Contemporary Food Engineering Series

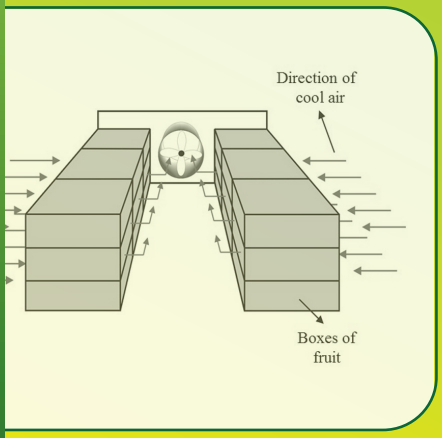
Da-Wen Sun, Series Editor

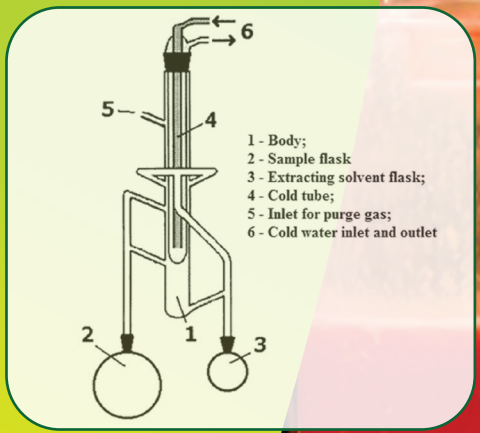
Advances in Fruit Processing Technologies

Edited by

Sueli Rodrigues

Fabiano André Narciso Fernandes





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Advances in Fruit Processing Technologies

Contemporary Food Engineering

Series Editor

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Series Preface

Contemporary Food Engineering

Food engineering is the multidisciplinary field of applied physical sciences combined with the knowledge of product properties. Food engineers provide the technological knowledge transfer essential to the cost-effective production and commercialization of food products and services. In particular, food engineers develop and design processes and equipment to convert raw agricultural materials and ingredients into safe, convenient, and nutritious consumer food products. However, food engineering topics are continuously undergoing changes to meet diverse consumer demands, and the subject is being rapidly developed to reflect market needs.

In the development of food engineering, one of the many challenges is to employ modern tools and knowledge, such as computational materials science and nanotechnology, to develop new products and processes. Simultaneously, improving food quality, safety, and security continues to be a critical issue in food engineering study. New packaging materials and techniques are being developed to provide more protection to foods, and novel preservation technologies are emerging to enhance food security and defense. Additionally, process control and automation regularly appear among the top priorities identified in food engineering. Advanced monitoring and control systems are developed to facilitate automation and flexible food manufacturing. Furthermore, energy saving and minimization of environmental problems continue to be important food engineering issues, and significant progress is being made in waste management, efficient utilization of energy, and reduction of effluents and emissions in food production.

The Contemporary Food Engineering Series, consisting of edited books, attempts to address some of the recent developments in food engineering. The series covers advances in classical unit operations in engineering applied to food manufacturing as well as such topics as progress in the transport and storage of liquid and solid foods; heating, chilling, and freezing of foods; mass transfer in foods; chemical and biochemical aspects of food engineering and the use of kinetic analysis; dehydration, thermal processing, nonthermal processing, extrusion, liquid food concentration, membrane processes, and applications of membranes in food processing; shelf-life and electronic indicators in inventory management; sustainable technologies in food processing; and packaging, cleaning, and sanitation. These books are aimed at professional food scientists, academics researching food engineering problems, and graduate-level students.

The editors of these books are leading engineers and scientists from many parts of the world. All the editors were asked to present their books to address the market's need and pinpoint the cutting-edge technologies in food engineering.

All the contributions have been written by internationally renowned experts who have both academic and professional credentials. All the authors have attempted to provide critical, comprehensive, and readily accessible information on the art and science of a relevant topic in each chapter, with reference lists for further information. Therefore, each book can serve as an essential reference source to students and researchers in universities and research institutions.

Da-Wen Sun
Series Editor

Series Editor

Professor Da-Wen Sun, PhD, is a world authority on food engineering research and education; he is a member of the Royal Irish Academy, which is the highest academic honor in Ireland; he is also a member of Academia Europaea (The Academy of Europe). His main research activities include cooling, drying, and refrigeration processes and systems; quality and safety of food products; bioprocess simulation and optimization; and computer vision technology.

In particular, his innovative studies on vacuum cooling of cooked meat, pizza quality inspection using computer vision, and edible films for shelf-life extension of fruits and vegetables have been widely reported in the national and international media. Results of his work have been published in about 600 papers, including over 250 peer-reviewed journal papers (h-index = 36). He has also edited 13 authoritative books. According to Thomson Scientific's *Essential Science IndicatorsSM* updated as of July 1, 2010, based on data derived over a period of ten years and four months (January 1, 2000–April 30, 2010) from the ISI Web of Science, a total of 2554 scientists are among the top 1% of the most cited scientists in the category of agriculture sciences, and Professor Sun is listed at the top with a ranking of 31.

Dr. Sun received his first class BSc honors and his MSc in mechanical engineering, and his PhD in chemical engineering in China before working at various universities in Europe. He became the first Chinese national to be permanently employed in an Irish university when he was appointed a college lecturer at the National University of Ireland, Dublin (University College Dublin [UCD]), in 1995. He was then continuously promoted in the shortest possible time to the position of senior lecturer, associate professor, and full professor. Dr. Sun is now a professor of food and biosystems engineering and director of the Food Refrigeration and Computerized Food Technology Research Group at UCD.

As a leading educator in food engineering, Dr. Sun has contributed significantly to the field of food engineering. He has guided many PhD students who have made their own contributions to the industry and academia. He has also, on a regular basis, given lectures on the advances in food engineering at international academic institutions and delivered keynote speeches at international conferences. As a recognized authority in food engineering, Dr. Sun has been conferred adjunct/visiting/consulting professorships by over ten top universities in China, including Zhejiang University, Shanghai Jiaotong University, Harbin Institute of Technology, China Agricultural University, South China University of Technology, and Jiangnan University. In recognition of his significant contribution to food engineering worldwide and for his outstanding leadership in the field, the International Commission of Agricultural and

Biosystems Engineering (CIGR) awarded him the CIGR Merit Award in 2000 and again in 2006; the U.K.-based Institution of Mechanical Engineers named him Food Engineer of the Year 2004; in 2008, he was awarded the CIGR Recognition Award in recognition of his distinguished achievements as the top 1% of agricultural engineering scientists around the world; in 2007, he was presented with the only AFST(I) Fellow Award in that year by the Association of Food Scientists and Technologists (India); and in 2010, he was presented with the CIGR Fellow Award (the title of "Fellow" is the highest honor in CIGR and is conferred upon individuals who have made sustained, outstanding contributions worldwide).

Dr. Sun is a fellow of the Institution of Agricultural Engineers and a fellow of Engineers Ireland (the Institution of Engineers of Ireland). He has also received numerous awards for teaching and research excellence, including the President's Research Fellowship, and has received the President's Research Award from UCD on two occasions. He is also the editor in chief of *Food and Bioprocess Technology—An International Journal* (Springer) (2010 Impact Factor = 3.576, ranked at the fourth position among 126 ISI-listed food science and technology journals); series editor of the Contemporary Food Engineering Series (CRC Press/Taylor & Francis Group); former editor of *Journal of Food Engineering* (Elsevier); and an editorial board member of *Journal of Food Engineering* (Elsevier), *Journal of Food Process Engineering* (Blackwell), *Sensing and Instrumentation for Food Quality and Safety* (Springer), and *Czech Journal of Food Sciences*. Dr. Sun is also a chartered engineer.

On May 28, 2010, he was awarded membership to the Royal Irish Academy (RIA), which is the highest honor that can be attained by scholars and scientists working in Ireland. At the 51st CIGR General Assembly held during the CIGR World Congress in Quebec City, Canada, in June 2010, he was elected as incoming president of CIGR and will become CIGR president in 2013–2014. The term of the presidency is six years—two years each for serving as incoming president, president, and past president. On September 20, 2011, he was elected to Academia Europaea (The Academy of Europe), which is functioning as European Academy of Humanities, Letters and Sciences and is one of the most prestigious academies in the world; election to the Academia Europaea represents the highest academic distinction.

Preface

Fruits are major food products and key ingredients in many processed foods. They are a rich source of vital nutrients and constitute an important component of human nutrition. Consumers nowadays are more aware of the importance of healthy foods and require food products with high nutritional value along with high standards of sensory characteristics. Thus, fruit processing has to preserve the nutritional value of the fruit, while also preserving its natural color and flavor. This book reviews new advances in fruit-processing technologies.

Fruits are highly perishable, and about 20%–40% of the fruits produced are wasted from the time of harvesting till they reach the consumers, either in natural form or in processed form. To reduce fruit loss and improve final sensory characteristics of processed fruits, new or improved technologies have been applied to fruit processing. This book reviews new technologies, such as ozone application, ultrasound processing, irradiation application, pulsed electric field, vacuum frying, and high-pressure processing, and improved technologies, such as ultraviolet and membrane processing, enzymatic maceration, freeze concentration, and refrigeration.

The effect of processing on sensory characteristics and nutritional value is addressed in each chapter. New trends in modified atmosphere packaging, effects of processing on aroma, and the use of fruit juices as a vehicle for probiotic microorganisms and prebiotic oligosaccharides as an alternative for dairy products are also covered in this book.

Editors

Sueli Rodrigues is currently a professor of food engineering at the Federal University of Ceará, Fortaleza, Brazil, where she teaches and does research on process and product development. She graduated in chemical engineering from the State University of Campinas, Campinas, São Paulo, Brazil, and received her PhD in chemical engineering in 2003 from the same university.

Dr. Rodrigues has published more than 65 papers in scientific journals. Her research interests include bioprocess, ultrasound, and drying technology, especially with fruit and functional food processing.

Fabiano André Narciso Fernandes is currently a professor of chemical engineering at the Federal University of Ceará, Fortaleza, Brazil, where he teaches and does research on process and product development. He graduated in chemical engineering from the Federal University of São Carlos, São Carlos, São Paulo, Brazil. He received his PhD in chemical engineering in 2002 from the Sate University of Campinas, Campinas, São Paulo, Brazil.

Dr. Fernandes has published more than 90 papers in scientific journals. His research interests include drying technology, ultrasound technology, and the field of reaction engineering.

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1 Ultraviolet Light for Processing Fruits and Fruit Products

Tatiana Koutchma and Marta Orlowska

CONTENTS

1.1 INTRODUCTION

During the last decade, there has been an increase in the production of fresh fruit and fruit products due to the health properties of fruits. Fruit products can be consumed in raw, minimally processed or processed, ready-to-eat/ready-to-drink forms as whole fresh fruits, fresh-cut fruits, and fruits as ingredients, beverages, juices, and jams. The processing of fruits starts after harvesting and consists of four activities: stabilization or preservation, transformation, production of ingredients, and production of fabricated foods. The role of processing technology in each stage implies the control of microbiological, chemical, and biochemical changes, which occur as a result of microbial and enzymatic activities, and oxidation reactions, which can lead to problems of safety, color, flavor, taste, and texture. Processing technologies that do not significantly alter the organoleptic or nutritional qualities of fruits and do not form any undesirable chemical compounds in the product have obvious advantages in modern food production. The interest in so-called minimal processing technologies led to the development of nonthermal or mild heat high-tech methods that have the potential to replace traditional thermal preservation techniques. They result not only in better quality and longer shelf life but also, potentially, in higher nutritional value or products with health benefits. A large number of studies have associated consumption of fruits and their products with decreased risk of development of diseases such as cancer and coronary heart disease (Hansen et al., 2003). This may be due to the presence of health-promoting phytochemicals such as carotenoids, flavonoids, phenolic compounds, and vitamins (Gardner et al., 2000), which have, in some cases, been shown to have disease-preventing properties. In this respect, it is of paramount importance to develop processing methods that preserve not only the safety of fruits but also the sensorial and nutritional quality and bioactivity of the constituents present in fruits and their products.

Ultraviolet (UV) light treatment of foods is a nonthermal physical method of preservation that is free of chemicals and waste effluents, which makes it ecologically friendly. It does not produce by-products. It is safe to use, although precautions must be taken to avoid human exposure to UV light and to evacuate ozone generated by vacuum and far UV wavelengths. Based on recent engineering advances and new scientific data, UV light technology in continuous and pulsed modes (cUV and PL) offers the promise of enhanced microbiological safety of fresh fruits and improved quality of fruit products that have a freshness of flavor, color, texture, and nutritional value closer to those of nontreated products. The discovery of UV inactivation of the chlorine-resistant parasites *Cryptosporidium parvum* and *Giardia* sp. has catalyzed the use of UV light in the water industry (Hijnen et al., 2006). UV has been utilized similarly in the disinfection of air, nonfood contact, and food contact surfaces, and recently was used for treatments of surfaces of solid foods and liquid

foods, beverages, and ingredients. Reports are available that indicate that application of UV light can also improve the toxicological safety of foods of plant origin through its ability to reduce levels of toxins such as patulin mycotoxin in fresh apple cider (Dong et al., 2010) and possibly to control browning through its effects on enzymes (Manzocco et al., 2009). Regarding the preservation of organoleptic and nutritional attributes, recent research has shown promising results in the exposure of fruit products to UV irradiation. In addition to higher cost-efficiency, sustainability, and broad antimicrobial effects, UV light not only minimally affects quality attributes but also has beneficial effects on the content of bioactive compounds. It has the potential for obtaining premium quality products that can lead to faster commercialization.

This chapter aims to provide detailed and critical information on the latest applications of continuous and pulsed UV light for processing fresh fruits and fruits products. The fundamental principles and features of UV light generation, propagation, and photochemistry are briefly reviewed, and the control measures to be adopted where UV technology can be utilized to enhance safety during fruit production are analyzed. Particular focus is given to the effects of UV light on the survival of pathogenic and spoilage microorganisms typical to fruits and the environment essential in fruit processing followed by a discussion of recent research into effects of UV light on quality and bioactive compounds.

1.2 BASICS OF UV PROCESSING OF FOODS OF PLANT ORIGIN

1.2.1 UV Light Sources

Light is emitted from gas discharge at wavelengths dependent on its elemental composition and the excitation, ionization, and kinetic energy of those elements. Gas discharges are responsible for the light emitted from UV lamps. UV light transfer phenomenon is defined by the emission characteristics of the UV source along with considering long-term lamp aging and absorbance/scattering of the product. Consequently, the performance of a UV system depends on the correct matching of the UV source parameters to the demands of the UV application. The commercially available UV sources include low- and medium-pressure mercury lamps (LPM and MPM), excimer lamps (EL), pulsed lamps (PL), and light-emitting diodes (LED). LPM and EL are monochromatic sources, whereas emission of MPM and PL is polychromatic. There are no reports on the application of EL in fruit processing, so this UV source is not discussed in this chapter.

1.2.1.1 Mercury Lamps

Mercury vapor UV lamp sources have been successfully used in water treatment for nearly 50 years and are considered as reliable sources for other disinfection treatments that benefit from their performance, low cost, and quality. Typically, three general types of mercury UV lamps are used: low-pressure (LPM), low-pressure high-output (LPHO), and medium-pressure (MPM). These terms are based on the vapor pressure of mercury when the lamps are operating. The effects of mercury vapor pressure on spectra distribution is shown in Figure 1.1. Vapor discharge lamps consist of a UV-transmitting envelope made from a tube of vitreous silica

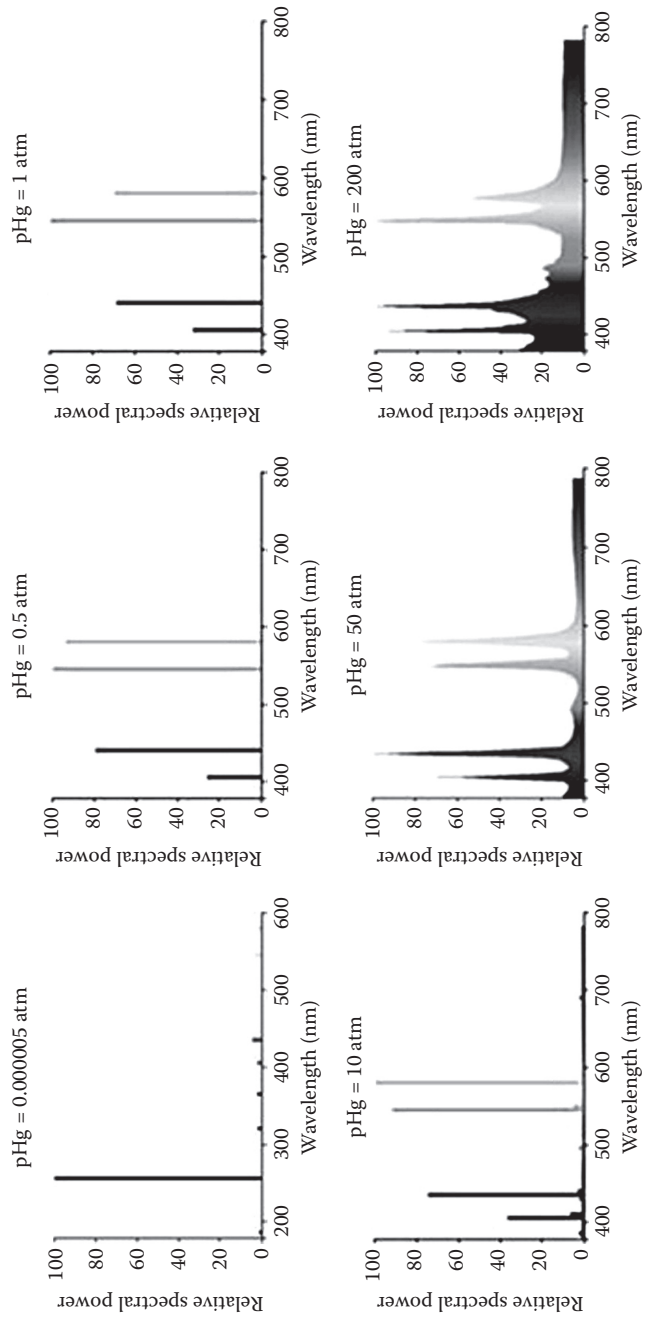

FIGURE 1.1 Effects of vapor pressure of mercury on output spectra distribution.

glass sealed at both ends. The envelope is filled with mercury and an inert gas. Argon, the most common filler, has ionization energy of 15.8 eV, whereas the lowest activated metastable state is at 11.6 eV (Masschelein and Rice, 2002).

LPM lamps are operated at nominal total gas pressures of 10^2–10^3 Pa, which corresponds to the vapor pressure of mercury at a temperature of 40°C. The emission spectrum of LPM is concentrated at the resonance lines at 253.7 and 185 nm. The 253.7 nm line represents around 85% of the total UV intensity emitted and is 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 of 185 nm, ozone is produced from oxygen and organic compounds can be oxidized (Voronov, 2007). The photons with the wavelength of 185 nm are responsible for ozone production, and the combination of both wavelengths is a very effective means for photochemical air treatment. The ratio of light at 185 nm to light at 253.7 nm varies from 12% to 34% depending on the operating current, wall temperature, and inert gas. The U.S. FDA regulations approved the use of LPM lamps for juice processing, and they have already been successfully commercialized (U.S. FDA, CFR part 179, 2000).

MPM lamps are operated at a total gas pressure of 104–106 Pa (Masschelein and Rice, 2002). Compared with 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. MPM lamps operate in the potential gradient range of 5–30 W/cm. The emission spectrum of MPM covers wavelengths from about 250 nm to almost 600 nm, which results from a series of emissions in the UV and in the visible range. MPM 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.

Recently, LPHO amalgam lamps that contain a mercury amalgam was developed and incorporated into disinfection applications; however, LPM and MPM are the dominant sources for UV disinfection treatment.

1.2.1.2 Environmental Impact

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 with LPHO (26–150 mg/lamp) and MPM lamps (200–400 mg/lamp). 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 lamps with mercury-free special technologies.

1.2.1.3 Pulsed Lamps

The efficacy of pulsed flash lamps (PL) is potentially greater than continuous sources due to high intensity and broader spectrum. PL technologies are promising due to their instant start, high intensity, and robust packaging with no mercury in the lamp, but more research is needed to establish them for fruit treatment applications. 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 ms. The emission is similar in wavelength composition to the solar light. The UV pulsed devices can deliver high-intensity UV, which can both penetrate opaque liquids better than mercury lamps and provide enhanced treatment rates. Figure 1.2 shows the normalized spectra of these three UV sources—LPM, MPM, and PL. Individual spectra are not comparable on a UV intensity basis but are comparable on a spectral basis with reference to which wavelengths dominate the respective wavelength outputs.

Table 1.1 provides a summary of some of the basic characteristics of common UV sources in commercial use and under development that can be used for comparison purposes. 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 LPHO 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. Lamps with special technologies such as PL UV and EL are promising due to the different spectral bands or specific wavelengths that they can provide with regard to 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 fruit processing applications.

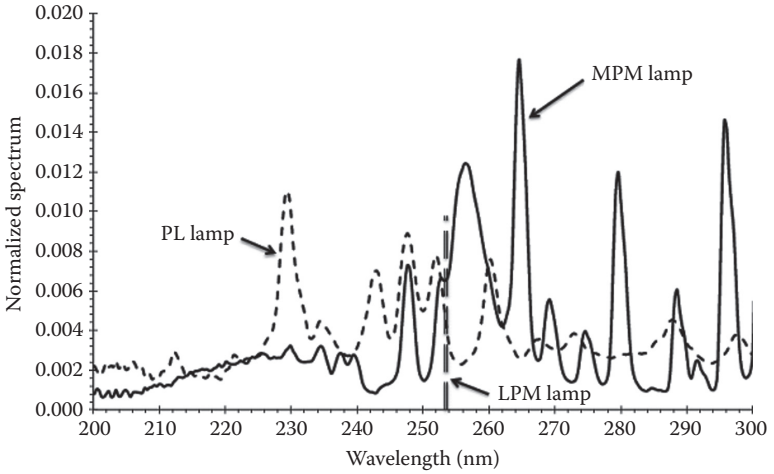

FIGURE 1.2 Comparison of spectrums of continuous (LPM and MPM) lamps and PL UV sources.

TABLE 1.1
Comparison of Efficiency Characteristics of Continuous and Pulsed UV Sources

UV Source	Electrical Efficiency (%)	UV Efficiency (%)	UV Intensity (W/cm^2)	Lamp Surface T (°C)	Lifetime, Month	Output Spectrum
LPM	50	38	0.001–0.01	40	18–24	Monochromatic 253.7 nm
Excimer	10–25	10–30	0.05–0.5	Ambient	13	Monochromatic selectable
MPM	15–30	12	12	400–1,000	0.5	Polychromatic 200–400 nm
Flash xenon	45–50	9	600	1,000–10,000	1	Polychromatic 100–1000 nm
Surface discharge	15–20	17	30,000	NA	NA	Polychromatic 200–800 nm

1.2.1.4 Light Emitting Diodes

In recent years, UV-LEDs have been developed with the following advantages: low cost, energy efficiency, long life, easy control of emission, and no production of mercury waste. The wavelength of the commercial UV-LED is around UV-A range (315–400 nm) and enables new applications in existing markets as well as open new areas. An LED is a semiconductor device that emits light when carriers of different polarities (electron and holes) combine generating a photon. The wavelength of the photon depends on the energy difference the carriers overcome in order to combine. An example of a UV-LED system that operates between 210 and 365 nm is the one formed by aluminum nitride (AIN), gallium nitride (GaN), and intermediate alloys. Currently, UV-LEDs are commercially available in research grade and limited quantities and their lifetimes reach the order of 200 h. It is very likely that in the near future, many applications that make use of mercury lamps today will be carried out by UV-LEDs.

1.2.2 UV Light Propagation

UV light emitted from the atoms and ions within the gas discharge of a UV source will propagate away from those atoms and ions. 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 on the surface or in the liquid.

Absorption (A) of light is the transformation of energy of light photons to other forms of energy as it travels through a substance. *Reflection* (R) 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 photons interact with a particle.

The scattering phenomenon plays an important role in disinfecting food liquids containing particles. Experimental measurements are usually made in terms of *transmittance* of a substance (T) or (UVT), which is defined as the ratio of the transmitted to the incident light irradiance. A convenient way of presenting information about UVT of materials is to give the values of their absorption coefficient at various wavelengths, over a given depth (e.g., 1 cm). Knowing this, the transmittance for any particular depth and the depth of the liquid that will absorb 90% of the energy at 253.7 nm can be calculated. Other important terms to characterize UV light treatments in fruit processing are *fluence rate* and *fluence*. Fluence rate is "the total radiant power incident from all directions onto an infinitesimally small sphere of cross-sectional area dA, divided by dA" (Bolton and Linden, 2003). Fluence is defined as the fluence rate multiplied by the exposure time. The term *UV dose* should be avoided as a synonym of fluence because dose refers in other contexts to absorbed energy, but only a small fraction of all incident UV light is absorbed by microorganisms (Bolton and Linden, 2003). In the case of PL, fluence is determined as energy per pulse multiplied by the number of pulses. The absorbed fluence indicates that radiant energy is available for driving the solution reaction. However, when UV light is absorbed by 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. The radiant energy delivered to the molecule or microorganism is called the effective or delivered germicidal UV dose. Microbial inactivation depends primarily on the effective dose. The formulas for calculations of the critical UV process parameters are available in the literature (Koutchma et al., 2008).

1.2.3 Basic Principles of Photochemistry

Photochemical reactions proceed as a direct result of radiation energy (photons) being introduced to a system. 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

$$A + h\nu \rightarrow A_{+}^{+} \rightarrow \text{Products} \tag{1.1}$$

The first step in this reaction is the absorbance of a photon by a reactant molecule (A), leading to the production of an electronically excited intermediate. The excited state can be for a period of 10^{-10}–10^{-8} s in which the energy of the electrons is increased by the amount of photon energy. Under some conditions, the intermediate may undergo a chemical change to yield products that are relatively stable. For a photochemical reaction to proceed, photons must have sufficient energy to promote the reaction to break or form a bond and photon energy must be absorbed to promote reactions. The bond energies of interest are generally coincident with photon energies in the UV portion of the spectrum. In particular, radiation with wavelength less than approximately 320 nm appears to be sufficiently energetic to promote photochemical reactions in biomolecules. The extent of chemical reaction 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 (472.27 kJ/Einstein) 112.8 kcal /Einstein (one Einstein represents one mole 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's absorbed.

1.3 UV LIGHT CONTROL MEASURES IN FRUIT PROCESSING FACILITIES

During the manufacturing process, fruits can be exposed to microbiological cross-contamination from surfaces, water, and the air, which can cause their spoilage and raise safety issues. The traditional approach to controlling such contamination has been to target specific sites within the manufacturing environment with cleaning and disinfection regimes. Sanitation, disinfection, and oxidation with UV light is a versatile, environmental-friendly technology, which can be used in fruit processing facilities for the treatment of air, surfaces, and water to reduce microbial contamination in different unit operations of plant foods production that are becoming more and more popular.

1.3.1 Air Treatment

Clean, fresh air is the basis of the industrial production of food products of plant origin. Microorganisms in the air, such as viruses, bacteria, yeasts, and fungi, can contaminate raw materials and intermediate products and spoil finished products during their processing and packaging. LPM sources are used very successfully in these applications, for disinfection in air intake ducting and storerooms and to ensure air of very low germ content in production areas. Short-wave UV radiation at 185 nm produces ozone from the oxygen in the ambient air so that this is activated for the oxidation process. UV oxidation breaks down pollutants in the exhaust air. For providing clean air in sensitive manufacturing food facilities, a combination of filters and UV light has been recommended. Basically, two applications of UV are becoming common. In one, the moving air stream is disinfected in much the same manner as with a water system. In the other application, stationary components of the system such as air conditioning coils, drain pans, and filter surfaces are exposed to help prevent mold and bacteria growth or to disinfect the filter to aid in handling. The UVT in air is higher than that in water, and, therefore, the number of lamps required in a large duct is quite reasonable. Common airborne virus and bacteria are readily deactivated with UV. Fungi (molds and spores) require much higher doses. In the moving air stream, high wattage lamps are used, usually without a quartz sleeve. UV lamp fixtures are placed in such a manner as to completely irradiate surfaces where bacteria and mold might collect and grow. Mathematical modeling software and bioassay testing have been developed to allow efficient design and validation of these systems (Kowalski and Bahnfleth, 2002). Low operating costs and reasonable equipment costs can make UV very cost effective.

1.3.2 Water Treatment

Control of microorganisms in industrial process waters is often necessary to maintain quality of the product or process. The fruit industry is a large-volume consumer

of water, and the potential for reuse or recycling of fruit processing water represents an attractive economic benefit to the industry. A combination of UV light and ozone has a powerful oxidizing action to reduce microbial load and the organic content of water to very low levels.

1.3.3 Nonfood and Food Contact Surface Disinfection

UV light is an economical step toward improved hygiene control measures in the food industry. Mold and biofilms can develop on nonfood surfaces (ceilings, walls, floors) and equipment including tanks and vats, cooling coils, and food contact surfaces of equipment such as cutting equipment and conveyor belts (Kowalski, 2006). In general, standard cleaning and disinfection procedures are adequate to contain these problems, but alternatives are available, including antimicrobial coatings like copper and TiO_2. UV irradiation of food processing equipment and surfaces, cooling coil disinfection systems, whole area UV disinfection, and after-hours irradiation of rooms when personnel are not present are all viable control options for maintaining high levels of sanitation and disinfection in food industry facilities (Kowalski and Dunn, 2002). UV light kills up to 99.9% of total germs on conveyor belts for transporting fruits and vegetables.

1.3.4 Packaging

The packaging technologies play an important role in extending the shelf life of fruits. UV light might be applied as pre- or postpackaging technology to reduce the microbial spoilage. As a prepackaging control measure, UV treatment of packaging in fruit filling plants, for example, for lids, cups, sealing, and packaging foils for drinks and beverages, helps to extend the shelf life of fruit stuff. When using cUV and PL as postpackaging treatment for packaged fruits, the considerations about transparency are referred to the packaging materials. For example, materials such as glass, polystyrene, and PET, which allow visible light to penetrate through the container, are not transparent to the UV wavelengths that are essential for microbial inactivation, and therefore, they are not suitable for cUV and PL treatments. On the other hand, polymers such as polyethylene, polypropylene, polybutylene, EVA, nylon, Aclar, and EVOH transmit UV light and hence meet the requirements for PLT very well (Anonymous, 2000). In addition, ink-printed labels or drawings could interfere with the light absorption of the treated item and should be avoided on the surface of packaging materials. Besides the intrinsic transparency of the material, for the success of a UV process it is very critical that the "condition" of the item to be treated is suitable for the penetration of the light. This means that the product surface should be smooth, clear, and without roughness, pores, and grooves, which could "shadow" the microbial cells from the light, causing less complete light diffusion and thus reducing process effectiveness; for the same reason, the item to be treated should be clean and free of contaminating particulates. In addition, items that have a complex geometry could have areas hidden from the light and could require a more accurate design of the treatment chamber in order for the light pulses to reach each point of the product surface.

TABLE 1.2
Application of UV Light Sources as a Control Measure in Fruit Processing

	Reported Applications			
UV Source	**Processed Water**	**Air**	**Surfaces**	**Low UVT Juices**
LPM	X	X	X	X
MPM	X	X		
Excimer lasers	X		X	X
Pulsed			X	X
LED	X	X	X	

1.3.5 Fresh Fruit and Cut Fruit Surfaces Treatment

CUV and PL treatments result in various levels of inactivation of spoilage and pathogenic microflora on the surface of a wide variety of solid foods. Comprehensive reviews of the literature in this field have been compiled by the U.S. FDA (2000) and by Woodling and Moraru (2005). The variability of the results (a 2- to 8-log reduction was generally reported) is most likely due to the different challenge microorganisms used in various studies, the intensity of the treatment, and the different properties of the treated substrates. Woodling and Moraru (2005) demonstrated that the efficacy of PL is affected by substrate properties such as topography and hydrophobicity, which affect both the distribution of microbial cells on the substrate surface and the interaction between light and the substrate (i.e., reflection and absorption of light). Surface disinfection of fresh and cut fruit products is a basis for longer shelf life. In designing a PL treatment for fruit items, both source (light wavelength, energy density, duration and number of the pulses, interval between pulses) and target (product transparency, color, size, smoothness, and cleanliness of surface) parameters are critical for process optimization, in order to maximize the effectiveness of product microbial inactivation and to minimize product alteration. Such alteration can be mainly determined by an excessive increase in temperature causing thermal damage to fruits and also by an excessive content of UV-C light, which could result in some undesired photochemical damage to fruit itself or to packaging materials. Table 1.2 summarizes current and future applications of cUV and PL available sources in fruit processing for air, surface, water, and low UVT fruit drinks and beverages.

1.4 UV TREATMENT OF WHOLE FRESH FRUITS

1.4.1 Antimicrobial Effect

Traditionally UV-light applications for treatments of whole fruits and vegetables were focused on the disinfection role with the objective to extend the shelf life as naturally occurring microflora may present on the surface of raw produce both of nonpathogenic or spoilage and pathogenic nature (Table 1.3).

TABLE 1.3
Fresh Produce and Typical Microflora Present on the Surface

Commodity	Microflora	Reference
Fruits (in general)	Fungi: *B. cinerea*, *Aspergillus niger*; Yeasts: *Canidia*, *Cryptococcus*, *Fabospora*, *Kluyveromyces*, *Pichia*, *Saccharomyces*, and *Zygosaccharomyces*; Bacteria: *Shigella* spp.	Martin-Belloso et al. (2006)
Carrot	*B. cinerea*	Mercier et al. (1993)
Lettuce	*Enterobacter*, *Erwinia*, *Escherichia*, *Leuconostoc*, *Pantoea*, *Pseudomonas*, *Rahnela*, *Salmonella*, *Serratia*, and *Yersinia*	Allende et al. (2006)
Tomato	*B. cinerea*	Charles et al. (2008)
Apple	*E. coli* O157:H7	Martin-Belloso et al. (2006)
Raspberry	*Cyclospora cayetanensis*	Martin-Belloso et al. (2006)
Strawberry	*Campylobacter jejuni* *B. cinerea*	Martin-Belloso et al. (2006), Erkan et al. (2008), Pombo et al. (2011)
Watermelon	*Salmonella* spp., *Shigella* spp.	Martin-Belloso et al. (2006)
Cantaloupe	*Campylobacter jejuni*	Martin-Belloso et al. (2006)
Pineapple	*E. coli* O157:H7, *Salmonella*	Strawn and Danyluk (2010)

During storage, fruits undergo biochemical and physiological changes that can result in loss of nutrients, color changes, and tissue disruption. Along with these undesirable changes, crops become more susceptible to pathogenic decay, which increases the possibility of illness incidences and also causes large economic losses.

Enhanced shelf life of UV-treated fruits can be associated with the germicidal effect on pathogens that may be present on the surface of the crops. However, the UV treatment requires that the whole surface of the object is exposed to the UV light for a time sufficient for any microorganisms present to accumulate a lethal dose. This also means that the topography of the surface determines the efficacy of UV treatment and presents its limitation due to shielding effects. The importance of the fruit positioning during the UV-C exposure of strawberries was reported by Stevens et al. (2005). The authors found that irradiation of the stem ends of the fruits resulted in lower decay during subsequent storage in comparison with the fruits exposing only one or two different sides to UV-C light.

Several studies have shown that UV processing of fresh produce is effective in the reduction of pathogenic bacterial population. For instance, Yaun et al. (2004) inoculated the surface of Red Delicious apples, leaf lettuce, and tomatoes with cultures of *Salmonella* spp. or *Escherichia coli* O157:H7. UV-C (253.7 nm) applied to apples inoculated with *E. coli* O157:H7 resulted in the highest log reduction of approximately 3.3 logs at 240 W/m^2. Lower log reductions were seen on tomatoes inoculated with *Salmonella* spp. (2.19 logs) and green leaf lettuce inoculated with both *Salmonella* spp. and *E. coli* O157:H7 (2.65 and 2.79 logs, respectively). PL UV light

was also applied to reduce the population of pathogenic bacteria on the surface of fruits. For instance, Bialka and Demirci (2007, 2008) exposed blueberries inoculated with *E. coli* O157:H7 and *Salmonella* to the PL (Xenon Corp.) emitting in a range from 100 to 1100 nm for 5, 10, 30, 45, and 60 s. The authors reported reductions between 1.1 and 4.3 $\log_{10}$ CFU/g of *E. coli* O157:H7 and 1.1 and 2.9 $\log_{10}$ CFU/g of *Salmonella*. Due to the high-intensity nature of the PL source, substantial increase in the temperature was observed during fruit processing that could contribute to the microbial reduction. The impact of the PL treatment on the nutrients of treated crops has not been studied yet.

The deterioration of many fresh fruits can be caused by fungi, which give rise to various infections on harvested plant produce. For example, *Monilinia fructicola* is the main cause of brown rot in peaches, apricots, nectarines, and plums. Stevens et al. (1998) revealed that UV treatment can reduce the fungal population on peaches. The surfaces of peaches were inoculated with spores of the *M. fructicola* and then fruits were subjected to the UV light. At UV fluence of 4.8 kJ/m^2, a decrease in growth of *M. fructicola* by approximately one order of magnitude was observed. Another study performed by Stevens et al. (2005) has shown that UV-C (253.7 nm) treatment at 7.5 and 1.3 kJ/m^2 resulted in higher resistance to bitter rot (*Colletotrichum gloeosporioides*), brown rot (*M. fructicola*), and green mold (*Penicillium digitatum*) in apples, peaches, and tangerines. González-Aguilar et al. (2001, 2007) demonstrated that exposure to UV-C light in the range of 250–280 nm at 4.93 kJ/m^2 lowered fungal decay of mango fruits stored for 18 days at 25°C by 60%. Significantly lower incidence of decay was also observed after UV-C treatment in kumquat fruit and bitter orange (*Citrus aurantium*) inoculated with *P. digitatum* (Rodov et al., 1992; Arcas et al., 2000). In the case of papaya fruits inoculated with *Colletotrichum gloeosporioides*, none of the UV-C (253.7 nm) treatments (0.2–2.4 kJ/m^2) was effective against anthracnose fungal sporulation (Cia et al., 2007). Another fungus, *Botrytis cinerea*, is the main cause of gray mold rot in many crops. Exposure to the UV-C light with the peak at the wavelength of 253.7 nm reduced the *B. cinerea* growth in carrots (Mercier et al., 1993), tomatoes at UV fluence of 3.7 kJ/m^2 (Charles et al., 2008), pepper fruits at UV fluence of 7 kJ/m^2 (Vicente et al., 2005), and strawberries (Erkan et al., 2008; Pombo et al., 2011). Erkan et al. (2008) reported that in UV-treated strawberries at fluence levels of 0.43, 2.15, and 4.30 kJ/m^2, after 20 days of storage at 10°C the percentage of fungal decay was 49.6, 29.6, and 27.98, respectively, while in control fruits the decay reached 89.98%. Similar observations have been reported by Pombo et al. (2011) who inoculated Strawberries with *B. cinerea* 8 h after UV-C treatment at the dose of 4.1 kJ/m^2. The reduction of fungal growth was found and can be attributed to the plant defense mechanism against pathogens induced by UV light.

1.4.2 Plant Antimicrobial Defense Mechanism Triggered by UV

Exposure to UV at very low doses over hours or even days triggers a series of biochemical events within the plant tissue. The term *hormesis* has been applied to this type of UV treatment. According to Shama (2007), hormesis involves the use of small doses of potentially harmful agents directed against a living organism or living tissue to elicit a beneficial or protective response. Hormetic UV treatment is

distinguished from conventional UV treatment. In conventional treatment, the UV is directed toward microorganisms that are present on the surfaces of an object, whereas in the case of hormetic UV treatment, the object itself is exposed to the incident UV. The purpose of the treatment is to elicit an antimicrobial response in the fruit tissue. Both types of UV treatment employ the same wavelengths; however, for hormetic treatments only low UV doses are applied (Shama and Alderson, 2005). The plant defense mechanism that is triggered by the hormetic UV dose is not yet fully known and understood. Figure 1.3 schematically presents some of the biochemical responses of plant membrane that were recently reported. It was found that UV-C hormetic treatment at UV fluences in the range of 0.4–4.3 kJ/m^2 stimulates the activity of several groups of enzymes that play different roles in plant antimicrobial defense actions. This includes (1) enzymes of peroxidases and reductases that are responsible for the oxidative burst and formation of lignin polymers generating structural barriers against invading pathogens; (2) glucanases and chitinases that exhibit lytic activities toward major fungal cell wall components; and (3) l-phenylalanine ammonia lyase (PAL)—involved in biosynthesis of phenolics, which are characterized by antioxidant and antimicrobial activities (Erkan et al., 2008; Pombo et al., 2011).

It was found that the higher accumulation of rishitin in UV-C-treated (253.7 nm, 3.7 kJ/m^2) tomato fruits was positively correlated with enhanced resistance against gray mold rot (Charles et al., 2008). In addition, the hormetic UV treatments result in protective effects against microorganisms throughout the entire tissue rather than at its surface only. Stevens et al. (1999) showed that sweet potatoes inoculated with spores of Fusarium solani at a depth of 12 mm below the surface could be successfully protected from infection following hormetic UV treatment. The research attention was also focused on citrus fruits and in fruits where the enhancement of resistance to phytopathogens such as *P. digitatum* has been attributed to accumulation of the phytoalexins scoparone. As example, Ben-Yehoshua et al. (1992) reported that UV illumination of lemon reduced susceptibility to *P. digitatu*, which was directly related to the level of scoparone in the treated fruit.

1.4.3 Effects on Bioactive Compounds

The reports related to UV hormesis in fresh produce showed that due to the induction of plant defense mechanisms accumulation of the phytochemicals in the plant cells can occur. Their antimicrobial and antioxidant properties are highly desirable as they can contribute to delaying the onset of ripening and consequently reducing economic losses due to spoilage. Moreover, the formation of bioactive phenolic compounds such as phenolic acids and flavonoids increases the nutritional value of UV-treated commodities. Phenolic acids and flavonoids are characterized by essential health promoting properties such as antiinflammatory, antihistaminic, and antitumor activities.

Several studies reported increase in and better maintenance of phenolics and flavonoid compounds in crops processed with the UV light. The type of the polyphenols as well as their accumulation and better maintenance during storage was highly dependent on the crop commodity and applied UV dose. González-Aguilar et al.

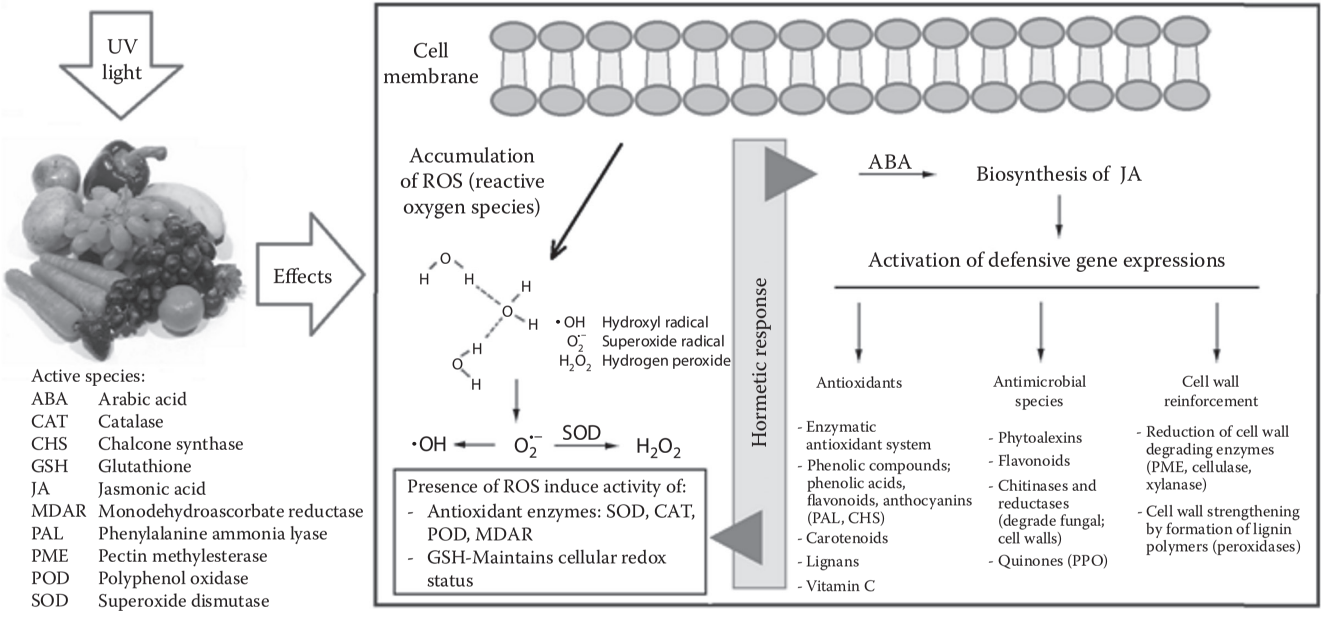

FIGURE 1.3 Schematic representation of biochemical responses in the plant tissue membrane triggered by the hormetic UV treatment. Enzymes that play crucial roles in the plant defensive mechanism are shown.

(2001, 2007) found higher levels of total phenols and polyamine compounds in mangoes irradiated with UV-C at 4.93 kJ/m^2 than in fruits exposed to 2.46 or 9.86 kJ/m^2. In other studies, authors also observed induction of polyamine compounds in peaches after UV-C exposure (González-Aguilar et al., 2004). The accumulation of polyamines in crops might be beneficial in increasing the resistance of fruit tissue to deterioration and chilling injury. In particular, exposure of citrus fruits to UV light was found to be advantageous in terms of the formation of flavonols. For example, Arcas et al. (2000) noted that due to UV-C exposure at 0.72 kJ/m^2, the content of naringin and tangeretin in the peel of *Citrus aurantium* fruits increased by 7% and 55%, respectively. Table 1.4 summarizes results of the recent studies of UV treatments of fruits where UV-related enhancement in the content of the bioactive compounds was observed.

1.4.4 Storage of Post-UV-Treated Fruits

The storage conditions, such as temperature or modified atmosphere, can adversely affect the levels of UV-formed phytochemicals. For instance, Vicente et al. (2005) observed increase in the antioxidant capacity in pepper fruits immediately after the UV-C exposure. During subsequent storage at 10°C, the antioxidant capacity of pepper decreased. However, after 18 days of storage, UV-treated fruits showed more antioxidants than control fruit. Allende et al. (2007) studied the effect of the modified atmosphere packaging on the quality of the UV-treated strawberries. The results revealed that strawberries stored under superatmospheric O_2 and CO_2-enriched concentrations at 2°C showed lower total phenolic contents after 5 days and a vitamin C reduction after 12 days when compared with the fruits that were kept in the air.

1.4.5 Formation of Vitamin D

Mushrooms are the only plant source of vitamin D_2 because they contain a high amount of ergosterol that can be converted to vitamin D_2 after exposure to UV irradiation (Mau et al., 1998; Jasinghe and Perera, 2005). All three c-UV bands (UV-A, UV-B, and UV-C) were applied for the postharvest treatment of edible mushrooms. Mau et al. (1998) found UV-B (310 nm) light more effective than UV-C (253.7 nm) in conversion of ergosterol to vitamin D_2 in common (*Agaricus bisporus*) mushrooms. It was found that due to exposure for 2 h to UV-B (9.86 kJ/m^2) and UV-C (14.71 kJ/m^2) light, the vitamin D_2 content in common mushrooms increased from 2.20 µg/g of dry weight to 12.48 and 7.30 µg/g, respectively. UV-B irradiation also affected the vitamin D_2 formation in Shiitake and Straw mushrooms, with the increase rates of 2.15 and 1.86 µg/h, respectively. However, Jasinghe et al. (2006) reported that UV-C exposure (23.0 kJ/m^2) for 2 h resulted in higher yields of vitamin D_2 in all treated kinds of mushrooms, Shiitake, Oyster, Abalone, and Button, when compared with the UV-A (25.2 kJ/m^2). It is known that the increase in phenol content might be accompanied by tissue browning. In the case of treatments of Shiitake and Straw mushrooms (Mau et al., 1998; Jiang et al., 2010), the changes in color were not observed. However, Mau et al. (1998) observed that both UV-B and UV-C treatments for 2 h resulted in discoloration of common mushrooms. Therefore, the optimal conditions for UV processing

TABLE 1.4
Examples of UV Treatments of Fruits with the Accumulation of Different Phytochemicals

Commodity	Affected Bioactive Compounds	Number/UV Lamp/ Power Fluence	Reference
Strawberries	Increase in antioxidant capacity and total phenolic content	3/LPM/8 W 2.15 kJ/m^2	Erkan et al. (2008)
Blueberries	Increase in antioxidant capacity, total phenolic and anthocyanins content	15/LPM/8 W, 2.15 and 4.30 kJ/m^2	Wang et al. (2009)
	Increased total phenolic content	1 UV-B fluorescent lamp (305–310 nm) 0.54 kJ/m^2	Eichholz et al. (2011)
Grape berries	Increased resveratrol derivatives content	1/LPM/N/A 0.01 kJ/m^2	Cantos et al. (2000)
		3/UV-B lamp (340 nm)/80 W	Cantos et al. (2000)
		N/A/LPM/510 W	González-Barrio et al. (2009)
Apples	Enhanced anthocyanins content	UV-B lamp (320 nm)	Ubi et al. (2006)
Peaches	Enhanced content of polyamine compounds	N/A/LPM/15 W 8.22 W/m^2	Gonzalez-Aguilar et al. (2004)
Mangoes	Enhanced contents of phenols and polyamine compounds (spermidine, putrescine, spermine)	N/A/LPM/15 W 8.22 W/m^2	González-Aguilar et al. (2001, 2007)
Kumquat	Enhanced phytoalexin scoparone content	LPM 0.2–1.5 kJ/m^2	Rodov et al. (1992)
Orange	Enhanced phytoalexin scoparone content	LPM 1.5–9.0 kJ/m^2	Rodov et al. (1992)
Bitter orange	Enhanced flavonols content (tangeretin)	1/LPM/N/A 0.1 W/m^2	Arcas et al. (2000)
Limon	Increased total phenolic content	6/UV-B lamp (280–400 nm)/N/A 0.052 and 0.077 kJ/m^2	Interdonato et al. (2011)
Pepper fruits	Increased antioxidant capacity	4/LPM/30 W 1, 3, 7 and 14 kJ/m^2	Vicente et al. (2005)
Green tomatoes	Increase in total phenolic content	2/UV-B lamp (311 nm)/N/A 20 and 40 kJ/m^2	Liu et al. (2011)
Onions	Enhanced quercetin content	UV-A (352 nm) 1.84 W/m^2	Higashio et al. (2005)
Shiitake mushrooms	Enhanced vitamin C, total phenolic, and total flavonoids levels	N/A/LPM/20 W 4 kJ/m^2	Jiang et al. (2010)

still need to be determined. As Jasinghe et al. (2006) concluded that the irradiation of 5 g of fresh Shiitake mushrooms for 15 min with UV-A or UV-B is sufficient to obtain the recommended allowances of vitamin D for adults (10 μg/day).

1.4.6 Effects on General Appearance

Nutritional value, color, flavor, and texture of fruits are the major factors that indicate product freshness and highly influence the consumer's choice. Deterioration and ripening during storage result in tissue damage, discoloration, and formation of off-flavor. UV technology can be also protective against these symptoms of senescence due to the activation of the plant defensive mechanism by the hormetic UV doses. According to Pombo et al. (2009), delay in the softening of plant produce could be associated with a decrease in the expression of a set of genes involved in cell-wall degradation, during the first hours after UV treatment. It was reported that optimal UV treatment can increase the shelf life of strawberries, apples, peaches, tomatoes, peppers, and broccoli by reducing the respiration rate and weight loss, retaining overall visual quality, delaying the ripening and electrolyte leakage, and maintaining firmness for a longer time, when compared with controls (Lu et al., 1991; Baka et al., 1999; Marquenie et al., 2002; Gonzalez-Aguilar et al., 2004; Lammertyn et al., 2004; Vicente et al., 2005; Costa et al., 2006; Allende et al., 2007; Lemoine et al., 2007; Pombo et al., 2009). In order to increase shelf life, the processing conditions, UV dose (kJ/m^2), and emission spectrums should be optimized for a given commodity of crops. Lammertyn et al. (2004) and Allende et al. (2007) recommended 1.0 kJ/m^2 as optimal fluence for the UV-C processing of strawberries since at higher treatments authors observed browning and dehydration of the sepals. UV-C fluence levels of about 4–5 kJ/m^2 were found to have the most beneficial effect on shelf life and quality of mango fruits (González-Aguilar et al., 2001, 2007) and Shiitake mushrooms (Jiang et al., 2010). Reports are available that application of UV light can protect the color of green commodities. For instance, Costa et al. (2006) and Lemoine et al. (2007) reported that exposure to the UV-C at peak emission of 253.7 nm and at fluence levels of 7–8 kJ/m^2 allowed retaining the highest levels of chlorophyll and hence preserves the green color of broccoli florets. Similarly, UV-B (312 nm) treatment at 8.8 kJ/m^2 delayed the chlorophyll breakdown in the broccoli and lime peel. Moreover, UV treatment resulted in reduced weight loss and shriveling of the lime fruits (Aiamla-or et al., 2009; Srilaong et al., 2011). Aiamla-or et al. (2009) reported that attempts to delay the yellowing of broccoli by UV-A light (342 nm) at 4.5 and 9.0 kJ/m^2 were not effective.

1.5 UV TREATMENT OF FRESH-CUT PRODUCE

Fresh-cut fruits became popular among consumers due to increased preference for minimally processed fresh-like and ready-to-eat products. Mechanical operations of fresh-cut fruits production, such as peeling, slicing, shredding, etc., often result in enzymatic browning, off-flavors, texture breakdown, and lower resistance of fresh-cut produce to microbial spoilage in comparison with the unprocessed commodities (Lemoine et al., 2007) because of presence of natural microflora on the surface of

raw commodities as shown in Table 1.3. Therefore, during operations of cutting and shredding, cross-contamination may occur, which might increase the risks of foodborne outbreaks.

To improve hygiene and safety during mechanical processing, sanitizing and dripping treatments are commonly applied. During washing and dipping steps, raw or fresh-cut material is immersed into the tap water containing sanitizing agents (chlorine, sodium hypochlorite) to remove spoilage microorganisms, pesticide residues, and plant debris from product surface (Martin-Belloso et al., 2006). To reduce the usage of sanitizing chemicals, UV light alone or in combination with ozone or another preservative agent was explored as novel processing alternatives. Fonseca and Rushing (2006) examined the effects of UV-C light (1.4–13.7 kJ/m^2 at 253.7 nm) on the quality of fresh-cut watermelon compared with the common sanitizing solutions. Dipping cubes in chlorine (40 µL/L) and ozone (0.4 µL/L) was not effective in reducing microbial populations, and cube quality was lower after these aqueous treatments compared with UV-irradiated cubes or control. In commercial trials, exposure of packaged watermelon cubes to UV-C at 4.1 kJ/m^2 produced more than 1-log reduction in microbial populations by the end of the product's shelf life without affecting juice leakage, color, and overall visual quality. Higher UV doses neither showed differences in microbial populations nor resulted in quality deterioration (13.7 kJ/m^2). Spray applications of hydrogen peroxide (2%) and chlorine (40 µL/L) without subsequent removal of excess water failed to further decrease microbial load of cubes exposed to UV-C light at 4.1 kJ/m^2. It was concluded that when properly used, UV-C light is the only method tested that could be potentially used for sanitizing fresh-cut watermelon. Similarly, exposure of sliced apples to UV-C resulted in higher (~1 log) reduction of *Listeria innocua* ATCC 33090, *E. coli* ATCC 11229, and *Saccharomyces cerevisiae* KE 162 in comparison with apples pretreated with antibrowning and sanitizing agents (1% w/v ascorbic acid—0.1% w/v calcium chloride). The combination of UV-C with antibrowning pretreatment better preserved the color of sliced apples during storage at 5°C for 7 days (Gómez et al., 2010). Other studies have shown that UV-C treatment applied alone was efficient in the reduction of the number of microbiological organisms present on the surface of fresh-cut crops. The examples of successful applications of UV-C light are given in Table 1.5.

Similarly to raw crops, the effectiveness of UV treatment on reduction of microbial deterioration and quality retention was defined by the delivered UV dose and overall characteristics of the surface exposed to the UV light. Allende et al. (2006) found a better preservation of "Red Oak Leaf" lettuce irradiated by UV-C light on both sides of the leaves. As optimal condition for the increasing of the shelf life of "Red Oak Leaf" lettuce, the authors recommended the UV fluence of 2.37 kJ/m^2. Undesirable quality changes occurring at higher fluences included tissue softening and browning. Lamikanra et al. (2005) stressed that the moment of the application of UV light during the fruit processing is an important factor. In their studies, the authors exposed the cantaloupe melon to UV-C at 254 nm during cutting and after cutting of the fruits. Cutting of cantaloupe melon under the UV-C light was as effective as postcut treatment in reduction of yeast, molds, and *Pseudomonas* spp. populations. However, fruit cutting during simultaneous exposure to UV-C resulted

TABLE 1.5
Summary of Studies of the Effect of UV-C Light on Reduction of Microorganisms in Fresh-Cut Produce

Fresh-Cut Commodity	Microbiological Organism	Number/UV Lamp/ Power Fluence	Reference
Watermelon	Mesophilic, psychrophilic, and enterobacteria	15/LPM/36 W 1.6, 2.8, 4.8, 7.2 kJ/m^2	Artés-Hernández et al. (2010)
Cantaloupe melon	Yeast, mold, *Pseudomonas* spp., mesophilic aerobes, lactic acid bacteria	1/LPM/N/A 0.0118 kJ/m^2	Lamikanra et al. (2005)
Apple	*L. innocua* ATCC 33090; *E. coli* ATCC 11229 and *Saccharomyces cerevisiae* KE 162	2/LPM/15 W 5.6 ± 0.3; 8.4 ± 0.5 and 14.1 ± 0.9 kJ/m^2	Gómez et al. (2010)
Pear	*L. innocua* ATCC 33090, *Listeria monocytogenes* ATCC 19114 D, *E. coli* ATCC 11229, and *Zygosaccharomyces bailii* NRRL 7256	2/LPM/15 W 15, 31, 35, 44, 56, 66, 79, and 87 kJ/m^2	Schenk et al. (2007)
"Red Oak Leaf" lettuce	*Enterobacter cloacae*, *Enterobacter asburiae*, *Erwinia carotovora* ECC71, *E. coli* RecA_ HB101 and RecA + MC4100, *Escherichia vulneris*, *Escherichia hermannii*, *Leuconostoc carnosum*, *Pantoea agglomerans*, *Pseudomonas fluorescens* Biotype G and A, *Pseudomonas corrugata*, *Pseudomonas putida* C552, *Pseudomonas tolaasii*, *Rahnela aquatilis*, *Salmonella typhimurium*, *Serratia ficaria*, *Serratia plymuthica*, *Serratia liquefaciens*, *Yersinia aldovae*	15/LPM/15 W 1.18, 2.37, 7.11 kJ/m^2	Allende et al. (2006)

in improved product quality, that is, reduced rancidity and respiration rate, and also increased firmness retention, when compared with postcut and control samples. Better preservation of fruits processed during the UV exposure can be related to the defense response of the wounded plant enhanced by the UV. Mechanical injury of the plant tissues activates the expression of wound-inducible genes. UV radiation is

capable of inducing the expression of plant defense-related proteins that are normally activated during wounding. For example, Lamikanra et al. (2005) reported significant increase in ascorbate peroxidase enzyme activity during storage of cantaloupe melon processed under UV-C light. Peroxidases protect plant cells against oxidation. Higher levels of terpenoids (β-cyclocitral, *cis*- and *trans*-β-ionone, terpinyl acetate, geranylacetone, and dihydroactinidiolide) were found in cantaloupe tissues, which can play important roles as phytoalexins in the disease resistance of a variety of plant families (Lamikanra et al., 2005; Beaulieu, 2007). Significant increase in antioxidative compounds, such as phenolics and flavonoids, was also observed by Alothman et al. (2009) in UV-treated fresh-cut banana, pineapple, and guava fruits. However, decrease in vitamin C was observed in all fruits.

In terms of UV effects on fruits' flavor, Beaulieu (2007) and Lamikanra et al. (2005) reported that fruits processed with UV light preserved their aroma to the same extent as nontreated control samples. Detailed studies of volatile compounds in thin-sliced cantaloupe tissues revealed that UV treatment is not responsible for the chemical transformations to ester bonds, esterase, and lipase decrease. However, Beaulieu (2007) indicated that improper cutting, handling, sanitation treatment, and storage can radically alter the desirable volatile aroma profile in cut cantaloupe and potentially leads to decreased consumer acceptance.

1.6 UV PASTEURIZATION OF FRESH JUICES

Fresh juices are popular beverages in the world's market. They are perceived as wholesome, nutritious, all day beverages. For items such as juices or juice beverages, minimal processing techniques are expected to be used to retain fresh physical, chemical, and nutritional characteristics with extended refrigerated shelf life. The U.S. FDA approval of UV light as an alternative treatment to thermal pasteurization of fresh juice products (U.S. FDA, 2000) led to the growing interest and research in UV technology. Key factors that influence the efficacy of UV treatment of fruit juices include optical properties, design of UV reactors, and UV effects on inactivation of pathogenic and spoilage organisms. There are a number of studies recently published that examined UV light not only as a potential means of alternative pasteurization by studying effects on microflora but also its effects on flavor, color, and nutrient content of fresh juices and nectars (Koutchma, 2009).

1.6.1 UV Absorption of Fresh Juices

Fruit juices are characterized by a diverse range of chemical, physical, and optical properties. Chemical composition, pH, dissolved solids (°Brix), and water activity have to be considered as hurdles that can modify the efficacy of UV microbial inactivation. Optical properties (absorbance and scattering) are the major factors impacting UV light transmission and consequently microbial inactivation. UV absorbance and transmittance at 253.7 nm are important parameters to design UV preservation process using an LPM or LPHO source. In the case of the broadband continuous UV and PL, it is important to measure the spectra of the absorbance or transmittance in the UV germicidal region from 200 to 400 nm. The juices can be transparent if

10% < UVT < 100%, opaque if UVT ~ 0%, or semitransparent if 0 < UVT < 10% for anything in between. In the majority of cases, juices will absorb UV radiation. For example, juices can be considered as a case of semitransparent fluid if they have been clarified (apple, grape, or cranberry juices) or opaque fluids if the juice contains suspended solids (apple cider, orange juice). Juice chemical composition such as vitamin content and concentration of dissolved and suspended solids determines whether the product is transparent, opaque, or semitransparent. The examples of the optical characteristics of clarified fresh juices and opaque juices with particles are shown in Figure 1.4.

The absorption coefficient of three commercial brands of clarified juices such as white grapes, apple, and cranberry falls in the range of 20–26 cm^{-1}, whereas the absorption coefficient of a commercial brand of the orange juice is almost twice higher about 40 cm^{-1} in the range of light path lengths up to 2 mm. As it can be noted in Figure 1.4b, juices with suspended particles did not follow the Beer–Lambert law that is typical behavior for the category of semitransparent juices. The Beer–Lambert law Equation 1.2 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

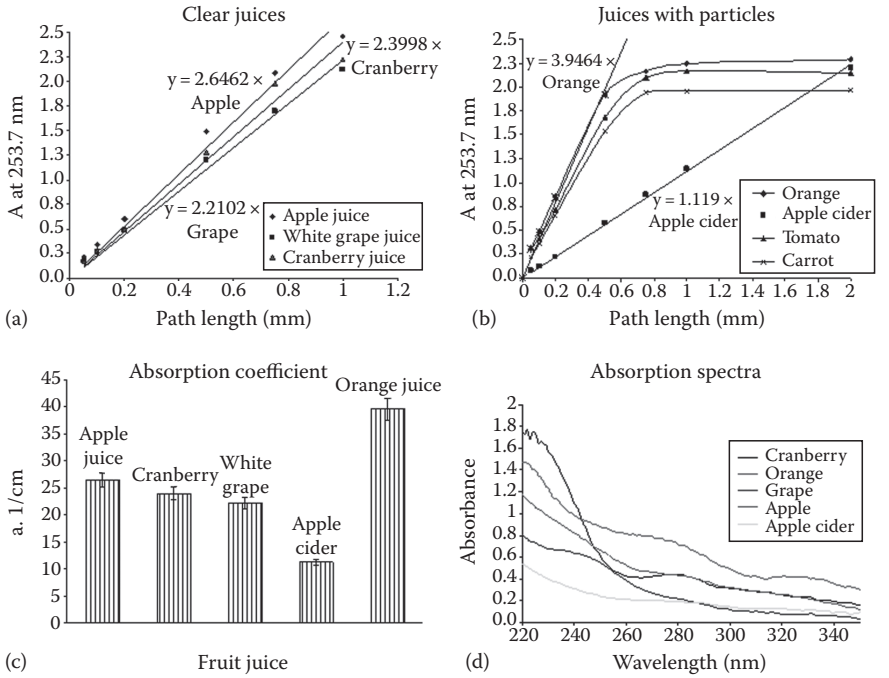

FIGURE 1.4 Absorption characteristics of fruit juices: (a) absorbance at 253.7 nm of clear apple, white grapes, and cranberry juice; (b) absorbance at 253.7 nm of juices with suspended particles orange, tomato, carrot, and apple cider; (c) absorption coefficients; and (d) absorption spectra in UV-C range. (Agriculture and Agri-Food Canada, unpublished data.)

is a measure of the amount of light absorbed per unit concentration absorbance or optical density, and path length of light (d, cm).

$$A = \varepsilon \times c \times d \tag{1.2}$$

This group of juices with suspended solids can be characterized by a nonlinear function of A vs. (ε, c, d) as non-Lambertian liquids. The absorption coefficient of fresh nontreated apple cider that contained suspended particles was approximately ~12 cm^{-1}, which is lower than other fruit juices with particles as well as clarified brands. The higher absorbance of the clarified commercial brands can be probably due to contribution of added preservatives and vitamin C. From this prospective, the UV treatment of freshly pressed fruit juices looks more favorable.

1.6.2 Design of UV Systems

A number of continuous flow UV systems were developed and validated for a variety of fruit juices or other fruit beverages ranging from exotic tropical juices and nectars, to the more common apple cider and apple juice. The reactor designs include traditional annular, thin-film, static, and dynamic mixers (Taylor–Coutte UV reactor) and coiled tube devices. Annular type laminar reactors were used for treatment of apple juice and cider (Worobo, 1999) and mango nectar (Guerrero-Beltrán and Barbosa-Cánovas, 2006). The length and gap size can vary depending on the type of treated juice or flow rate. Thin-film reactors are characterized by laminar flow with a parabolic velocity profile. 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 with 0.8 mm gap "CiderSure" UV reactor, which was approved for safe use to reduce the microbial load of apple cider. UV treatment of orange juice was reported by Tran and Farid (2004) using a vertical single UV lamp thin-film reactor. The thickness of the film was approximately 0.21–0.48 mm. Another commercial thin-film reactor is the PureUV/SurePure reactor that was used for treatment of apple juice, guava-and-pineapple juice, mango nectar, strawberry nectar, and two different orange and tropical juices (Keyser et al., 2008). This reactor is a single-lamp system with a thin fluid film formed between the lamp surface and a surrounding rippled or undulating outer wall. The reactor consisted of inlet, outlet chambers, and a corrugated spiral tube between the chambers. Another type of static mixers is coiled tube UV reactors that are used to increase liquid delivery to UV source by more mixing due to Dean effect (Dean, 1927). Salcor Inc. has promoted a UV reactor in which juice is pumped through the Teflon tubes coiled in a helix, with 12 LPM lamps inside and 12 lamps outside the helix (Anonymous, 1999; Koutchma et al., 2007). The curved flow path can result in a pair of counter-rotating vortices with their axis along the length of the coil. Koutchma et al. (2007) validated the performance of a coiled UV module 420 model (Salcor Inc., Fallbrook, CA) for fresh tropical juice pasteurization. Geveke (2005) processed apple cider with a single lamp UV system surrounded by a coil of UV transparent Chemfluor tubing. Forney et al. (2004) used dynamic mixer Taylor–Coutte design to improve UV inactivation efficiency in apple juice.

1.6.3 Inactivation of Pathogenic, Nonpathogenic, and Spoilage Organisms

Table 1.6 summarizes results of several reports on inactivation of pathogenic and nonpathogenic bacteria in fruit juices using continuous UV light sources. These data were obtained using static (collimated beam device) and continuous flow UV systems. The approaches to determine UV fluence also differed, so reported results are not directly comparable.

Bobe et al. (2007) studied the presence and concentrations of pathogenic and indicator microorganisms in apple cider processed in Michigan. Neither *E. coli* O157:H7 nor *Salmonella* were detected in any tested cider samples, suggesting a very low frequency of pathogens in apple cider. The persistent and relatively high frequency of generic *E. coli* observed in samples indicated a continued risk of pathogen contamination in apple cider, especially when it is untreated. Basaran et al. (2004) compared log reductions among the *E. coli* strains in the apple cider made of different cultivars. The result failed to show any statistically significant relationship. However, the results of this study indicate that regardless of the apple cultivar used, a minimum 5-log reduction is achieved for all of the strains of *E. coli* O157:H7 tested. Gabriel and Nakano (2009) examined the UV resistance of strains of *E. coli* (K-12 and O157:H7), *Salmonella* (enteritidis and typhimurium), and *Listeria monocytogenes* (AS-1 and M24–1), which were individually suspended in phosphate-buffered saline (PBS) and apple juice prior and exposed to UV radiation (220–300 nm). The AS-1 and M24–1 strains of *L. monocytogenes* were found to be most resistant to UV in PBS (0.28–0.29 min), whereas the AS-1 strain was most resistant in juice (1.26 min). The AS-1 strain of *L. monocytogenes* and *E. coli* O157:H7 were most heat resistant when suspended in PBS (4.41 min) and juice (4.43 min), respectively. Ye et al. (2007) reported that *Yersinia pseudotuberculosis* was less resistant to UV light than *E. coli* K12.

Table 1.7 summarizes results of reported studies in terms of inactivation of spoilage microorganisms in fresh juices. Variations in UV fluence levels can be accounted for due to limitations in dosimetry and fluid absorbance measurements. Molds spores are considered to be very UV resistant, with the resistance higher than that of *B. subtilis* spores, followed by yeasts and lactic bacteria (Warriner et al., 2004, unpublished proprietary data). However, data on UV effectiveness against food-borne pathogenic and spoilage microorganisms of high importance are limited or available in confidential reports and need to be generated. Data generated in the air or water cannot be used for the calculation of UV processing of low UVT food liquids. The results should be considered by juice processors in selecting appropriate surrogate organisms for UV light process lethality validations.

1.6.4 Inactivation of Enzymes

Enzymatic activity actually depends on the native structure of the protein which, by principle, can be modified following photooxidation promoted by UV and visible light exposure reported to occur via two major routes: (1) direct photooxidation

TABLE 1.6
UV Inactivation of Pathogenic and Nonpathogenic Microorganisms in Fresh Juices

	Type of UV Reactor						
Juice	Flow Regime	Number/UV Lamp/Power	Gap Size (mm)	Fluence, (mJ/cm^2)	Test Organism	Log (*No/N*)	Reference
Apple cider	Thin-film laminar	10/LPM	NA	9–61	*E. coli* O157:H7	3.8	Wright (2000)
Apple cider	Laminar	8/LPM/39 W	0.8	14.32	*C. parvum* Oocyst	5	Hanes et al. (2002)
Apple cider	Laminar	8/LPM/39 W	0.8	14	*E. coli* O157:H7 (933, ATCC 43889, and ATCC 43895	5	Basaran et al. (2004)
Apple juice	Petri dish	220–300 nm/15 W	D = 5	At 50 cm up to 0–33 min	*E.* coli (K-12 and O157:H7) *Salmonella (enteritidis and typhimurium)* *Listeria monocytogenes* (AS-1, M24–1)		Gabriel and Nakano (2009)
Orange juice	Petri dish	4/LPM/30 W		2.19 J/cm^2	*E. coli* O157:H7	5	Oteiza et al. (2010)
Apple cider	Laminar	8/LPM/ 39 W	0.8	NA	*E. coli* ATCC 25922	5–6	Worobo (1999)
Apple juice	Thin laminar	8/LPM/ 39 W	0.8	14.5	*E. coli* K12	3–4	Koutchma et al. (2004)
Apple cider	Turbulent	12/LPM/42 W	5–10	0.75	*E. coli* K12	<1	Koutchma et al. (2004)
Apple juice	Dean flow	1/LPM/15 W	Id 3.6	34 J/mL	*E. coli* K12 *L. innocua*	3.4 2.5	Geveke (2005)
Apple juice	Taylor Coutte	4/MPM/0.684	5.5 2	21.7	*E. coli 15597*	3–5	Forney et al. (2004)
Apple juice	Thin-film laminar	1/LPM/15	5		*Yersinia pseudotuberculosis* *E. coli* K 12	1 1	Ye et al. (2007)

TABLE 1.7
UV Inactivation of Spoilage Microorganisms in Fresh Juices

	Type of UV Reactor						
Juice	**Flow Regime**	**Number/UV Lamp/Power**	**Gap Size (mm)**	**Fluence (mJ/cm²)**	**Test Organism**	**Log (*No/N*)**	**Reference**
Orange	Thin-film laminar vertical	1/LPM/30W	0.21–0.48	74	APC	0.53	Tran and Farid (2004)
					Yeasts	0.36	
Apple	Laminar	2/LPM/25W	NA	45,000	*E. coli*	1.34	Guerrero-Beltrán and Barbosa-Cánovas (2005)
					APC[a]	4.29	
					Y&M[b]	5.10	
Mango nectar	Laminar	2/LPM/25W	NA	45,000	APC	2.94	Guerrero-Beltrán and Barbosa-Cánovas (2006)
					Yeasts	2.71	
Model of tropical juices	Turbulent, Dean flow	24/LPM/65W	ID 10–12	21.5	Yeasts	Up to 6	Koutchma et al. (2007)
Orange					Molds	1.5	
Guava					Molds	1.2	
Carrot					APC	3.2	
Pineapple					Y&M	1.0	
Apple	Turbulent Re > 7500	1–10/LPM/100W	NA	234	APC	>3.50	Keyser et al. (2008)
					Y&M	>2.99	
Guava-and-pineapple				1,404	APC	3.31	
				468	Y&M	2.23	
Mango nectar				702	APC	0.40	
					Y&M	0.44	
Strawberry nectar				1,404	APC	1.32	
					Y&M	2.45	

[a] aerobic plate count
[b] yeasts and molds

arising from the absorption of radiation by the protein structure or bound chromophore; (2) indirect protein oxidation mediated by singlet oxygen generated by energy transfer by either protein bound or other chromophores (Davies and Truscott, 2001). The effect of UV light on the activity and structure of food enzymes is still a matter of speculation. Limited and controversial information is available in the literature.

Color is a very important quality parameter in fruit juices. It is related to nonenzymatic and enzymatic browning, due to polyphenol oxidase (PPO) activity. The effect of UV light on the inactivation of enzymes related to food quality is diverse. While Noci et al. (2008) reported no effect of UV on apple PPO activity, Manzocco et al. (2009) reported about 80% inactivation of PPO at approximately 1250 mJ/cm^2 of UV fluence. Guerrero-Beltrán and Barbosa-Cánovas (2006) found that after UV treatment of mango nectar at 44,633 mJ/cm^2 PPO reduced activity to 19%. Falguera et al. (2011) irradiated apple juices made from four different varieties (Golden, Starking, Fuji, and King David) for 120 min with a polychromatic mercury lamp of 400 W in a range of 250 and 740 nm with an incident energy of 3.88×10^{-1} E/min. The treatment was effective in the inactivation of PPO after 100 min, while peroxidase was completely destroyed in 15 min in all the four varieties. It should be noted that major absorbance peak of the PPO enzyme matched with the largest peak of the emission spectrum of the lamp.

One important factor in orange juice appearance is the "cloud" formed by pectin. Pectin methylesterase (PME) is an enzyme that tends to de-esterify pectin, and whose inactivation is consequently pursued. Tran and Farid (2004) reported the results of UV treatment of reconstituted orange juice. In addition to the decimal reduction dose for the standard aerobic plate count, effects on shelf life, pH, color, vitamin C, and destruction of PME enzyme were studied. The shelf life of fresh squeezed orange juice was extended to 5 days as a result of limited exposure to UV light of 73.8 mJ/cm^2. No destruction of PME (5%), which is a major cause of cloud loss of juices, was reported whereas the activity of this enzyme was significantly decreased (70%) by mild heat treatment at 70°C for 2 s.

1.6.5 Effects on Essential Vitamins

Vitamins even though they may be present in small amounts in fresh juices, are of concern because some vitamins are considered light sensitive. Water-soluble light-sensitive vitamins include C (ascorbic acid), B12 (cobalamin), B6 (pyridoxine), B2 (riboflavin), and folic acid. Fat-soluble, light-sensitive vitamins include A, K, E (alpha-tocopherol), and carotene. Most studies were conducted on the effects of light on vitamins in the wavelength range of 290–700 nm, which includes both UV and visible light. They have involved exposure to fluorescent lamps, but there are limited data available at 253.7 nm. Since 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 affected the magnitude of absorption coefficient. The destruction of vitamin C during exposure to UV light may alter the absorption properties of treated juice. Ye et al. (2007) measured vitamin C content before and after UV treatment. Two brands of packaged apple juice (pasteurized, no preservatives), Sahara Burst and Gordon Food Service, were enriched with Vitamin C. The UV system consisted of four chambers with varied lengths and a single LPM bulb at output power