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Effects of Radiation Technologies on Food Nutritional Quality

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Abstract

Generally, foods are thermally processed to destroy the vegetative microorganisms for food preservation. However, only thermal treatment triggers many unwanted biochemical reactions, which leads to undesirable sensorial and nutritional effects. Therefore, a number of nontraditional preservation techniques are being developed to satisfy consumer demand with regard to nutritional and sensory aspects of foods. Ensuring food safety and at the same time meeting such demands for retention of nutrition and quality attributes has resulted in increased interest in emerging preservation techniques. These emerging food preservation technologies can extend the shelf life of unprocessed or processed foods by inactivating the enzymes, reducing the food spoiling microbial growth rate or viability without altering the food quality attributes including flavor, odor, color, texture, and nutritional value. On the emerging technology, sphere promising results have been attained by the radiation processes. Ionizing radiation has been widely used in industrial processes, especially in the sterilization of medicals, pharmaceuticals, cosmetic products, and in food processing. Nonionizing radiation has been used in surface decontamination, as on the packaging sector. Although radiation techniques, as the other traditional or emerging techniques, can impair alterations that can modify the chemical composition and the nutritional value of foods, these changes depend on the food composition, the irradiation dose and factors such as temperature and presence or absence of oxygen in the irradiating environment. The aim of this chapter is to discuss retention or loss of vitamins and minerals in several food products submitted to a radiation process (gamma irradiation, short wave ultraviolet, microwave, and pulsed electric fields).

Keywords: nutritional, nonionizing radiation, ionizing radiation, micronutrient, macronutrient, emerging technologies

1. Introduction

The first food preservation methods were developed by men in the beginning of its existence. Since ancient times, radiation has been used as a preserve food method, when used to preserve meats, fish, fruits, and vegetables from solar energy. In the drying method, the men realized that some fruits and vegetables were still edible and the meat lasted longer without spoiling, once this process consists in removal of part of the water from the food to a final concentration. The microorganisms present in food need water for their vital functions, and by reducing the water content, it is possible to decrease considerably the microbiological growth in the food [1].

The growing demand from the consumers for high quality products reveals the need to apply of new food preservation techniques that provide microbiological safety in the production, increasing the commercial validity, and still provide minimal biochemical alterations, promoting the maintenance of the nutritional and sensorial quality of the products [2].

Some of the currently proposed methods inhibit microbial growth, even in some cases, they cause enzyme inactivation, without the considerable increase of the product temperature. Moreover, these processes promote little damage to pigments, flavor compounds, and vitamins; and in contrast to conventional processes that apply high temperatures, the original sensory and nutritional characteristics of the food are maintained, with no significant loss of fresh product quality [3].

Throughout the centuries, the food preservation techniques have been improving with the increase of scientific development. These methods include freezing, drying, canning, pickling preparation, pasteurization, fermentation, cooling, controlled atmosphere storage, and application of preservatives, and among the emerging technologies, the highlight is the radiation technique [4].

The terminology radiation refers to the physical processes of emission and propagation of energy, either by means of wave phenomena, or by the kinetic energy from the particles. In a simpler way, radiation is energy that spreads from one point to another in space or in a material environment. Irradiation is the process of applying this energy to a material, such as food, with the purpose of sterilizing or preserving them through the destruction of microorganisms, parasites, insects, and other pests [5, 6].

There are various forms of radiant energy emitted in various ways that belong to the electromagnetic radiation spectrum, and these include radio waves, microwaves, infrared radiation, visible light, ultraviolet, X-rays, and gamma rays. These forms of energy differ in the wavelength, frequency, force of penetration, and other effects that they exert on biological systems. As can be observed in **Figure 1**, in general, it can be said that in the electromagnetic spectrum, there are two types of radiation: ionizing and nonionizing [7].

Of all the bands of the electromagnetic spectrum, the best known is the narrow band of visible light, shown in the expanded form in the **Figure 1**. The human brain recognizes these wavelengths as the different colors ranging from violet to red. The sunlight, as the human being is able to see with the naked eye, is the sum of multiple electromagnetic waves with different

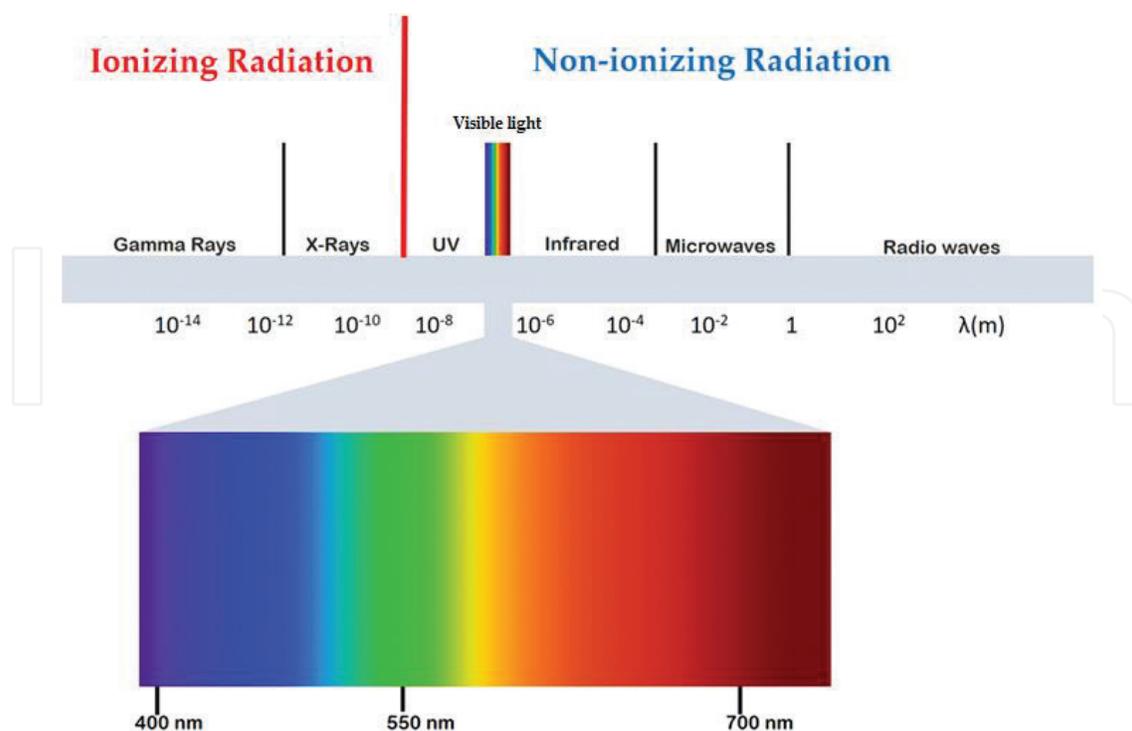


Figure 1. Electromagnetic spectrum.

wavelengths in the visible range. Sir Isaac Newton was the first to realize this fact in the late 1660s by passing the sunlight into a rainbow using a prism and turning it back into white light with a second prism [8].

2. Nonionizing radiation

In search for new and better food preservation methods, the research has turned to the possibility of using radiations in different ranges of frequencies, such as nonionizing radiations. This type of radiation does not have sufficient energy to break molecular bonds or remove electrons from atoms; in other words, perform ionization. The types of frequencies characterized as nonionizing are ultraviolet, infrared, radiofrequency, laser, microwave, and visible light [9, 10]. However, the use of nonionizing radiation has low interest as a food preservation method, in contrast to ionizing radiations [7].

2.1. Microwave radiation

Electromagnetic energy in the microwave region (300 MHz–300 GHz) has been extensively studied as an alternative energy source for sterilization. Microwave radiation has enormous applications in our daily routine, from communication systems, medical applications, to the level of industrial application [11, 12].

Microwave radiation does not carry enough energy to ionize food molecules or to generate free radicals [13]. The basic principle of the process is the baking by molecular vibration that

penetrates superficially in the foods, and the depth of penetration ranges from 2 to 4 cm. The process makes the food vibrates and consequently heating the water, fat, and sugar molecules. However, microwave heating leads to uneven distribution of the temperature in the product. In addition, the products do not show nonenzymatic darkening and surface crust formation, which might be advantageous in some applications [10].

The use of microwave energy has been reported in the literature as a method used for improving microbiological quality and extending shelf life. The use of microwave irradiation resulted in the conclusion that microbial cell death occurs due to the heat produced by the irradiation and due to the electric field created by the microwaves, which promotes a change in the secondary and tertiary structure of the microorganism proteins [12, 14]. Currently, microwave energy has been applied in the pharmaceutical industry, and in drying, thawing and sterilization processes in the food industry.

Despite the limitations of this technology, the application of microwave energy has advantages in the decontamination of utensils and in the process time, which entails the reduction of energy costs and also eliminates the chemicals commonly used in some of the conventional methods. All these reasons make this technology economically and environmentally viable, to be implemented in industrial systems, provided that its limitations are reviewed, such as the lack of uniformity in the distribution of heating in systems without temperature and power control [14, 15].

2.2. Ultraviolet radiation

Ultraviolet (UV) radiation was discovered in 1801 by the German scientist Johan Ritter, who perceived an invisible form of light beyond violet capable of oxidizing silver halides, which was named ultraviolet light at the end of the nineteenth century [16]. The UV-light occupies a wide wavelength range in the nonionizing region of the electromagnetic spectrum, between X-rays (100 nm) and visible light (400 nm) [17]. The wavelength of UV-light is divided into three bands—UV-A, UV-B, and UV-C.

The long (UV-A, 400–320 nm) and middle (UV-B, 320–280 nm) wavelengths are present in sunlight and have some germicidal value. However, the short wavelengths or UV-C (280–100 nm) have high germicidal capacity and do not naturally exist, having to be produced by the conversion of electric energy [18].

The UV-light can be applied as a continuous or pulsed mode. The continuous mode is the conventional method, the light being emitted continuously without interruption. In pulsed UV-light mode, the UV-light is released as intermittent pulses using a capacitor, which allow to increase the energy intensity per pulse. Therefore, the pulsed mode is more effective for microbiological inactivation and the most used method [19].

The use of UV-light as a nonchemical disinfection method is increasingly gaining acceptance by its germicidal power. The equipment used in the UV method has a low maintenance cost, besides being considered an “eco-friendly” technology that eliminates the need to use many chemical treatments, while is able to guarantee high levels of security [20].

UV-light is a physical process that offers several advantages, such as it does not produce by-products that could change the characteristics of the food, does not generate chemical residues, and it is a cold process, dry, simple, effective, and low cost in relation to other sterilization processes, besides not generating any type of ionizing radiation [21].

UV-light has been applied in water purification and has been used in beverage industries; in industries, it has been applied in final cleaning, in the rinsing water of CIP (Clean-in-Place) systems and in the disinfection of packaging surfaces and storage tanks [20].

2.3. Pulsed electric field

The pulsed electric field (PEF) technology, also known as high-intensity electric field pulses (HELP), refers to the application of high voltage pulses ($20\text{--}80\text{ kV cm}^{-1}$) in a product situated between two electrodes [22]. The inactivation of pathogenic and spoilage bacteria, yeasts, and some enzymes related to food quality have been demonstrated by several authors, although

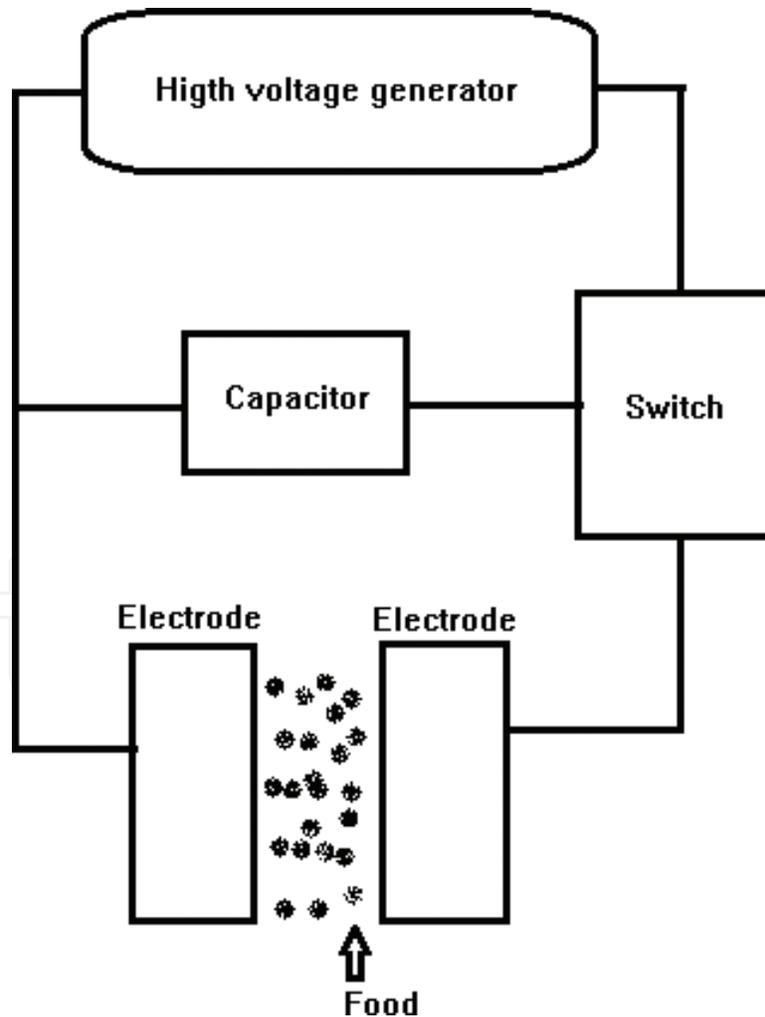


Figure 2. Outline of pulsed electric field.

bacterial spore is not eliminated through this treatment [23, 24]. Regarding to this limitation, other methods are used in combination with irradiation technologies for the elimination of bacterial spores.

The technology consists of subjecting the product to repeated high-intensity fields with short-time electrical pulses, (ms or μ s), with the purpose of causing the inactivation of enzymes and destruction of microorganisms [25]. The outline of pulsed electric field technology is shown in **Figure 2**.

Regarding food quality attributes, PEF is considered superior to conventional heat treatment because it avoids or reduces changes in sensory and physicochemical properties [26]. Many studies have reported the advantage of the application of PEF for the conservation of the micronutrient content of foods, once that is expect the thermolabile vitamins to be conserved, since the electric pulse method does not constitute a heat treatment. There are several factors that influence the results from the pulsed electric field on the microorganisms. These factors are related with the parameters of the process (time, field intensity, temperature, and number of pulses), to the characteristics of the product, and the characteristics of the microorganisms present in the product [27].

The application of PEF for food preservation has shown to be a promising alternative to traditional thermal methods. Although there are not products processed by pulsed electric fields on the market, the great number of works related to such technology and its advantages claim to believe that soon the market will experience the emergence of this and other nonthermal food technologies [28, 29].

3. Ionizing radiation

Nowadays, the types of radiations commonly used in the treatment of foods are the ionizing radiations. Ionizing radiation is classified as ionizing because its energy is high enough to displace electrons from atoms and molecules and to convert them into electrical charges, called ions [5].

Ionizing radiation is transmitted by high-energy particles (alpha, protons, electrons, and neutrons) or electromagnetic waves (X-rays and gamma rays). Only electromagnetic radiation (X-rays and gamma rays) and electron-beam radiation are the two forms of ionizing radiations applied on food among the various existing forms of ionizing radiation. While the propagation of electromagnetic radiation is in the form of waves, the radiation by emission of electrons (corpuseular radiation) is based on the transmission of energy by the acceleration of the electrons [30, 31].

The irradiation of food, physical method of treatment, is based on submit of the product, already packaged or in bulk, to controlled doses of ionizing radiation for sanitary, phytosanitary and/or technological purposes [30].

3.1. Gamma radiation

The frequency of the gamma rays is above 10¹⁹ Hz, which implies in wavelengths below 10–12 m. Radiation equipment is composed of one high energy radiation source (isotope

source) to produce gamma rays, or less frequently, by an equipment which emits high electron-beam energy [32, 33]. Gamma radiation is produced from the excited nucleus of radioactive elements, such as Cobalt 60 (^{60}Co) and Cesium 137 (^{137}Cs) [34, 35].

The process of irradiation by gamma rays has several advantages: low heat generation, low energy requirements, irradiation of packaged or frozen products, and cause changes in the food nutritional value similar or inferior to other methods of conservation [36]. Nevertheless, as disadvantages of the gamma radiation are the high initial cost and difficulty in establishing the necessary doses, because certain doses can cause the death of some insects, however, others still can be found alive [37]. Despite all the benefits, a number of barriers still persist and prevent irradiated foods from being widely marketed, mainly related to the cost of their use and the resistance from the consumers due to a lack of information on food induced radioactivity [38].

In order to ensure the quality of a food, from the microbiological point of view and the nutritional quality, several methods are available for the food industries, including the use of radiation. In view of the requirements of consumers for assurance of microbiological safety and maintaining the natural characteristics of the product, the present chapter focuses on nutritional variation in food products submitted to radiation processes, such as gamma irradiation, UV-C, microwave, and pulsed electric fields.

4. Effects of radiation on food nutritional composition

The radiation techniques have been widely studied and, like most food processing techniques, can induce some changes that are able to modify the chemical and nutritional characteristics on foods. These changes are dependent on some factors such as the radiation dose, the constitution of the irradiated food, the type of packaging, and how it was processed, besides the variables of the process as temperature and oxygen saturation on the atmospheric [39].

Activists and consumers have been questioned about the nutritional value of foods submitted to these processing techniques. The main questions and hypotheses about the use of irradiation are related to the excessive denaturation of nutrients, the conception that there is generation of toxic substances in irradiated foods, and they became radioactive [39, 40]. However, research conducted since the 1950s does not confirm these hypotheses of radioactivity in food, demonstrating there is no induction [21, 41]. Thus, the radiation methods used in food are considered safe and effective, according to several agencies such as the Food and Drug Administration (FDA) and the United Nations (UN) [42, 43].

Among the advantages cited by studies related to food irradiation are the minimal changes caused in food constituents [44]. According to research, macronutrients—carbohydrates, proteins, and lipids—are relatively stable when they come in contact with doses of ionizing radiation up to 10 kGy [39, 45].

Regarding to micronutrients, in particular vitamins are perceived since they are sensitive to any processing technique. Thus, vitamins are unstable in food and dependent on specific

parameters such as the cooking time or time of exposure to the method, pH, temperature, and among others. The water-soluble vitamins are labile to any process technique, and the fat-soluble vitamins are destroyed by the radiation methods [46–48].

4.1. Macronutrients

When food is irradiated, its components may be subject to significant changes. Among the existing macronutrients, the carbohydrates are less sensitive to radiation. Some of the glycosidic bonds linking the monosaccharides break when exposed to radiation, reducing the degree of polymerization and subsequently increasing the viscosity of polysaccharide solutions.

Regarding proteins, the amino acid chains can be altered in the presence of water, due to electron transfer, and might accelerate the denaturation protein process by altering the secondary and tertiary structures before destroying the amino acid chains. Nevertheless, the denaturation is less intense than in a thermal processing. In the case of lipids, in the presence of oxygen, radiation processes can accelerate oxidation, and other reactions such as the production of free radicals, the formation of hydrogen peroxides, and the destruction of compounds as carboxylic acids and antioxidants. Thus, radiation processes are not recommended for products with a high fat content [49, 50].

The effects of UV-C on the composition of macronutrients in eggs were evaluated, demonstrating that cholesterol is oxidized to cholesterol oxides in contact with UV-C light, presenting reduction in doses higher than 5.910 J cm^{-2} . In addition, UV-C light seems to be able to generate vitamin D3 (cholecalciferol), from the precursor 7-dehydrocholesterol. However, further testing may be required to identify oxidation products and to evaluate the production of vitamin D3 [51]. Unlike the results found for UV-C light applied in eggs, in pasteurization, cholesterol levels remained almost unchanged in the temperature range of $110\text{--}120^\circ\text{C}$, and less than 10% was oxidized after 80 hours of heating, corroborating with the fact that cholesterol is quite resistant to heat up to that temperature. However, cholesterol levels are extensively oxidized by exceeding the temperature range [52]. In relation to the protein content, it was observed that in the presence of oxygen, the total amount of protein decreased, occurring an aggregation of the proteins, and after the UV-C treatment, this situation indicates that some sulfhydryl groups were oxidized to the formation of new disulfide bonds [51].

Analyzing the effects of UV-C light on cow's milk and comparing the results with the pasteurization treatments, it is possible to visualize there was no change in fat concentration. On the protein content, there were no significant changes when compared to the samples treated with ultraviolet against the raw milk [53]. Therefore, it is suggested that ultraviolet radiation is an alternative to traditional heat treatments, for better preserving the nutrients, unlike pasteurization that causes nutrient loss. The effects of gamma radiation on milk proteins demonstrate that solubility decreases, probably due to the denaturation and agglomeration of proteins [54].

A study was conducted on the effects of agricultural production systems (organic and conventional), UV-C radiation and different types of drying (greenhouse and lyophilization) in grape waste and flour formulated from the wastes. The results showed, regardless of the

method, there was no interference in the fiber contents, but it was observed that the samples that were produced by the method of organic cultivation with application of UV-C light showed a higher protein content [55].

The effects of different thermal treatment methods were conducted in beef and chicken burgers cooked in microwave, conventional oven, and fry in oil. Samples of the two types of burgers submitted to microwave process obtained the highest loss of moisture, weight, and greater degree of retraction. In the chicken burger, the loss of moisture resulted in higher percentages of fat, protein, and ashes. In the beef hamburger, the highest percentage of proteins and ashes were observed in the microwave treatment, while the highest percentage of lipids was found in the oil frying treatment [56].

Studies on the application of UV-C light to tilapia fillets demonstrated that this type of treatment was not able to increase lipid oxidation due to the low fat content in this type of food. Regarding the protein content, UV-C light provided an increase in the carbonyl content with changes directly related to the doses of applied radiation, presenting a pro-oxidant action [57]. Action that can be explained by the capacity of stimulus of generation and reactivity of oxygen species, causing the protein oxidation, raises carbonyl formation [51]. In the literature, the oxidative effect of proteins and lipids has a direct connection and might vary according to the protein and lipid composition and pro-oxidant and antioxidant compounds of a food [58, 59, 60, 61]. Therefore, these chemical modifications promoted by UV-C light depend on the nutritional composition and the dose to be used [62].

4.2. Micronutrients

At commercial doses, gamma irradiation causes no higher nutrient loss than the other methods used in food processing. The destruction of vitamins from the use of ionizing radiation applying doses of up to 60 kGy does not differ from the degradation generated from the cooking process [63]. The degradation of vitamins presents varied sensitivity to gamma radiation, since this level depends on the doses used and the state of matter from the food analyzed. The fat-soluble vitamins in descending order of sensitivity to gamma radiation are Vitamin E > Vitamin A > Vitamin D > Vitamin K. While the order of sensitivity of water-soluble vitamins is thiamine > ascorbic acid > pyridoxine > riboflavin > cobalamin > nicotinic acid [50, 64]. However, studies related to the effects of radiation on the content of vitamins are still inconclusive. In order to minimize nutrition losses and negative effects on sensory quality, some factors are applied, such as the use of low doses (less than 10 kGy) of gamma radiation and controlled conditions of process such as temperature and presence of oxygen [49, 50].

Among the nonthermal technologies used in food, UV-light treatment presents great commercial potential as an alternative for thermal treatments in liquid foods, such as pasteurization. However, as well the other methods used in food preservation, UV-light causes changes in the vitamin content. UV-light treatment has been shown to be able to significantly alter vitamin content in milk samples when compared to the traditional pasteurizing process. The vitamins present in the cow's milk in descending order of sensitivity are C > E > A > B2. However, the number of sample passes through the UV-C system and the initial vitamin concentration in a sample are important factors to affect the level of loss in vitamin content [65].

The minerals present in foods (i.e., iron, phosphorus, and calcium) are not affected by technologies that employ radiation [42]. No more data were reported in the literature relating the effects of irradiation on vitamins and minerals, and more studies are needed.

4.3. Antioxidant activity

The relationship between the treatments that use radiation and the antioxidant content of foods is still inconclusive. Several studies discuss that radiation treatments have demonstrated the decrease or increase in antioxidant activity of foods, and these variations are related to the type of treatment, the dose of radiation used, the exposure time, and the composition and state of matter of the raw material [66].

With positive effect, it is proven that the ultraviolet radiation, when applied in appropriate conditions, is able to increase the antioxidant capacity of fruits and vegetables, being a technology with commercial potential to be used in post-harvest stages in order to extend shelf life and increase quality, such as papaya, grape, and pineapple [67, 68]. Supposedly, UV-C radiation is able to increase phenolic content and antioxidant enzymatic activities as a defense mechanism against oxidative stress, thus increasing the antioxidant activity of vegetables [67, 69, 70].

In commercial doses, it is not possible to obtain conclusive answers regarding the effect of gamma radiation on the content of the antioxidant activity in foods. However, most of the studies mention gamma radiation as a conservation method related to the increase or maintenance to the potential of the antioxidant activity of foods such as, soybean, olive, starch, and safflower powder [66, 71–74]. However, it is possible to find studies that report the reduction of antioxidant activity when the radiation process is mediated with another parameter, as changes in moisture and application of different doses of gamma radiation in mung bean [75].

4.4. Food allergens

Food processing methods using radiation, ionizing, and nonionizing can be used to reduce the potential of food allergenicity. The UV-light, gamma irradiation, and ultrasound have the capacity to reduce the allergenicity of food proteins from the formation of protein aggregation, protein crosslinking, and/or amino acid sequence alteration. Studies carried out with the application of gamma radiation on cow's milk proteins have demonstrated the reduction of the allergenicity and antigenicity of the proteins when submitted to the irradiation process [54]. However, to date, the processes that involve radiation are not capable of completely inactivating the allergenic compounds [76].

5. Conclusions

The technologies that involve radiation are pointed out as promising methods to be used in food preservation. Some methods used cause the elimination or decrease the growth of microorganisms, without significant nutritional losses. When applied in a controlled manner, the radiation processes promote equal or inferior damages in the nutritional quality of the food when compared to the conventional processes. At commercial doses of up to 10 kGy,

macronutrients and minerals are stable against radiation techniques. Vitamins have a higher degree of sensitivity than macronutrients when exposed to treatments that use some type of radiation. However, nutrient degradation can be reduced by using lower radiation doses and using an oxygen saturated atmosphere.

Acronyms and abbreviations

CIP	clean-in-place
FDA	Food and Drug Administration
HELP	technology, also known as high-intensity electric field pulses
PEF	pulsed electric field
UN	United Nations
UV	ultraviolet

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