambient	>6	Monochromatic tunable

as a case of semitransparent or opaque liquids if the juice contains suspended solids.

If multiple species that absorb light are present in a liquid sample, the total absorbance at a given wavelength is the sum due to all absorbers (Eq. 2)

$$A = (\varepsilon_1 \times c_1 \times d) + (\varepsilon_2 \times c_2 \times d) + \ldots \quad (2)$$

where the subscripts refer to the molar absorptivity and concentration of the different absorbing species that are present in the liquid. Molar absorptivity of apple juice, orange juice, and multifruit juice was determined from the linear regression of absorbance at 253.7 nm versus concentration as reported by Oteiza et al. (2005). The following absorptivities were reported: 0.0715, 0.3528, and 0.7233 (L/mol/cm) for apple, orange, and multifruit juice, respectively.

The absorption coefficient (α), base e (α_e) called Naperian absorption coefficient or base 10 (α_{10}), called the logarithmic coefficient, is also used in the calculations and is defined as the absorbance divided by the path length (m^{-1}) or (cm^{-1})

$$\alpha_e = 2.303\ A/d \quad (3)$$

The absorption coefficient is a function of wavelength.

The irradiance of UV light or fluence rate (E) is affected when it passes through a substance according to the following equation (Eq. 4)

$$E_1/E_0 = 10^{-\sum \varepsilon cd} = 10^{-\alpha_{10} d} = 10^{-A} = e^{-\alpha_e d} \quad (4)$$

where E_1 and E_0 and are the UV light irradiances (mW/cm^2) incident on the substance and transmitted through a length d (cm), respectively. As UV absorbance increases, the intensity throughout the product in the reactor decreases and results in a reduction of UV dose delivery.

Penetration depth (λ) is the depth (cm) where the initial flux I_o drops by a specified percentage of its value at the quartz sleeve, for example, 95% or 99%. The penetration depth is defined by Eq. 5

$$\lambda = 1/\alpha_e \quad (5)$$

Experimental measurements are usually made in terms of *transmittance* of a substance (T), which is defined as the ratio of the transmitted to the incident light irradiance (Eq. 6). In practice, because of reflections at the quartz/air interfaces, I_o is the spectrophotometer reading with pure solvent in the cell and I_1 is the reading with the solution of interest in the cell.

$$T = I_1/I_o \quad (6)$$

As opposed to absorption coefficient that is a characteristic of the material only, the transmittance depends on thickness. A convenient way of presenting information about UV transmittance of materials is to give the values of their absorption coefficient at various wavelengths. Knowing this, the transmittance for any particular depth and the depth of the liquid which will absorb 90% of the energy at 253.7 nm can be calculated from Eqs. 4 and 5.

Reflection is the change in the direction of propagation experienced by light deflected by an interface.

Scattering is the phenomenon that includes any process that deflects electromagnetic radiation from a straight path through an absorber when lights interact with a particle. UV light scattered from particles is capable of killing microbes. Much of the scattered light is in the forward direction and is a significant portion of the transmitted UV light. The scattering phenomenon plays an important role in disinfecting food liquids with particles.

UV Process Calculations

The suspensions of microorganism that are irradiated can be considered as dense packages of absorbing molecules separated from each other by the suspension liquid. The UV absorption of suspension liquid itself may vary compared with the case if the liquid is water, an inorganic buffer solution or glucose salts medium. In homogenous solutions, if a uniform layer is exposed to a parallel beam of monochromatic UV radiation at an incident fluence rate E_o, the fluence rate of the unabsorbed radiation emerging after passage through the layer is expressed by the following equation

$$E = E_o \times 10^{-A} \text{ or } E = E_o e^{-A \ln 10} \quad (7)$$

If the broad side area of the solution, S, is exposed to the fluence H_o, which is the product of fluence rate and the time, $H_o = E_o t$, the equation to calculate absorbed energy can be obtained from Eq. 8

$$H_{abs} = (E_o - E)tS = E_o t\left(1 - e^{-A \ln 10}\right)S = H_o\left(1 - e^{-A \ln 10}\right)S \quad (8)$$

The absorbed fluence indicates that radiant energy is available for driving the solution reaction. However, when UV light is absorbed by a solution, it is no longer available for inactivating the microorganisms. The remaining interactions including reflection, refraction, and scattering change the direction of UV light but the light is still available for inactivation.

UV Absorption of Liquid Foods

A comparison of the absorption coefficients and transmittance of selected juices, beverages, and liquid foods at 253.7 nm is given in Table 2. The transmittance of UV light through juices and other liquid foods is low compared to water due to their high optical density and results from high UV light absorption and scattering. Accordingly, other terms

Table 2 Absorption coefficients and transmittance at 253.7 nm of water, beverages, and liquid foods

Substance	Absorption coefficient, cm^{-1}	Transmittance, 1 cm, %	Transmittance, 0.1 cm, %	Penetration for 90% absorption, cm
Water	0.01	97.72	99.77	100
Waste water	14	~0	3.98	0.07
Clear apple juice	15	~0	3.16	0.067
Apple cider	40	~0	0.01	0.025
Orange juice	100	~0	0.00	0.010
Liquid sucrose	4.5	0.0032	35.48	0.022
Beer	16	~0	2.51	0.063
Coca-cola, bottled	31	~0	0.08	0.032
Milk, raw	290	~0	0.00	0.003
Egg white	104	~0	~0	0.001
Wine, sherry	9	~0	12.59	0.111

used to characterize liquid foods in relation to UV treatment are "ultra low" and "low UV transmittance liquids". In addition, due to the exponential nature of Lambert's law, the transmittance changes rapidly with changes in thickness d for large values of α. The practical significance of this observation is that for the liquids with high absorption, a small change in their thickness or absorption coefficient produces a large change in transmittance.

The variations of UV absorptions coefficients and physico-chemical properties among seven varieties of juices were reported by Koutchma et al. (2007). Semitransparent juices such as lillikoi (α_{10}=11.70 cm^{-1}), watermelon ((α_{10}= 23.60 cm^{-1}), and apple juice (α_{10}=25.90 cm^{-1}) were characterized by the lowest absorptivity. Orange and guava juices that contain particulates and pulpy materials had somewhat similar α_{10} of 47.90 to 45.80 cm^{-1}. Carrot and pineapple juices were almost opaque liquids with $\alpha_{10}>$ 60 cm^{-1}. Turbidity of juices due to the presence of suspended solids was in a range from 1,000 NTU for apple and lillikoi juices to >4,000. The variety of juices tested represented different pH groups, Brix levels, and varying viscosities. Apple, lillikoi, and orange juices belonged to the high acid food group (pH<3.7). Pineapple juice (pH 3.96) is within the group of acid or medium acid foods (3.7<pH<4.5). However, carrot (pH 5.75), watermelon (pH 5.19), and guava nectar (pH 6.32) are in the group of low acid foods (pH<4.5). Lillikoi, apple, guava, and watermelon juices represented less viscous, Newtonian fluid products, whereas carrot, orange, and pineapple juices were characterized by higher viscosity and non-Newtonian behavior. These differences showed not only the importance of full characterization of liquid foods to design a proper preservation process but also the choice of the correct UV reactor to deliver a scheduled process.

Effect of Dissolved Solids

The presence of dissolved organic solutes and compounds in liquid foods leads to strong UV attenuation effects. The major components of apple juice/cider are sugars including fructose, sucrose, and glucose followed by organic acids mainly malic acid and a very low amount of ascorbic acid (Fan and Geveke 2007). It was found that the three sugars absorbed little UV in the range of 240–360 nm although the fructose solution had higher UV absorbance at 260–280 nm than glucose and sucrose solutions. All three sugars had high absorbance around 200 nm. 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%). Apple ciders also had UV-C absorbance at wavelengths below 240 nm.

Four commercial brands of apple juice were characterized by Ye et al. (2007) in terms of their UV absorption effects. It was found that the absorption coefficients of the tested apple juices ranged from 39.1 to 7.1 cm^{-1} and a correlation with vitamin C contents was observed. In general, the larger values of vitamin C content resulted in the larger absorption coefficients of juices. The apple juice that had the highest α_{10} of 39.1 cm^{-1} was enriched with vitamin C (0.3 mg/mL). Whereas the least absorptive apple juice with α_{10} of 7.1 cm^{-1} was not enriched with vitamin C and characterized by the lowest magnitude of L (lightness), a (yellowness), and b (greenness). For apple juices with higher values of absorption coefficients, higher L values were observed. Due to the correlation between vitamin C contents and UV light absorption, the understanding of UV light effects on the destruction of vitamin C during treatment becomes critical from the point of view of UV dose delivery.

Effect of Suspended Solids

Suspended solids (SS) cannot only attenuate the UV dose via light scattering, but may also provide a site for the aggregation of bacteria to particles surfaces. The negative impact of SS on both UV dose transmission and absorbance

is well documented for unfiltered water because particles can absorb, scatter, and block UV light (Christenen and Linden 2001). Very little research has been done to examine the effects of SS on UV processing of liquid foods. The effects of high levels of SS on the UV light transmission that is characteristic for juices are not understood. The range of particle size distributions in apple cider from a Placerville producer was estimated by Unluturk et al. (2004). The particles of apple cider were larger than the wavelength of UV light at 254 nm, possibly causing more light scattering in the forward direction with enhanced backscattering. The effect of the concentration of SS on the absorption coefficient was studied and reported by Koutchma et al. (2004) using model solutions of caramel and dried apple particles. The apparent increase of absorption coefficient was found to be due to the light scattering by particles. Because the average UV light dose is generally calculated based on absorption coefficient measurements, the dose may be overestimated for fluids with a large SS concentration and a smaller soluble absorbance component.

Due to very limited data on absorptive properties of liquid foods, beverages, and fresh juices, which have a major effect on microbial inactivation under UV treatment, it is highly desirable that sufficient UV absorbance data be properly measured, characterized, and reported. The absorbance measurement techniques should account for the presence of the suspended particles and their effect on the estimation of the absorbed UV dose. In addition, the effect of some essential compounds such as vitamin C on the absorption effects needs to be taken into account during UV treatment.

UV Light Inactivation of Foodborne Microorganisms and Competitive Effects in Liquid Foods

UV-C light inactivates microorganisms by damaging their nucleic acid that absorbs UV light from 200 to 310 nm. The primary mechanism of inactivation by UV is the creation of pyrimidine dimers which prevent microorganisms from replicating, thereby rendering them inactive and unable to cause infection. The UV lamp emitting at 253.7 nm is operating very close to the optimized wavelength for maximum absorption by nucleic acids.

UV Sensitivity of Pathogenic and Spoilage Microorganisms

UV light sensitivity of microorganisms of concern is a key factor affecting efficacy of UV treatment of liquid foods and varies significantly. This variation may be due to: cell wall structure, thickness, and composition; to the presence of UV absorbing proteins; or to differences in the structure of the nucleic acids themselves. The UV sensitivity is also strongly related to the ability of the microbe to repair UV damage.

UV doses required for reducing populations of microbial groups by a single order of magnitude—a quantity referred to as the D values is often used to characterize the UV sensitivity of microorganisms. Survival curves (UV dose–response) are constructed to demonstrate the susceptibility of a specific organism to different doses of UV light. Table 3 provides a summary of numerous UV disinfection studies and shows the ranges of average D values of various microbial groups. The range for bacteria excludes *Deinococcus radiodurans*, which are the most UV-resistant bacteria isolated to date. The D value of *Deinococcus* ranged from 19.7 to 145 mJ/cm^2. A summary of reported data on the UV dose–response of various organisms such as pathogens, indicators, or organisms encountered in the application, testing of performance, and validation of UV disinfection technologies was published by Cairns (2006). These tables reflect the state of knowledge and include the variations in techniques and biological response that currently exists. In most cases, the data were generated from LPM sources for which the lamp fluence rate (intensity) can be measured empirically and multiplied by exposure time to obtain a UV dose.

Microbial UV dose–response varies with the wavelength of UV light. The action spectrum of a microbe is a plot of its UV sensitivity as a function of the wavelength. The dependence of the first-order inactivation constant k_1 on wavelength is similar to the dependence of the UV absorption of nucleic acid. The inactivation constant peaks at or near 260 nm, has a minimum near 230 to 240 nm, and drops to zero near 300 to 320 nm. The inactivation constant increases below 230 nm; however, the strong absorption of UV light by water at these wavelengths limits germicidal action (Spikes 1981).

Three pathogen groups are of primary concern in water treatment: bacteria, viruses, and protozoa. Although there have been numerous studies published on inactivation of microorganisms by UV light, the most resistant micro-

Table 3 UV inactivation doses (mJ/cm^2) measured at 253.7 nm for various microbial groups

Microbial group	D value (mJ/cm^2)
Enteral bacteria	2 to 8
Cocci and micrococci	1.5 to 20
Spore formers	4 to 30
Enteric viruses	5 to 30
Yeast	2.3 to 8
Fungi	30 to 300
Protozoa	60 to 120
Algae	300 to 600

organisms of public health significance have not been fully determined. Bacterial spores and viruses appear to be the most resistant forms; however, viruses may not be of concern when water, fruit juice, or beverages are the products undergoing treatment. *Bacillus subtilis* spores are commonly used as a bioassay organism in water treatment because of their resistance to inactivation requiring about 36 mJ/cm^2 for a 1-log reduction (Chang et al. 1985). Bacteria and (oo)cysts of *Cryptosporidium* and *Giardia* are more susceptible with a fluence requirement of <20 mJ/cm^2 to achieve a 3-log reduction. In general, gram-positive bacteria are more resistant to UV light than gram-negative bacteria. Among foodborne pathogenic vegetative bacteria, the majority of data published are related to UV sensitivity of strains of *Escherichia coli* that varies in the range of 2 up to 12.5 mJ/cm^2 for 1-log reduction (Sommers et al. 1989). Based on unpublished proprietary research data, it can be assumed that the UV sensitivity of *Listeria monocytogenes* (*L. innocua*), *Salmonella*, and *Staphylococcus aureus* in liquid foods is somewhat similar to UV sensitivity of *E. coli*. The UV sensitivity of spoilage microorganisms also needs to be considered for treatment of ESL drinks, beverages, liquid foods, and ingredients. Food-related spoilage microorganisms include yeasts (*Saccharomyces cerevisiae*), ascospores, lactic acid bacteria, and spores (*Alicyclobacillus*, *B. coagulans*, *C. pasteuranum*, *C. botulinum*). Molds spores are considered to be very UV-resistant, somewhat close to the resistance of *B. subtilis* spores, followed by yeasts and lactic bacteria. However, data on UV effectiveness against foodborne pathogenic and spoilage microorganisms of high importance are limited or available in confidential reports and need to be generated.

Measuring UV Inactivation

The UV dose–response of microorganisms is determined by measuring the concentration of microbes capable of replication after exposure to a measured UV dose. Laboratory dose–response data from collimated beam (CB) tests are commonly used as a basis for determining the necessary delivered UV dose for water treatment. The bench-scale CB device (Qualls et al. 1983; Kuo et al. 2003) has evolved as a standard method. The CB test procedure may be not appropriate for high absorptive liquid foods that have to be stirred in a Petri dish due to a non-uniform fluence in the sample. The performance of an ideal device to measure inactivation kinetics should result in uniform delivery of UV energy in the liquid sample. Murakami et al. (2006) reported that in order to overcome the disadvantages of the traditional CB approach, static thin films of model liquid were exposed to UV light using quartz cuvettes. Since many UV devices in the industry are continuous flow annular reactors, Ye et al. (2007) proposed to use single lamp annular reactors to measure UV inactivation kinetics. UV fluence was calculated using mathematical modeling tools to evaluate distributions of residence time and fluence rate in the liquid. The parameters of UV inactivation kinetics obtained from this novel method can be more reliable and accurate compared to the CB test because the flow and UV fluence distributions were taken into account during computations. Research is needed to develop a design of the laboratory UV reactor that can be used as a standard device to generate kinetic data in low UVT liquids. In addition, the challenges of kinetic data analysis in low UVT liquids need to be addressed starting from the concept, definitions and units of UV fluence and dose, and inactivation rate.

UV Inactivation Kinetics

Various modeling approaches have been proposed to describe and predict UV inactivation kinetics (Collins and Selleck 1972; Severin et al. 1983; Kowalski 2001). Among them, the first-order inactivation model is the simplest approach. It assumes that the inactivation rate changes with respect to pathogen concentration, N, and fluence rate, E, such that

$$\frac{dN}{dt} = -k_1 EN \tag{9}$$

where k_1 is the first-order inactivation constant, cm^2/mJ. k_1 is based on the fluence absorbed by the liquid or Einsteins absorbed by the liquid and delivered to the molecule or organism and indicates the amount of radiant energy required to drive the reaction and ideally does not depend on absorbance.

The first-order inactivation reaction was also defined as the pseudo-first-order model or mixed second order model (Severin et al. 1983; Chiu et al. 1999). If k_1 and E are constant, by integration,

$$\frac{N}{N_0} = \exp(-kEt) \tag{10}$$

In the literature, two main deviations from first-order UV disinfection kinetics have been observed. Some authors (Hoyer 1998; Sommer et al. 1998) observed no inactivation of bacteria or bacterial spores at low UV fluences followed by a normal log-linear relationship at higher UV fluences. This was described by a shoulder model. The second deviation from the linear kinetics is no further increase in inactivation at high fluences, called tailing. The cause of tailing is still under debate. Several causes have been hypothesized, such as experimental bias, hydraulics, aggregation of microorganisms, or a resistant subpopulation, but no conclusive evidence is available for any of these (Kuo et al. 2003; Hijnen et al. 2006; Cairns 2006). Unluturk et al.

(2008) and Ngadi et al. (2003) reported non-linear two-phase kinetics of *E. coli* in liquid egg and apple juice using standard CB set-up and continuous stirring of the sample during irradiation at varied depths. The non-homogeneity of UV treatments was not considered and the thickness of the samples was not optimized by these authors. Altic et al. (2007) demonstrated that breaking up clumps of *M. avium* subsp. *paratuberculosis* cells by additional circulating suspensions of broth or milk through the UV machine with the lamp switched off before UV treatment resulted in a more linear character of inactivation curves. Murakami et al. (2006) reported linear inactivation plots of *E. coli* K12 in model caramel solution. However, two-phase inactivation curve was observed in model caramel solution with particles indicating that the bacteria were not equally exposed to UV light.

Sigmoidal shaped UV inactivation curves were often observed and reported in the literature (Harris et al. 1987). The series-event inactivation model was proposed by Severin et al. (1983) to account for the lag at low fluence. It assumes that inactivation of microbial elements takes place in a stepwise fashion,

$$M_0 \xrightarrow{k_{SE}E} M_1 \xrightarrow{k_{SE}E} \cdots M_i \xrightarrow{k_{SE}E} \cdots M_{n-1} \xrightarrow{k_{SE}E} M_n \xrightarrow{k_{SE}E} \cdots \tag{11}$$

The inactivation rate at each step is the first order with respect to the fluence rate E,

$$\frac{dN_i}{dt} = k_{SE}E(N_{i-1} - N_i) \tag{12}$$

where subscript i is the event level and k_{SE} is the inactivation constant in the series-event inactivation model. k_{SE} is assumed to be the same for different event levels. When n elements (a threshold) of microorganisms have been inactivated, the microorganisms will become non-viable. If k_{SE} and E are constant, the concentration of surviving microorganisms N is determined by the following equation:

$$\frac{N}{N_0} = \exp(-k_{SE}Et)\sum_{i=0}^{n-1}\frac{(k_{SE}Et)^i}{i!} \tag{13}$$

where n is a threshold. It is obvious that if $n=1$, the above equation will be reduced to the first-order model.

Ye et al. (2007) showed that the first-order and series-event inactivation models can be used to predict microbial inactivation in the high absorptive caramel model of juices. The inactivation constants in Fig. 1 were obtained by fitting the same experimental data of *E. coli* K12 (ATCC 25253) with different thresholds (Ye 2007). At low fluence, the first-order model was not able to account for the shouldered survival curve and overestimated log reductions. At high fluence, the series-event model predicted higher log reductions than the first-order model. The series-event and

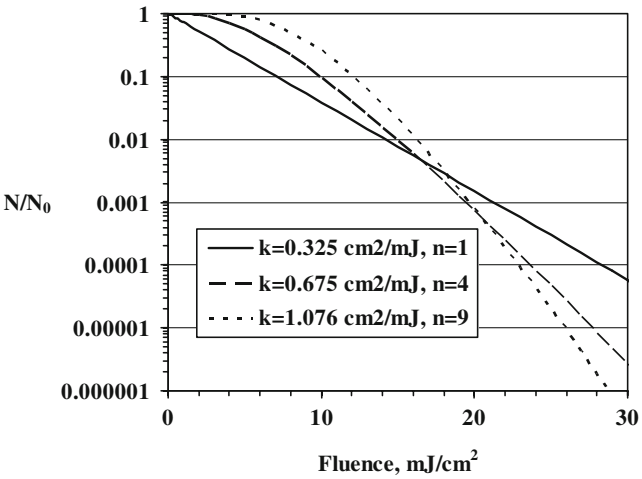

Fig. 1 UV inactivation curves with different thresholds (Ye 2007)

the first-order models, however, predicted similar microbial log reductions at the intermediate fluence values between 14 and 20 mJ/cm^2. Both models were used to estimate inactivation rate constants for *E. coli* K12, *Yersinia pseudotuberculosis*, and *B. subtilis* ATCC 6633 spores based on the experimental data generated in annular single lamp reactors in caramel model solutions with varied absorption coefficients. The inactivation rate constants obtained are summarized in Table 4. It was concluded that the series-event inactivation model was better suited to fit experimental data than the first-order inactivation model (Ye et al. 2007). The reaction rate constant k (k_1, or k_{SE}, cm^2/mJ) and decimal reduction dose D value (D=2.3/k, mJ/cm^2) are used in the process calculations and they are required to design a preservation process.

Effect of Physico-chemical Parameters of Liquid Foods

Key factors that influence the efficacy of UV treatment include UV reactor design, fluid dynamics parameters, and absorptive properties. Koutchma et al. (2004) and Murakami et al. (2006) reported that the inactivation rate of *E. coli* K12 was mainly affected by the absorbance of the model solution. The inactivation rates of the solutions with α=6 and 21 cm^{-1} were 0.58 and 0.14-log reduction per mJ/cm^2, respectively. Similar findings on the effect of absorbance were reported by Oteiza et al. (2005). A linear relationship was found between the D values obtained for *E. coli* strains and the absorptive coefficients of fresh fruit juices tested.

The effect of food product characteristics like pH, dissolved solids, and suspended solids also needs to be considered. Modeling of UV inactivation kinetics should be combined with knowledge of properties of real liquid foods and beverages. In addition, these parameters may vary from one lot to another. A clear understanding must be

Table 4 Inactivation rate parameters calculated using first-order model and series-event model

Microorganism	Event level, n	Inactivation rate k, cm^2/mJ	Global min SSD	R^2	D, mJ/cm^2
B. subtilis (spores)	1	0.0204	75.30	0.94	112.72
	4	0.096	1.93	0.92	23.86
E. coli K12	1	0.325	0.354	0.907	7.08
	4	0.675	0.133	0.987	3.41
Y. pseudotuberculosis	1	0.557	0.402	0.916	4.12
	3	0.984	0.212	0.972	2.33

established on how variation in product characteristics can affect UV inactivation parameters. In this way, appropriate operating parameters can be developed. Koutchma et al. (2004) and Murakami et al. (2006) reported the effects of pH and dissolved solids (Brix) on UV inactivation of *E. coli* K12 in a model caramel system using a laminar flow thin film UV reactor manufactured by CiderSure and static thin film cuvettes. It was found that individually, pH and Brix had no significant effect on the rate of *E. coli* destruction under the conditions tested. Ngadi et al. (2003) also found that the pH of the medium did not affect the inactivation of *E. coli* O157:H7, since similar inactivation characteristics were obtained for both apple juice and liquid egg white. Hijnen et al. (2006) concluded that the efficacy of UV disinfection is not affected by conditions like temperature, pH, and reactive organic matter. However, the UV light transmittance through the liquid and reflectance at the air–liquid surface are temperature-dependent because the physical properties of the liquid change with changing temperatures.

Murakami et al. (2006) studied the effect of suspended solids using an apple cider model. Apple solids obtained by centrifuging commercial apple cider were added to the buffer solution to simulate cider. Initial test levels were pH=3 and 5, Brix=10 and 20, caramel=0.13% and 0.40%, and SS=0.0, 2.5 and 5.0 g/mL. Inactivation plots in malate buffer at SS=0 and 2.5 g/mL of solids were linear indicating the decrease in inactivation rate due to the particles. In the solution with SS=5 g/mL, the inactivation plot was interpreted as having two linear components.

The efficacy of bactericidal action of UV light can be modified by combining with other chemical or physical agents. One such approach is to apply the principle of advanced oxidative process based on the generation of highly reactive antimicrobial radicals from hydrogen peroxide (H_2O_2; Xie et al. 2008). Radical formation from H_2O_2 is enhanced in the presence of oxidization agents such as ozone or UV light at 254 nm. The combination of UV light and H_2O_2 has been applied for several decades for carton decontamination in aseptic packaging (Warriner et al. 2000) and also for wastewater treatment (Thiruvenkatachari et al. 2006). UV light in combination with H_2O_2 has been also applied for fresh produce decontamination (Xie et al. 2008). A number of hybrid techniques have been reported in the literature which include the combination of UV radiation and ozonation for the treatment of humic acids and low molecular weight organic compounds (Jyoti and Pandit 2004). Photocatalytic inactivation of *E. coli* by concentration of TiO_2 in combination with UV irradiation was reported by Benabbou et al. (2007). The addition of titania at a low concentration of 0.25 g/L improved the inactivation of *E. coli* in the presence of UV-A and UV-B, but a detrimental effect was observed under UV-C. The disinfection efficiency increased as a function of light intensity.

Biodosimetry

The delivery of UV dose within a reactor at full scale is one of the challenges to ensure a specific log-reduction (SLR) in numbers of the most resistant pathogen. Biodosimetry studies are used to assess UV dose or reduction equivalent fluence also called germicidal fluence (H_{germ}) which is the amount of radiant energy that has to be delivered to microorganisms to achieve SLR. A biodosimetry involves passing a challenge microorganism through the UV reactor, measuring the average log inactivation achieved, and relating that inactivation to a single decimal reduction dose (D_c value) based on the known UV dose–response of that microorganism from lab scale CB studies.

$$H_{germ} = D_c \times SLR \tag{14}$$

With an ideal reactor delivering a single dose, the biodosimetry is a measure of the dose delivered to all microorganisms. In practice, the inactivation of a pathogen cannot be precisely determined using biodosimetry data unless the reactor's dose distribution is known or the challenge microorganism has the same UV dose–response curve as the pathogen. The range of inactivation is bounded by the inactivation expected with an ideal and worst case reactor. Dose delivery by a UV reactor is a function of the hydraulic flow through the reactor or RTD distribution and the UV fluence rate field generated by the lamps. Microorganisms passing through a UV reactor may travel close to the lamps and be exposed to relatively high UV fluence, or travel along the reactor walls or between lamps and be

exposed to lower UV fluences. Microorganisms may pass through the reactor relatively quickly or be caught in dead zones. As such, microorganisms leaving a UV reactor receive different UV doses, and dose delivery by the reactor is best described using a dose distribution. Therefore, accurate determination of the inactivation kinetics parameters (k or D values) and knowledge of UV light absorption effects in liquid foods is vital in any UV preservation process. In addition, accurate representation of radiation irradiance and velocity fields are required in the development of the UV process.

UV Light Effects on Quality of Foods

Photodegradation of organic molecules in foods is a result of photochemical reactions that occur as a direct result of radiation energy (photons) being introduced to a substance. In view of the wavelengths used in most UV light treatments, the molecules (A) are primarily affected by energy absorption that results in photochemical reactions. In the general case, the process may be viewed as

$$A + h\nu \rightarrow A_{+}^{+} \rightarrow \text{Products.} \quad (15)$$

Two critical conditions must be met for a photochemical reaction to proceed: (1) photon must be absorbed to promote reactions, and (2) photons must have sufficient energy to promote a reaction to break or to form a bond. The extent of chemical reaction if the molecule absorbs the photon of light depends upon the quantum yield and fluence of incident photons. A quantum yield is a ratio of absorbed photons that cause a chemical change to the total absorbed photons. UV light at 253.7 nm has a radiant energy of 112.8 kcal/Einstein (one Einstein represents 1 mol of photons). It is theoretically possible for 253.7 nm light to affect the O–H, C–C, C–H, C–N, H–N, and S–S bonds if it is absorbed (Spikes 1981).

Foods vary enormously in their sensitivity to UV light. It is usually stated that the following nutrients are "light sensitive": vitamin A, carotenes, cyanobalamin (vitamin B_{12}), vitamin D, folic acid, vitamin K, riboflavin (vitamin B_2), tocopherols (vitamin E), tryptophan, and unsaturated fatty acid residues in oils, solid fats, and phospholipids (Spikes 1981). However, these nutrients differ greatly in their basic photosensitivity and in the wavelength of the light involved. It was reported that vitamin D is photochemically altered by UV light. In addition to nutrients, certain food pigments are also light-sensitive. Nucleic acids are the strongest 253.7 nm light absorbers. In general, only unsaturated organic molecules absorb at wavelengths greater than 220 nm. The longer the conjugated chain in the molecule, the longer the wavelength of maximum absorption. Carbohydrates are not especially sensitive to light.

Vitamins

Vitamins even though they may be present in small amounts in fresh juices are of concern because some vitamins as was discussed earlier are considered light-sensitive. Vitamin C is characterized by high UV absorbance within the germicidal wavelength range (peak at approximately of 260 nm) but does not absorb light significantly above 300 nm. The content of vitamin C also affects the absorption coefficient. Vitamin A is another vitamin of great importance along with vitamin C in fresh juices because they both contribute more than 2% nutritional value to the Recommended Daily Allowance. The destruction of the essential vitamins in orange juice was reported by Anonymous (1999) after treatment in the commercial Salcor UV module (Salcor Co, CA, USA) at a flow rate of 7.5 gpm after seven passes through a system when total accumulative UV dose was 298.9 mJ/cm^2. Table 5 is a summary of the UV treatment impact on the contents of eight essential vitamins listed (Anonymous 1999). The highest destruction of riboflavin and beta carotene (~50%) may be observed; however, in terms of vitamins C, B_6, and A, only 16.6% to 11% of those vitamins were destroyed after exposure to UV light.

Shelf Life and Quality Changes in Fruit Juices and Milk

There are only a few studies recently published that examined the effects of UV light on shelf life, flavor, color, and nutrient content of fresh juices including apple juice/cider, orange juice, and mango nectar (Tandon et al. 2003; Tran and Farid 2004; Guerrero-Beltran and Barbosa-Canovas 2006). Tandon et al. (2003) did not find significant

Table 5 Summary of essential vitamins contents in orange juice before and after UV treatment in the Salcor UV module

Orange juice	Vitamin C, mg/100 g	Vitamin B_6, mg/100 g	Folic acid, mg/100 g	Thiamin B_1, mg/100 g	Riboflavin, mg/100 g	Vitamin E, IU/100 g	Vitamin A, IU/100 g	Beta carotene, IU/100 g
Treated	28.2	0.031	4	0.03	0.01	0.16	49	19
Untreated	33.8	0.037	4	0.05	0.02	0.16	55	37
Remaining %	83.4	83.8	100	60	50	100	89.1	51.4

differences among the freshly processed ciders with regard to taste and preference. The sensory tests confirmed the results obtained from the analytical and microbiological evaluation: similar quality at the beginning of the storage study but significant differences after that due to the fermentation of the UV-treated samples. The UV samples did not maintain this quality after 1 week of storage. Tran and Farid (2004) reported the shelf life of fresh squeezed orange juice was extended to 5 days as a result of exposure to UV light of 73.8 mJ/cm^2. The color and pH of the orange juice were not significantly impacted. The measured degradation of vitamin C was 17% under UV exposure of 100 mJ/cm^2 which was similar to that found in thermal treatment. Guerrero-Beltran and Barbosa-Canovas (2006) studied the inactivation of *S. cerevisiae* and polyphenoloxidase activity (PPO) in mango nectar (pH of 3.8, 13.0 °Brix) treated with UV light. UV-treated mango nectar maintained yellow and orange-yellow colors for 26 days of storage. PPO activity remained barely constant after 30 days of storage.

It is well known that milk and milk products are highly light-sensitive products. However, short wavelength UV light is used to produce vitamin D. This wavelength range also produces off-flavors and destroys certain nutrients. Sensory and chemical consequences of treating goat milk using an UV fluid processor were assessed by Matak et al. (2007) who concluded that UV irradiation at the wavelength of 253.7 nm produced changes in the sensory and chemical properties of fluid goat milk.

Loss of nutrients and development of off-flavors during UV processing of juices and other liquid foods need further investigation and the attempts should be made to minimize the damaging effects of UV light on antioxidants, oxidation of lipids, changes in texture and color, and formation of off-flavors and aromas. These effects are very likely dependent on wavelength and dose and will be different for different liquid foods and food compounds. Consequently, in order to determine the best way to use UV, it is necessary to test each food for its spectral response to UV. In addition, knowledge of the kinetics of vitamin degradation from UV irradiation will allow optimization of microbial inactivation while minimizing vitamin losses.

UV Treatment of Fresh Juices and Other Liquids

FDA approval of UV light as an alternative treatment to thermal pasteurization of fresh juice products (US FDA 2000) led to the growing interest and research in UV technology. The correct UV reactor design can reduce the interference of high UV absorbance and viscosity associated with some liquid food products and therefore improves the inactivation efficiency. The flow pattern inside the UV reactor strongly influences the total applied UV dose, since the position and the residence time of the microorganisms in certain regions of the irradiance field can vary significantly. A number of UV light static and continuous flow apparatus were developed and validated for a variety of beverages ranging from exotic tropical juices to the more common apple cider and apple juice for use in pasteurization. Table 6 summarizes the technical characteristics of UV apparatus used for treatments of various fresh juices and reported data of their inactivation performance.

Laminar Flow Reactors

The first design approach uses an extremely thin film UV reactor to decrease the path length and thus avoid problems associated with lack of penetration. Thin film reactors are characterized by laminar flow with a parabolic velocity profile. The maximum velocity of the liquid is observed in the center, which is twice as fast as the average velocity of the liquid; this results in non-uniform processing conditions (Koutchma and Parisi 2004). The two laminar flow designs shown in Fig. 2 are a thin film CiderSure reactor (FPE Inc., Macedon, NY, USA) and the Taylor–Couette flow UV reactor (Forney et al. 2004).

Extensive research of the application of UV light for fresh apple cider by Worobo (1999) yielded a design and production model of a thin film “CiderSure” UV reactor. In this unit (Fig. 2a), LPM lamps are mounted within a quartz sleeve running centrally through the reactor. Juice is pumped from a reservoir through a 0.08-cm annular gap between the inner surface of the chamber and the outer surface of the quartz sleeve. The flow rate is controlled by a computer interface that reads the UV transmission using UV sensors. Three individual treatment chambers are connected in tandem around eight concentrically located tubes. Worobo (1999) reported that apple cider of different varieties was used to test the ability of this unit to deliver 5-log reduction of *E. coli* O157:H7. It was concluded that a greater than 5-log reduction was achieved after a single pass through the reactor.

Wright et al. (2000) examined the efficacy of UV light for reducing *E. coli* O157:H7 in apple cider. For their studies, a model CIDER-10uv (Ideal Horizons, Poultney, VT, USA) was used to deliver dosages ranging from 0.94 to 6.1 mJ/cm^2. This unit was stated to have ten individual UV chambers connected in series through which the apple cider was pumped as a thin film. UV treatment significantly reduced the pathogen with a mean reduction of 3.81-log CFU/mL. Absorbance, turbidity, pH, and other physical or chemical parameters of the juice were not examined.

A similar UV treatment system was used by Hanes et al. (2002) to determine the inactivation of *Cryptosporidium parvum* oocysts in fresh apple cider. For these studies, a

Table 6 Inactivation performance of UV reactors used to process fresh juices

Researcher	UV reactor				Juice	Test microorganism		
	Number of lamps	Type	Output power, W	Gap Size, mm		Type	UV dose, mJ/cm^2	Log inactivation
Laminar flow								
Worobo (1999)	8	LPM	39	0.8	Apple cider	*E. coli* ATCC 25922	NA	5–6
Wright et al. (2000)	10	LPM		NA	Apple cider	*E. coli* O157:H7	9–61	3.8
Hanes et al. (2002)	8	LPM	39	0.8	Apple cider	*C. parvum* oocyst	14.32	5
Koutchma et al. (2004)	8	LPM	39	0.8	Apple juice	*E. coli* K12	14.5	3–4
Guerrero-Beltran and Barbosa-Canovas (2006)	2	LPM	25	NA	Apple juice	*S. cerevisiae*	5,135	1.34
						L. innocua		4.29
						E. coli		5.10
Tran and Farid (2004)	1	LPM	30	0.21	Orange juice	APC	12.3–120	2
				0.48		Yeasts, Molds		3
Guerrero-Beltran and Barbosa-Canovas (2006)	2	LPM	25	NA	Mango nectar	*S. cerevisiae*	5,135	2.71
						APC, yeasts, molds		2.94
Turbulent flow								
Koutchma et al. (2004)	12	LPM	42	6–10	Apple cider	*E. coli* K12	0.75	<1
Keyser et al. (2008)	1–10	LPM	100	NA	Apple juice	APC	229.5 J/L	3.5
					Guava/pineapple juice	Yeasts		
						Molds	1,377 J/L	3.0
						Yeasts		4.48
						Molds		
					Orange juice 1	APC	167 J/L	1.32
						Yeasts		
						Molds		
					Orange juice 2	APC	167 J/L	<1
						Yeasts		
						Molds		
Additional mixing effects								
Koutchma et al. (2007)	24 Dean effect, coiled tubing	LPM	65	ID 10–12	Models of tropical juices	*E. coli*	21.5	Up to 6
					Orange juice	APC		1.5
					Guava	Yeasts		1.2
					Carrot	Molds		3.2
					Pineapple			1.0
Geveke (2005)	1 27–83 ml/min, coiled tube	LPM	15	ID 1.6	Apple cider	*E. coli*	34 J/mL	3.4
						L. innocua		2.5
Forney et al. (2004)	4 Taylor–Couette flow	MPM	0.684	5.52	Apple juice	*E. coli* 15597	21.7	3–5

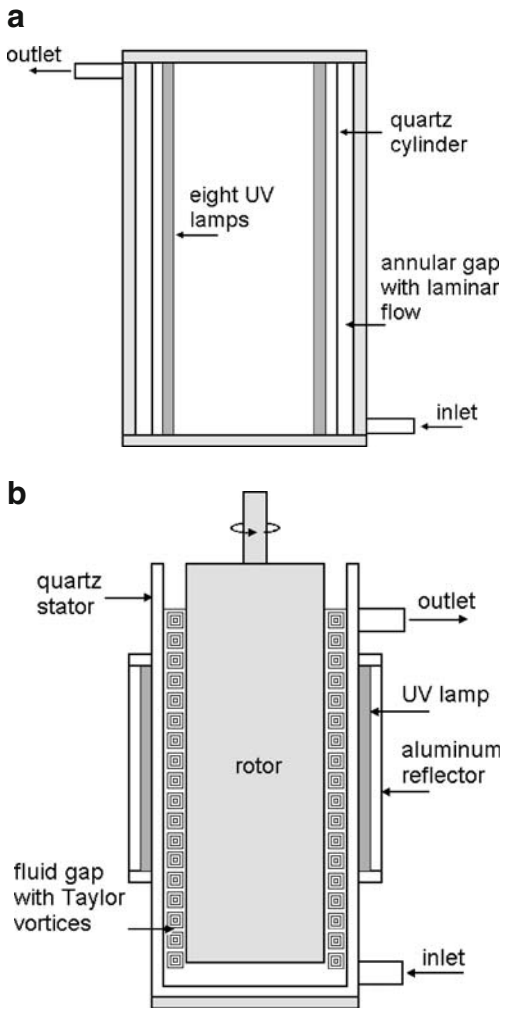

Fig. 2 Schematics of **a** a laminar thin film reactor (CiderSure) and **b** a laminar Taylor–Couette UV reactor (Koutchma 2008)

CiderSure 3500A was used. Apple cider was treated at 14.32 mJ/cm^2 for 1.2 to 1.9 s. This level of treatment successfully reduced oocysts from 10^6/mL to below the lower limit of detection, which were 23 oocysts per milliliter.

Guerrero-Beltran and Barbosa-Canovas (2006) studied inactivation of *S. cerevisiae*, *E. coli*, and *L. innocua* by UV light in apple juice. Two annular single lamp reactors from Atlantic UV Co. were connected in series and calculated *Re* numbers indicated that laminar flow was achieved during trials. The reduction of 1.34-log, 4.29-log, and 5.10-log after 30 min of UV treatment was reported for *S. cerevisiae*, *E. coli*, and *L. innocua*, respectively, at incident UV fluence of 45 mJ/cm^2. These authors also processed mango nectar with UV light and examined inactivation of *S. cerevisiae* and polyphenoloxidase using the lab scale UV reactors described above. A 3-log reduction after treatment for 30 min and shelf life extension up to 20 days for mango nectar were reported by these researchers.

UV treatment of orange juice was reported by Tran and Farid (2004) using a vertical single LPM UV lamp (6 W output power) thin film reactor. The thickness of the film was approximately 0.21–0.48 mm. The applied UV dose in the range of 12 to 147.6 mJ/cm^2 resulted in 3-log reduction of aerobic bacteria, yeasts, and molds.

Forney et al. (2004) developed a UV reactor that pumps fluid through the annular gap between two concentric cylinders (called Taylor–Couette flow), as shown in Fig. 2b. To provide sufficient exposure and to reduce the fluid boundary layer thickness, UV radiation source is contained within the outer stationary cylinder. The smaller inner cylinder is rotating and at low rotation rates, a laminar flow with vortices is established within the annular gap of several millimeters. The flow characteristics of this reactor approached ideal plug flow with a residence time that is uncoupled from the hydrodynamics or boundary layer characteristics. Commercial apple and grape juices inoculated with *E. coli* were treated in the Taylor–Couette reactor. Three to 5-log reductions of *E. coli* were reported. The UV dose of 9 mJ/cm^2 for a 4-log reduction in the pathogen level was determined.

Turbulent Flow Reactors

A second design approach increases the turbulence within a UV reactor to bring all liquid into close proximity of the UV light during the treatment. The higher flow rates achieved under turbulent conditions provide improved homogeneity of the flow when the fastest flowing particle travels 1.1–1.2 times faster than the volume averaged particle, and theoretically, each volume of the product will be exposed to UV light due to better mixing. Unfortunately, as turbulence increases, the pressure drops across the reactor, and the high flow rate to ensure turbulent flow is coupled with a reduced fluid residence time which can lead to complications in scale-up. In the Aquionics UV reactor (Hanovia Ltd, Slough, England, UK), treatment is achieved by passing liquid through a stainless steel chamber containing UV emitting low pressure arc tubes (Fig. 3a). Each single arc tube is mounted in a quartz sleeve and fitted within the chamber allowing the liquid to pass the sleeve on all sides (Koutchma et al. 2004).

Koutchma et al. (2004) examined individual physical and chemical factors in a model fluid that simulated pH, Brix, and a range of absorbencies of apple juice and cider for their effects on the efficacy of UV light on the destruction of *E. coli* K12 bacteria using a laminar and turbulent flow treatment system. A thin film flow-through laboratory UV unit ("CiderSure" Model 1500, FPE Inc.) and "Aquionics" UV reactor (Hanovia Ltd) were used in the study. The single factor found to consistently affect the efficacy of UV light inactivation in juice was absorbance.

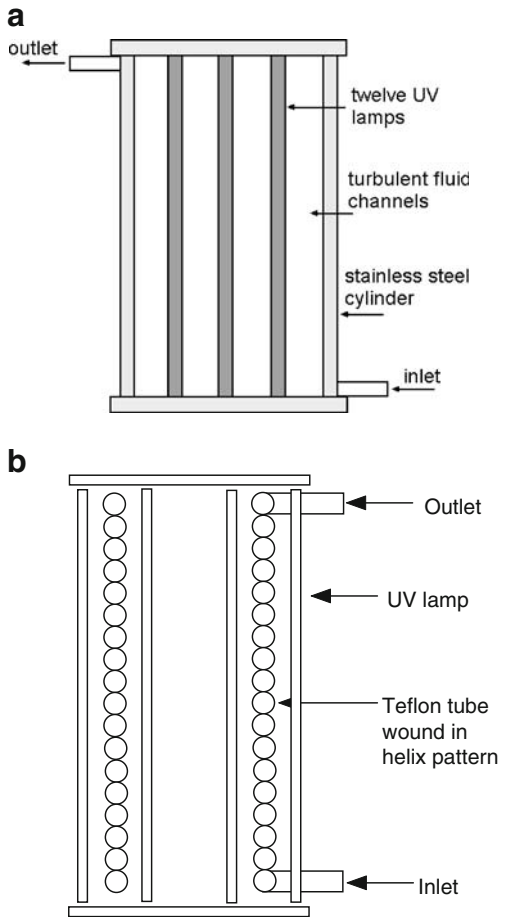

Fig. 3 Schematics of **a** turbulent channel reactor and **b** Dean flow reactor (Koutchma 2008)

The flow rates and mixing in the turbulent flow also affected microbial inactivation: the higher the flow rates, the higher the UV inactivation rates in the turbulent flow reactor. Regression equations were developed to describe the relationship between the rate of reduction of *E. coli* K12 and absorption coefficients in a thin film reactor and for the turbulent flow UV reactor.

In 2007, Keyser et al. reported that a novel system PureUV (Milnerton, South Africa) was used for the treatment of apple juice, guava-and-pineapple juice, mango nectar, strawberry nectar, and two different orange and tropical juices. The reactor consisted of inlet and outlet chambers and a corrugated spiral tube between the chambers. The UV lamp was mounted in a quartz sleeve inside the spiral tube. The tangential inlet created both a high velocity and turbulence (Re>7,500) even at a minimum flow rate of 3,800 L/h in the inlet chamber, and the liquid product was brought into contact with the UV radiation while flowing in a gap between sleeve and spiral tube. UV dosage levels up to 2,066 (J/L) were successfully applied to reduce microbial load in the different fruit juices and nectars. In comparison to heat pasteurization, juices treated with UV light did not change taste and color profiles. The authors concluded that optimization was essential for each specific juice.

Dean Flow Reactors

The UV module shown in Fig. 3b contains a coiled Teflon tube with UV lamps and reflectors placed both inside and outside the coiled tube, increasing not only UV irradiance of the flowing liquid, but its uniformity as well. The coiled tube promotes additional turbulence and causes a secondary eddy flow effect, also known as a Dean effect, and results in a more uniform velocity and residence time distribution (Dean 1927). A few reports are available on using coiled tube UV reactors to promote the additional mixing of fresh juices. Geveke (2005, 2008) processed apple cider and liquid egg white with a single lamp UV reactor surrounded by a coil of UV transparent Chemfluor tubing. *E. coli* K12 and *L. innocua* were used for inoculation of apple cider. It was reported that the population of *E. coli* K12 was reduced by 3.4-log after being exposed for 19 s to a 15-W LPM lamp. The population of *L. innocua* was more resistant to UV and was reduced by 2.5-log after being exposed for 58 s. The energy for the process was calculated as the ratio of lamp power to the flow rate and was equal to 34 J/mL. The population of *E. coli* in egg white was reduced by 4.3-log after being exposed to UV at 50 °C for 160 s. Inactivation was linearly dependent on treatment time and was adequately described using first-order kinetics. The electrical energy of the process was calculated to be 44 J/mL. Inactivation was directly dependent on temperature and inversely dependent on pH.

Koutchma et al. (2007) validated the performance of a coiled UV module 420 model (Salcor Inc., Fallbrook, CA, USA) with 24 lamps for fresh juices pasteurization. All tested fruit juices highly absorbed UV light, with absorption coefficients ranging from 11 to 78 cm^{-1} for lillikoi and pineapple juices, respectively. Of the juices examined, pineapple juice appeared to be the "worst case scenario" in terms of UV absorptivity and high viscosity. A caramel model solution was developed to mimic juice absorption properties of fruit juices and was used for inoculation studies with *E. coli* K12 bacteria. The 5-log reduction standard under turbulent flow required by the FDA was achievable in juices that were characterized as Newtonian liquids with an absorption coefficient less than 15 cm^{-1} after one pass. Turbulent flow was not developed in more viscous orange and pineapple juices at the flow rates tested. The inactivation performance in relation to spoilage microflora in tropical juices with pulp (orange, pineapple, guava nectar) was measured after two passes at flow rates of 4 gpm. No more than 1-log reduction of the aerobic plate count (APC) was achieved in orange, guava, and pineapple juices; however, the APC was reduced more than 3-logs in

carrot juice. Approximately 1.2–1.6-log reductions of yeasts and up to 1.6-log reduction of molds were achieved in treated juices.

The current 21 CFR 179 food additive regulation recognizes distinctions between flow patterns and stipulates the use of turbulent flow for UV light reactors used to treat fresh juices. However, the presence of dead spaces in the reactor may affect the average residence time of the fluid in the reactor and requires tracer analysis to measure the residence time distribution. A desirable design for UV reactors with ideal flow will indicate that every element of liquid resides in the reactor for the same time period and all microorganisms would receive an equivalent UV dose, if the UV irradiance were equal at all points. However, it is important to recognize that treatment of some high viscosity fluids or fluids with pulp will be incompatible with some of the reactor designs.

Conclusions

Ultraviolet light processing can be a viable non-thermal alternative in liquid foods and beverages based on sufficient evidence in the literature on the success of this method for eliminating or reducing the levels of most types of undesirable microorganisms. Compared to other non-thermal processing methods, UV treatment has received less attention. Little is known about the interaction of UV light with a complex food matrix that can often be referred to as radiative transfer in a semitransparent or turbid medium. Within a food product, several factors can influence the delivery of the UV dose. One factor found to consistently affect the efficacy of UV light inactivation in a liquid system was absorbance. Changes and variation in UV absorbance of food products needs to be considered in the design of the preservation process and reactor performance validation. The presence of particles can shield microorganisms from the UV irradiation. UV treatment does not demonstrate linear inactivation kinetics. Initial treatment damages or injures cells, which is demonstrated by a shoulder in the inactivation curve. Rapid inactivation is often followed by a tailing of survival. Some of the tailing effects can be explained by shielding effects of the microbes in the food matrix. In addition, the most resistant microorganisms of public health significance have not been fully determined. Bacterial spores and viruses appear to be the most resistant forms. The device to measure UV inactivation in low UVT liquids needs to be designed in order to deliver uniform UV dosage.

The effect of UV light on quality of foods requires further study. UV light can adversely affect food by generating free radicals in products by a wide variety of organic photochemical reactions. Possible undesirable effects include damage to vitamins and proteins, destruction of the antioxidants, oxidation of lipids, changes in color, and formation of off-flavors and aromas. Tests of light-sensitive vitamins in apple, carrot, and orange juices have shown that beta-carotene, vitamin C, and vitamin A are degraded by UV treatment. Loss of nutrients and development of off-flavors during UV processing of juices need further investigation, and attempts should be made to minimize the damaging effects of UV light on different groups of food products. In addition, the effects of UV light on the potential formation of chemical compounds in foods that may present a health threat should be evaluated to determine if there are toxicological or chemical safety concerns associated with products that have undergone UV treatment. The potential of UV light to destroy undesirable compounds or pollutants such as furans or dioxins also deserves closer examination.

The success of UV technology depends on the correct alignment of the UV source parameters to the specific demands of the UV application. Mercury lamps, the dominant sources for UV treatment, are highly developed and provide good efficiency, long life, and compact size for various applications. Low pressure mercury lamps are easy to install and operate. They are readily available with a well-established and quantified emission spectrum at comparatively low cost. Medium pressure lamps have higher emission intensity in the UV-C range; however, the source is polychromatic. The lamp source operates at high temperatures and at higher electrical potential. Lamp material and enclosures of MPM lamps age faster than LPM. Special technology lamps are promising due to instant start and robust packaging with no mercury in the lamp. Light sources such as pulsed lamps, excimer lamps, and UV light emitting diodes hold promise for future applications and more research is needed to establish them for food applications. Recent developments in UV lamp technology are encouraging; however, more work is needed in the design of UV reactors capable of providing sufficient UV doses to all parts of the treated liquid.

References

Altic, L., Rowe, M., & Grant, I. (2007). UV light inactivation of *Mycobacterium avium subsp. paratuberculosisin* in milk as assessed by *FASTPlaque* TB phage assay and culture. *Applied and Environmental Microbiology*, *73*(11), 3728–3733. doi:10.1128/AEM.00057-07.

Anonymous. (1999) A food additive petition for the use of ultraviolet light in the reduction of microorganisms on juice products. Submitted to FDA regarding CFR 21 179. Glendore Calif. California Day-Fresh Foods Inc, 1–117.

Benabbou, A. K., Derriche, Z., Felix, C., Lejeune, P., & Guillard, C. (2007). Photocatalytic inactivation of *Escherischia coli*: Effect of concentration of TiO2 and microorganism, nature, and intensity of UV irradiation. *Applied Catalysis Environmental*, *76*, 257–263. doi:10.1016/j.apcatb.2007.05.026.

Cairns, B. (2006). UV dose required to achieve incremental log inactivation of bacteria, protozoa and viruses. *IUVA News*, *8*(1), 38–45.

Chang, J. C. H., Ossoff, S. F., Lobe, D. C., Dorfman, M. H., Dumais, C. M., Qualls, R. G., et al. (1985). UV inactivation of pathogenic and indicator microorganisms. *Applied and Environmental Microbiology*, *49*(1), 1361–1365.

Chiu, K., Lyn, D. A., Savoye, P., & Blatchley, E. R. (1999). Effect of UV system modification on disinfection performance. *Journal of Environmental Engineering*, *125*, 7–16. doi:10.1061/(ASCE)0733-9372(1999)125:1(7).

Christenen, J., & Linden, K. (2001). Ultraviolet disinfection of unfiltered drinking water: particle impacts. Conference Proceedings of First International Congress on UV technologies. IUVA, Washington, DC, June 14–16.

Clarke, S. (2006) Ultraviolet light disinfection in the use of individual water purification devices. Technical paper TIP #31-006-0206 15.

Collins, H. F., & Selleck, R. E. (1972). Process kinetics of wastewater chlorination, *SERL Rep.,* Univ. of Calif., Berkeley, 72–5.

Dean, W. R. (1927). Motion of fluid in a curved pipe. *Philosophical Magazine and Journal of Science*, *4*, 208–223.

EPA, Office of Water. (1995) National Primary Drinking Water Regulations Contaminant Fact Sheets Inorganic Chemicals—Technical Version. EPA 811-F-95-002-T, Washington, D.C.

Fan, X., & Geveke, D. (2007). Furan formation in sugar solution and apple cider upon ultraviolet treatment. *Journal of Agricultural and Food Chemistry*, *55*(19), 7816–7821. doi:10.1021/jf071366z.

Forney, L., Pierson, J. A., & Ye, Z. (2004). Juice irradiation with Taylor–Coutte Flow: UV inactivation of *Escherichia coli*. *Journal of Food Protection*, *67*(11), 2410–2415.

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

Geveke, D. (2008). UV inactivation of *E. coli* in liquid egg white. *Food and Bioprocess TechnologyFood Bioprocess Technol*, *1*(2), 201–206. doi:10.1007/s11947-008-0070-1.

Guerrero-Beltran, J. A., & Barbosa-Canovas, G. V. (2006). Reduction of *Saccharomyces cerevisiae, Escherichia coli and Listeria innocua* in apple juice by ultraviolet light. *Journal Of Food Process Engineering*, *28*, 437–452. doi:10.1111/j.1745-4530.2005.00040.x.

Hanes, D. E., Orlandi, D. H., Burr, M. D., Miliotis, M. G., Robi, J. W., Bier, G. J., et al. (2002). Inactivation of *Crytosporidium parvum* oocysts in fresh apple cider using ultraviolet irradiation. *Applied and Environmental Microbiology*, *68*, 4168–4172. doi:10.1128/AEM.68.8.4168-4172.2002.

Harris, G. D., Adams, V. D., Sorensen, D. L., & Curti, M. S. (1987). Ultraviolet inactivation of selected bacteria and viruses with photoreactivation of the bacteria. *Water Research*, *21*, 687–692. doi:10.1016/0043-1354(87)90080-7.

Hijnen, W. A. M., Beerendonk, E. F., & Medema, G. J. (2006). Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: A review. *Water Research*, *40*, 3–22. doi:10.1016/j.watres.2005.10.030.

Hoyer, O. (1998). Testing performance and monitoring of UV systems for drinking water disinfection. *Water Supply*, *16*(1/2), 424–429.

Jyoti, K., & Pandit, A. (2004). Ozone and cavitation for water disinfection. *Biochemical Engineering Journal*, *18*, 9–19. doi:10.1016/S1369-703X(03)00116-5.

Keyser, M., Müller, I., Cilliers, F. -P., Nelb, W., & Gouwsa, P. -A. (2008). UV radiation as a nonthermal treatment for the inactivation of microorganisms in fruit juices. *Innovative Food Science and Emerging Technologies*, 9, 348–354.

Koutchma, T. (2008). UV-light for processing foods. *Ozone: Science And Engineering*, *30*(1), 93–98. doi:10.1080/01919510701816346.

Koutchma, T., & Parisi, B. (2004). Biodosimetry of *Escherichia coli* UV inactivation in model juices with regard to dose distribution in annular UV reactors. *Journal of Food Science*, *69*(1), E14–E22.

Koutchma, T., Keller, S., Parisi, B., & Chirtel, S. (2004). Ultraviolet disinfection of juice products in laminar and turbulent flow reactors. *Innovative Food Science and Emerging Technologies*, *5*, 179–189. doi:10.1016/j.ifset.2004.01.004.

Koutchma, T., Parisi, B., & Patazca, E. (2007). Validation of UV coiled tube reactor for fresh fruit juices. *Journal of Environmental Engineering*, *6*, 319–328. doi:10.1139/S06-058.

Kowalski, W. J. (2001). Design and optimization of UVGI air disinfection system, Ph.D. thesis, Pennsylvania State University.

Kuo, J., Chen, C., & Nellor, M. (2003). Standardized collimated beam testing protocol for water wastewater ultraviolet disinfection. *Journal of Environmental Engineering*, *8*, 773–779.

Masschelein, W. J. (2002). *Ultraviolet light in water and wastewater sanitation*. Boca Raton: CRC.

Matak, K. E., Sumner, S. S., Duncan, S. E., Hovingh, E., Worobo, R. W., Hackney, C. R., et al. (2007). Effects of ultraviolet irradiation on chemical and sensory properties of goat milk. *Journal of Dairy Science*, *90*, 3178–3186. doi:10.3168/jds.2006-642.

Meier, J., Slater, A., Bourgeous, K., & Salveson, A. (2007). *Microwave UV—The future of UV disinfection*. Los Angeles: UV and Ozone World Congress.

Murakami, E., Jackson, L., Madsen, K., & Schickedanz, B. (2006). Factors affecting the ultraviolet inactivation of *Escherichia coli* K12 in apple juice and a model system. *Journal of Food Process Engineering*, *29*, 53–71. doi:10.1111/j.1745-4530.2006.00049.x.

Ngadi, M., Smith, J., & Cayouette, B. (2003). Kinetics of ultraviolet light inactivation of *Escherichia coli* O157:H7 in liquid foods. *Journal of the Science of Food and Agriculture*, *83*, 1551–1555. doi:10.1002/jsfa.1577.

Oms-Oliu, G., Martín-Belloso1, O., & Soliva-Fortuny1, R. (2009). Pulsed light treatments for food preservation. A review. *Food and Bioprocess Technology* (in press). doi:10.1007/s11947-008-0147-x.

Oteiza, J., Peltzer, M., Gannuzzi, L., & Zaritzky, N. (2005). Antimicrobial efficacy of UV radiation on *Escherichia coli* O157:H7 in fruit juices of different absorptivities. *Journal of Food Protection*, *68*(1), 49–58.

Ozer, N., & Demirci, A. (2006). Inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* inoculated on raw salmon fillets by pulsed UV-treatment. *International Journal of Food Science & Technology*, *41*, 354–360. doi:10.1111/j.1365-2621.2005.01071.x.

Qualls, R., Flynn, M. P., & Johnson, J. D. (1983). The role of suspended particles in ultraviolet disinfection. *Journal of Water Pollution Control Federation*, *55*, 1280–1285.

Schaefer, R., Grapperhaus, M., & Linden, K. (2007). *Status report on the development and use of pulsed UV technologies for treating water*. Los Angeles: UV and Ozone World Congress.

Severin, B. F., Suidan, M. T., & Engelbrecht, R. S. (1983). Kinetic modeling of UV disinfection of water. *Water Research*, *17*(11), 1669–1678. doi:10.1016/0043-1354(83)90027-1.

Sommer, R., Haider, T., Cabaj, A., Pribil, W., & Lhotsky, M. (1998). Time fluence reciprocity in UV disinfection of water. *Water Science And Technology*, *38*(12), 145–50. doi:10.1016/S0273-1223(98)00816-6.

Sommers, R., Weber, G., Cabaj, A., Wekerle, J., Keck, G., & Schauberger, G. (1989). UV inactivation of microorganisms in water. *Zentralblatt fur Hygiene und Umweltmedizin*, *189*, 214–24.

Spikes, J. (1981). Photodegradation of foods and beverages. In K. C. Smith (Ed.), *Photochemical and Photobiological Reviews* (vol. 6, (pp. 39–81Plenum)). New York.

Supplement to Journal of Food Protection (2006) NACMCF requisite scientific parameters for establishing alternative methods of pasteurization, 69(5), 1190–1216.

Tandon, K., Worobo, R., Churley, J., & Padilla-Zakour, O. (2003). Storage quality of pasteurized and UV treated apple cider. *Journal of Food Processing and Preservation*, *27*, 21–35. doi:10.1111/j.1745-4549.2003.tb00498.x.

Thiruvenkatachari, R., Ouk Kwon, T., & Shik Moon, I. (2006). Degradation of phthalic acids and benzoic acid from terephthalic acid wastewater by advanced oxidation processes. *Journal of Environmental Science and Health. Part A, Environmental Science and Engineering*, *41*, 1685–1697.

Tran, M. T., & Farid, M. (2004). Ultraviolet treatment of orange juice. *Innovative Food Science and Emerging Technologies*, *5*(4), 495–502. doi:10.1016/j.ifset.2004.08.002.

U.S. Food and Drug Administration (2000). 21 CFR Part 179. Irradiation in the production, processing and handling of food. *Federal Register*, *65*, 71056–71058.

U.S. Food and Drug Administration. Code 21CFR179.41 Title 21—Food and drugs (page 438) Part 179—Irradiation in the production, processing and handling of food. Subpart B—Radiation and radiation sources. Sec. 179.41 Pulsed light for the treatment of food.

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

Unluturk, S., Mehmet, R., Atılgan, A., Baysal, H., & Tarı, C. (2008). Use of UV-C radiation as a non-thermal process for liquid egg products (LEP). *Journal of Food Engineering*, *85*, 561–568. doi:10.1016/j.jfoodeng.2007.08.017.

Voronov, A. (2007). *New generation of low pressure mercury lamps for producing ozone*. Los Angeles: UV and Ozone World Congress.

Warriner, K., Rysstad, G., Murden, A., Rumsby, P., Thomas, D., & Waites, W. (2000). Inactivation of *Bacillus subtilis* spores on aluminum and polyethylene preformed cartons by UV-excimer laser irradiation. *Journal of Food Protection*, *63*, 753–757.

Warriner, K., Kolstad, J., Rumsby, J., & Waites, W. (2002). Carton sterilization by UV-C excimer laser light: Recovery of *Bacillus subtilis* spores on vegetable extracts and food simulation matrices. *Journal of Applied Microbiology*, *92*, 1051–1057. doi:10.1046/j.1365-2672.2002.01641.x.

Woodling, S. E., & Moraru, C. I. (2005). Influence of surface topography on the effectiveness of pulsed light treatment for the inactivation of *Listeria innocua* on stainless steel surfaces. *Journal of Food Science*, *70*(7), 345–51. doi:10.1111/j.1365-2621.2005.tb11478.x.

Worobo, R. (1999). Efficacy of the CiderSure 3500 Ultraviolet light unit in apple cider. CFSAN Apple cider food safety control workshop.

Wright, J. R., Sumner, S. S., Hackney, C. R., Pierson, M. D., & Zoecklein, B. W. (2000). Efficacy of ultraviolet light for reducing *Escherichia coli* O157:H7 in unpasteurized apple cider. *Journal of Food Protection*, *63*, 563–567.

Xie, Y., Hajdok, C., Mittal, G., & Warriner K. (2008). Inactivation of MS2 F(+) coliphage on lettuce by a combination of UV light and hydrogen peroxide. *Journal of Food Protection*, *71*(5), 903–907.

Ye, Z. (2007). UV disinfection between concentric cylinders, Ph.D. thesis, Georgia Institute of Technology.

Ye, Z., Koutchma, T., Parisi, B., Larkin, J., & Forney, L. (2007). Ultraviolet inactivation kinetics *of E. coli* and *Y. pseudotuberculosis* in annular reactors. *Journal of Food Science*, *72*(5), E271–E278.