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Review

Advances, Applications, and Comparison of Thermal (Pasteurization, Sterilization, and Aseptic Packaging) against Non-Thermal (Ultrasounds, UV Radiation, Ozonation, High Hydrostatic Pressure) Technologies in Food Processing

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Abstract: Nowadays, food treatment technologies are constantly evolving due to an increasing demand for healthier and tastier food with longer shelf lives. In this review, our aim is to highlight the advantages and disadvantages of some of the most exploited industrial techniques for food processing and microorganism deactivation, dividing them into those that exploit high temperatures (pasteurization, sterilization, aseptic packaging) and those that operate thanks to their inherent chemical–physical principles (ultrasound, ultraviolet radiation, ozonation, high hydrostatic pressure). The traditional thermal methods can reduce the number of pathogenic microorganisms to safe levels, but non-thermal technologies can also reduce or remove the adverse effects that occur using high temperatures. In the case of ultrasound, which inactivates pathogens, recent advances in food treatment are reported. Throughout the text, novel discoveries of the last decade are presented, and non-thermal methods have been demonstrated to be more attractive for processing a huge variety of foods. Preserving the quality and nutritional values of the product itself and at the same time reducing bacteria and extending shelf life are the primary targets of conscious producers, and with non-thermal technologies, they are increasingly possible.

Keywords: food processing; food quality and safety; food preservation; pathogens reduction; process optimization

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1. Introduction

The prevention of the growth of pathogenic microorganisms in food has advanced through the development of various preservation systems [1]. One of the most serious challenges facing the food industry today is ensuring the food quality. The absence of spoilage and pathogenic microorganisms in food is usually ensured by both the addition of various preservatives and the addition of antimicrobial agents. There are many cases in which chemical agents and synthetic additives are used with controversial ingredients to guarantee the safety and quality of food. In this context and under the constant pressure of consumers for more natural products and for more free chemical foods with clean labels, the food industry is constantly looking for alternative forms of food processing that meet the demands of consumers [2].

The abundance of nutrients found in many categories of foods are an excellent substrate for the growth of microorganisms, and their inactivation is a critical parameter for food safety. Although the preservation and processing by thermal methods, such as pasteurization, sterilization, and aseptic packaging, have been efficient for microorganism and spoilage enzymes inactivation, at the same time, they present reduced results related to nutritional characteristics and sensory appearance [3]. Heat-sensitive nutrients are the ones that are usually affected first. Thus, ingredients such as vitamins, color, flavor, and carbohydrates are significantly degraded with the degree of degradation depending on many parameters [4]. In addition to the negative effects that these technologies have on quality characteristics, there are other negative effects that must be seriously considered in choosing the appropriate treatment method. The heat used in these technologies is produced by fuel consumption or by heaters and then transferred to food. The mechanisms of convention or conduction are the main ways of this transfer. Therefore, this option is not an environmentally friendly option, as it imposes energy consumption. In addition, it is well established that thermal processing requires water treatment, which makes it an expensive technology, and it is also technologically unsuitable [5].

On the other hand, several novel non-thermal processing technologies are an alternative to traditional thermal methods, but they do not use temperature to inactivate microorganisms and enzymes [6]. These techniques are constantly gaining popularity in the fields of treatment, preservation, and decontamination [7], as consumers' demand for safe, minimally processed, and high nutritional value foods has become very strong [8]. In the case of plant-based foods, these technologies cause microstructural changes in both plant tissues and plant-based beverages, enhancing the extraction capacity of carotenoids, phenolic compounds, vitamins and minerals extractability, and/or bioaccessibility, which is essential to exert their positive effects on health [9].

High-pressure processing (HPP), ultrasound (US), ultraviolet light (UV), and ozonation are non-thermal processes, which are used at an industrial and commercial scale. Chemical, biological, and physical properties can be modified through these techniques, with positive effects in many quality characteristics. Processing time and intensity, as well as processing conditions, are some of the most important factors associated with the success of these methods, so they should be optimized for each food category before their widespread application [10,11]. Figure 1 summarizes some aspects of thermal and non-thermal technologies.

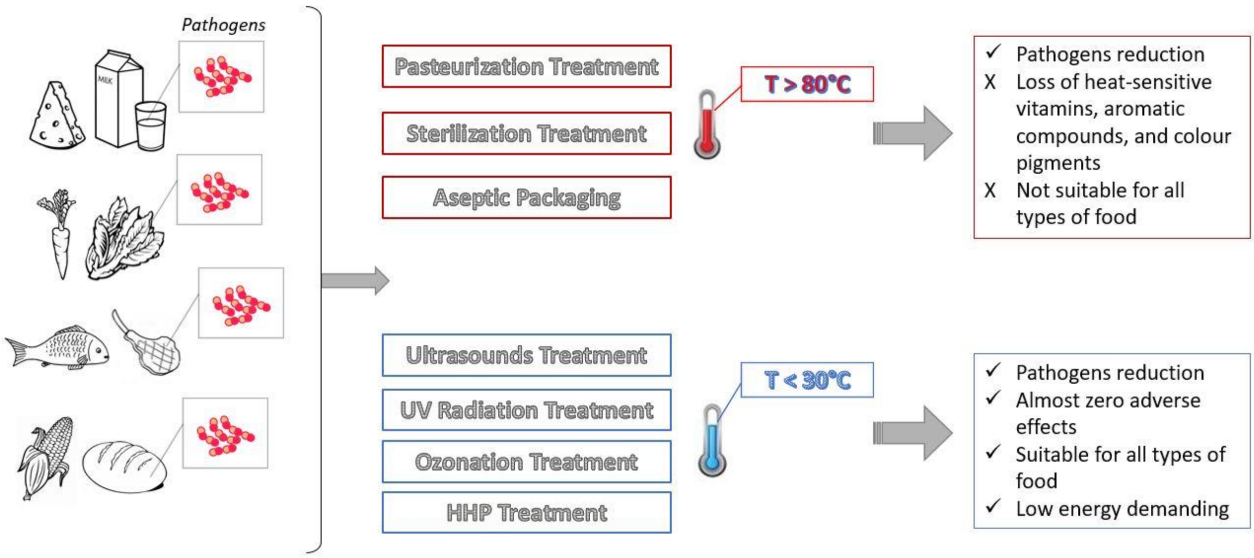

Figure 1. General aspects of thermal and non-thermal techniques.

Furthermore, the development of these new methodology strategies can help the food processing industry in the treatment of raw materials in order to give consumers a high-quality and healthier food, still maintaining cheap prices [12–14].

Due to the existence of many different processing methods, it is important to examine their safety, and it is advisable to evaluate them according to their efficiency and suitability in their application in food production. The purpose of the review is to present the recent advances of the last decade (2011–2021) in thermal against non-thermal technologies in food processing and highlight those with the greatest potential in the food industry.

2. Thermal Technologies in Food Processing

Pasteurization, Sterilization, and Aseptic Packaging

One of the most important unit operations in food processing is thermal processing.

Food preservation depends on major food operations, such as canning, pasteurization, and sterilization, in order to destroy pathogenic bacteria. Conventional in-container thermal processing involves the hermetical canning of food followed by heat treatment for a specific time–temperature in order to inactive pathogenic bacteria growth and extend the product shelf life with minimum quality deterioration. Examples are high-temperature short time (HTST), low-temperature long time (LTLT) or ultra-high temperature (UHT).

Seal integrity, sufficient process lethality, and post-process hygiene are the most important factors to be considered in thermal processing. A hermetic seal brings seal integrity, thus helping in preventing recontamination and creating an environment inside the container that prevents the growth of other microorganisms of higher heat resistance. It also helps in preventing toxin production from pathogens. The time–temperature schedule for the required process lethality should be effective to eliminate the most heat-resistant mesophilic anaerobic spore-forming pathogen *Clostridium botulinum.*

Aseptic processing being an alternative thermal food processing and packaging technique involves the packaging of commercially thermally sterilized products into sterilized containers and then sterile sealing under sterile conditions to prevent microbial product recontamination [15]. However, we should stress out that this process cannot stand alone, since it does require one of the thermal processes (pasteurization or sterilization) prior to aseptic packaging. Aseptic systems use ultra-high-temperature (UHT) sterilization, which is a fast heating treatment at temperatures higher than pasteurization temperatures. A typical aseptic process involves receiving a food material, in-flow heating, holding at a sufficient time for sterilization, and cooling down in order to fill it in. Containers are usually pre-sterilized and quality checked. Then, filling and hermetic sealing follows in aseptic containers, as shown in Figure 2 [16,17]. In aseptic filling, the food product and the package are continuously sterilized separately and then meet in the aseptic filler, which has a sterile environment, and this makes it different to other traditional methods of food packaging.

A high rate of microbial destruction and improved product quality, such as better texture, flavor, and color, is achieved with aseptic processing compared to traditional thermal processes, such as canning. The benefits of aseptic processed foods are attractive and include a higher shelf life, better nutritional and sensory properties, and wider packaging sizes and container materials [18].

The design for aseptic processing varies for different foods. There is a demand for aseptic processing of low acid food ($pH > 4.6$) and high-viscous food containing discrete particles. Aseptic processing design for heterogeneous food products (liquid–particulate food) is more complicated and challenging [19] due to irregular solids' particle size distribution, different residence times, the temperature measurements of moving particles, and the estimation of convective heat transfer coefficients at the particle surface.

The lethality value (F_0) of an aseptic processing in food is used to quantify target spore inactivation in the sterilization process. Design of the aseptic food processing system should include heat and hold (sterilization) of every particle of food product for at least the minimum time specified in the process [20]. Commercial sterility needs to be accomplished in the coldest location (normally, center) of the fastest moving particle.

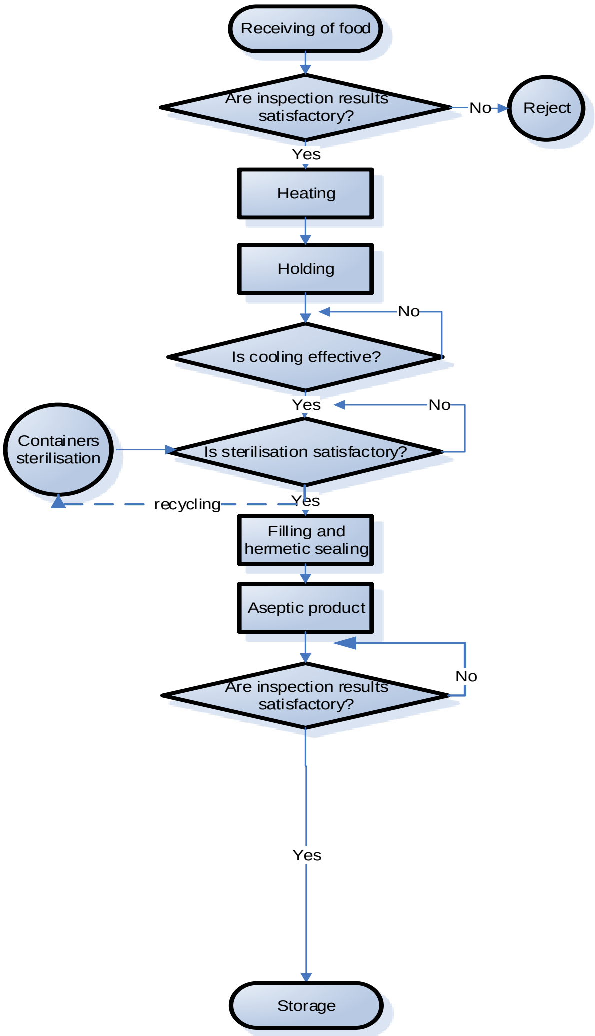

Figure 2. Flow diagram of aseptic processing.

The temperature in the center of the fastest moving particle depends on the properties of the particles and carrier fluid, particles' velocity and rotation, their residence time distribution (RTD), and characterization of the heat transfer mechanism [21,22]. The thermal process should be assessed by determination of the heat transfer coefficient (h_{fp}) between the fluid and particle in the continuous flow conditions. The fluid flow field around the solid particle, the thermal and rheological properties of the fluid, and the dimensions of the particle and pipe are key parameters affecting the fluid-to-particle convective heat transfer coefficient (h_{fp}) [17].

The main problem involves the solid particles, especially at the geometrical center position in the product, where sufficient heat treatment or minimum sterilization value should be assured. The particles are hydraulically conveyed through the process equipment in a liquid carrier; hence, it is difficult to measure the temperature in the center of the suspended particles. Therefore, mathematical models should be applied to describe the sterilization process, which are essential for process design and prediction of the particle dynamics and spatial and temporal variations in the temperatures of the particles moving throughout the continuous process system [23].

Ultra-high temperature (UHT) processed and aseptically filled products are described by [24], including products such as liquid dairy products, baby foods, desserts, sauces, soups, fruit juices, and soft drinks. A high heat treatment (135–150 °C) for a very short time (3–5 s) is carried out followed by aseptic filling into a variety of packaging format, including cardboard cartons, plastic bottles, glass bottles, and foil pouches.

Large plastic materials or metal drums or large flexible pouches could be alternatively employed. Heat (saturated steam, superheated steam, hot air, mixture of hot air and steam), chemicals (hydrogen peroxide, ozone, chlorine, peracetic acid), irradiation (ionizing rays, ultraviolet, infrared), or a combination of these methods are the methods used to sterilize packages for aseptic processing [25].

Pasteurization is a heat treatment method used to kill pathogenic microorganisms in food, helping to reduce or eliminate pathogens in low and high-moisture foods. Technologies employed to pasteurize low-moisture foods include conventional thermal processes such as baking, roasting, and extrusion, controlled condensation steam processes, and energy-based technologies such as irradiation, radio frequency heating, and cold atmospheric plasma [26]. For the microbial inactivation of high-moisture food such as juices or pulp, the methods exploited include thermal pasteurization, dielectric heating, and microwaves, for example [27–29]. Pasteurization is a relatively mild heat treatment of food, usually lower than 100 °C, aimed at destroying the vegetative cells of all pathogenic as well as most nonpathogenic microorganisms. Pasteurization is usually combined with another means of preservation, such as acidity, low water activity, and low-temperature storage [30–33].

Commercial sterilization is the application of heat (or other appropriate treatment) to free food from any viable form of pathogenic and toxin-forming microorganisms, as well as of non-health significant microorganisms, which could grow in the food under normal conditions of the storage and distribution of the product.

According to Stumbo [34] (1973), "Whether the term sterilization or pasteurization is used to label a heat treatment designed to reduce the microbial population of a food, the basic purpose of the heat treatment is the same—that is, to free the food of microorganisms that may endanger the health of food consumers or cause economically important spoilage of the food in storage and distribution."

Steam has been used in the pasteurization of low-moisture foods processes (Table 1) versus irradiation and gaseous pasteurization using ethylene oxide (EtO) or propylene oxide (PPO).

Ethylene oxide (EtO) and propylene oxide (PPO) are fumigants effective in achieving significant reductions of microbial populations on low-moisture foods. EtO is used to treat spices, but it is known to cause loss of volatile compounds [35–37]. PPO is used to treat a variety of low moisture foods including nuts, spices, cocoa beans, and dried fruits [38,39]. Table 1 presents the effect of pasteurization treatments on different microorganisms in human food.

Table 1. Effect of pasteurization treatments on different microorganisms in human food. Adapted from [15].

Process	Food	Experimental Parameters	Target Organism	Microbial Inactivation or Reduction	Reference
Steam	Paprika	130–170 °C, 4–6 s	Indicators (e.g., Enterobacteriaceae, coliforms, yeast, mold)	3–4 log reduction	[40]
Steam	Pistachios	88 °C, 4 min	*Enterococcus faecium*	4 log reduction	[41]
Steam	Seeds, black peppercorns	85 °C, 1 min	*Salmonella enterica*, *Escherichia coli* O157:H7	>5 log reduction	[42]
Steam	Almonds, pistachios	200 °C, 15–30 s	*S. enterica*, *E. coli* O157:H7, *Listeria monocytogenes*	>5 log reduction in 15 s (almonds) and 30 s (pistachios)	[43]
Steam	Black peppercorn, cumin seeds	85 °C, 1–2 min	*S. enterica*	5 log reduction	[37]
Steam	Almonds	95 °C, 25 s	*Salmonella Enteritidis* PT 30	5 log reduction	[44]

The development of several commercially available systems that utilize controlled condensation steam (CCS) processes to pasteurize low-moisture foods has been demonstrated. CSS processes may operate at elevated pressure, at atmospheric pressure, or under vacuum. However, CCS processes maintain temperature near the saturation temperature to control condensation on the product. Pressurized processes (e.g., Ventilex) utilize high temperature (130–170 °C) and short time (4–6 s; HTST), whereas vacuum processes (e.g., Napasol, Steripure, Log5) reduce the saturation vapor pressure and can operate at temperatures below 100 °C and still maintain saturated steam conditions [29].

In Revtech, Safesteril, and Steristep systems, adding sensible heat to the product along with steam is controlled condensation and maintains the dry saturated condition of steam. Therefore, these CCS processes are named dry steam processes due to the very minimal condensation on the food product.

Another type of dry steam is superheated steam (SHS), where the temperature exceeds that of saturated steam at the same pressure. In order to reach much higher temperatures than the saturation point, SHS is also produced by adding heat to saturated steam using an electric resistance heater [30].

Radio frequency (RF) heating can rapidly raise the temperature of agricultural commodities volumetrically and significantly reduce heating time to avoid the quality loss caused by slower heating rate in conventional thermal treatments [45,46]. RF heating may provide more than 4 log reductions of target pathogens in agricultural commodities [47–49].

It is a potential pasteurization method for controlling *Salmonella* while maintaining product quality. Li explored the application of RF treatments to control *E. coli* ATCC 25922 in pre-washed in-shell almonds without quality losses [50].

3. Non-Thermal Technologies in Food Processing

3.1. Ultrasounds

Ultrasound (US) waves used in food applications can be categorized into low-intensity and high-intensity class. The low-intensity or high-frequency ultrasound waves have a typical frequency greater than 100 kHz and intensities below 1 W/cm^2 and are defined as diagnostic waves due to their ability to evaluate the structure and physicochemical properties of the food product both during processing and storage [51]. The high-intensity and low-frequency ultrasound waves have frequency ranges from 20 to 100 kHz, and intensities are in the range of 10 to 1000 W/cm^2.

Differently from low-intensity US, this type of US is considered disruptive, since it produces significant modifications on the physical, biochemical, and mechanical properties of food products [52]. US produces bubbles that undergo collisions. Consequently, these generate cavitation phenomena, resulting in high temperature and pressure up to 5000 K and 50 MPa, respectively [53]. Hence, changes in the pH, stress, temperature, and pressure are caused by these strong explosions and high temperatures. In addition, these changes in an enzyme environment can imply the inactivation of enzymes due to the modifications in the enzyme structure caused by destruction of van der Waals binding and hydrogen bonding, which result in loss of enzyme activity [54,55]. Commonly used devices that produce US are the US probe and US bath, as represented in Figure 3.

Considering all the non-thermal processes, US can be regarded as very versatile. In fact, used alone or in combination with other methods, this technology can ensure high process yields and positive results on the quality of foods. US can significantly assist several industrial processes such as filtration, freezing, separation, drying, emulsion, thawing, brining, oxidation, homogenization, meat tenderization, sterilization, and extraction thanks to their capability of improving energy and mass transfer, mixing, and retention of food characteristics as well as reducing thermal and concentration gradients [56–61].

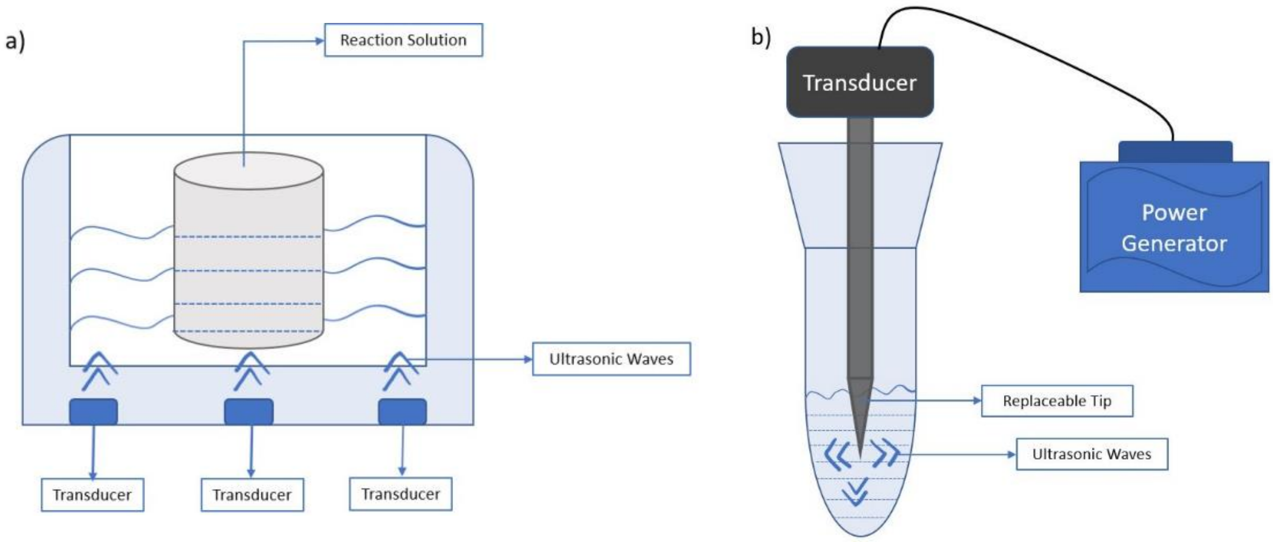

Figure 3. US bath (**a**) and US probe (**b**). Adapted from [56].

Additionally, if ultrasounds are applied previous to drying, an enhancement in drying kinetics is always observed, implying a positive effect on the drying process and a reduction in total energy consumption [4,5]. Furthermore, if the product it is not soaked in a liquid medium, the loss of hydrophilic nutrients and compounds is reduced [62].

In the freezing-related process, high-intensity US helps to control the size and the size distribution of the ice crystals as well as enhance the efficiency of the freezing and the quality of the frozen food, reducing at the same time the process time [59,63].

This non-thermal technique has been also studied as a method to control the nucleation of a crystallization process, in particular for chocolate, honey, fats, and frozen foods [64]. Moreover, the antioxidant [65], antitumoral [66], anticoagulant [67], and anti-inflammatory [68] properties of ultrasound-treated polysaccharides from vegetables, plants, and fungi have been analyzed, as well as nanoparticles production from food polysaccharides [69,70].

In addition to all the good aspects of this emerging food treatment, there are some conditions that cause negative impacts on foods, for example color [71], antioxidants [72], and polysaccharides modifications [73] as well as degradation of fats, radicals formation, and oxidation [74] in high content lipid foods, in particular during emulsification, homogenization, cutting, and extraction steps [75].

From here on, we will present the method of operation and the manifold studies that investigate and utilize US.

The tool most used in the generation of ultrasound is a transducer that transforms electrical signals into acoustic energy of the desired intensity. Magnetostrictive and piezoelectric are the two type of transducers largely used for the production of ultrasound waves. Magnetostrictive transducers behave as electroacoustic transducers to create the ultrasonic waves. The principle of magnetostriction is that these transducers work—which is described as the consequent variation in length per unit length due to magnetization on the application of the magnetic field—only if the material utilized is magnetostrictive. A piezoelectric transducer exploits the conversion among acoustic and electrical energies. The piezoelectric transducer (or sensor) takes advantage of electrical charges generated on its surface when a quartz crystal or any piezoelectric material is subjected to a force designated as piezoelectricity [52].

3.1.1. Application in Fruits and Vegetables

Generally for fresh and slightly processed fruits and vegetables, juices, and purees, changes in color, a drop of microbial load, enzyme inactivation, and enhancements in drying characteristics have been noticed [76–78]. US can be used as pre-treatment prior to fruits and vegetables drying, since it increases the drying kinetics, in particular if an osmotic solution is employed during the process [4]. This appears with strawberry, papaya, pineapple, pomegranate, guava, and melon. In distilled water, a water loss can occur with apple or papaya. On the other side, banana, mushrooms, strawberry, and melon gain water during US treatment [4]. It has been demonstrated that for strawberries, a 5 min cleaning step with US can efficiently reduce 16 pesticide residues by 91.2% [6]. Similarly, for lettuce surfaces, US with frequencies of 20, 40, and 60 kHz can be used to remove 92.31% of abamectin b1 (AB), 89.36% of alphamethrin (AL), and 95.25% of emamectin benzoate (EB) after 8 min of ultrasonic cleaning without showing any changes in nutritional properties [76].

The ultrasound technology has gained much attention due to its inhibitory effect on browning enzymes thanks to the capability of breaking the cell membranes [5]. In particular, it has been discovered that ultrasound in combination with temperature and high pressure is more effective against polyphenol oxidase (PPO) [53]. In Oriental sweet melon, for 5 mL of juice, Liu et al. [79] estimated 65% of inactivation of polyphenol oxidase. As well as with 10 mL extract of Satsuma mandarin, 63.7% of PPO was deactivated [80]. Still talking about enzyme inactivation, Yeoh et al. demonstrated that in fresh pineapple, the activity of phenylalanine ammonia lyase increases substantially, whereas the polyphenol oxidase and polyphenol peroxidase (POD) have a drop in relation to the control group [81]. Similarly, pineapple juice had its content of PPO reduced after 10 min of US treatment as well as a viscosity decline of 75% [82]. PPO decreased also on fresh cut potatoes after a treatment of 5 min with US. The degree to which pH is affected reduced with longer treatments, but no change in color was noticed; a 10 min treatment has been revealed to damage the potatoes' cell [83].

US has been shown also to assist other techniques, for example extraction. Antioxidant, carotenoids, phenols, anthocyanins, aromas, and natural dyes can be extracted easier from pomegranate, tomatoes, garlic, and grape seeds in combination with US. This happens also with herb and spices and oleaginous seeds from which oil extraction is faster [84].

The sonication of fruit juices involves an enhancement of their quality as well as an increase of shelf life due to a reduction in spoilage microorganisms. In particular, an exposition to US produces in grapefruit juices an enhancement of total antioxidant capacity, ascorbic acid, flavonoids and flavonols, and total phenolics. Furthermore, also apple juice has been studied under US influence, which cause a rise in total carotenoids, viscosity, minerals such as Na, K, and Ca, and of the concentration of sugar and polyphenolic compounds after a treatment of 60 min at 20 °C [85]. Similarly for orange, sweet lime, carrot, and spinach juices, a US sterilization treatment retains most of the nutrients compared to the classic thermal pasteurization [86]. In addition, for Cape gooseberry juice, color values, total phenols, ascorbic acid, carotenoids, and retinol activity equivalent (RAE) have been evaluated after US treatment. Researchers showed a significant decreases in the chromaticity as well as a yellowing in all the juice samples sonicated. Likewise, the other studies registered important increases in total phenols, RAE value, and carotenoids and their availability [87].

US has found application as a pre-treatment for sweet potatoes prior to frying. It helps reduce 71.47% of the oil uptake during the frying step at 170 °C [88]. Using US before drying and subsequently frying potato strips is also useful to avoid the oil uptake during the last cooking step [89].

Exploiting US technology, it is also possible to obtain starch nanoparticles (SNP) without any additives from cassava, corn, and yam starches, which contain 8%, 25%, and 30% of amylose, respectively. The SNP production starts with 30 min of sonication of aqueous starch suspensions at 10%w/w. Subsequently, the particles are dried for 48 h at 35 °C [90].

3.1.2. Application in Meat and Fish Products

The use of ultrasounds in meat from pork, beef, chicken, and rabbits induces tenderness enhancement, improvements in water dynamics of tissue, increase in the water-holding capacity and color enhancement, along with acceleration of mass transfer and increase of shelf life [91–94]. Furthermore, US technology assists industrial processes and affects positively some process parameters as observed for meat brining, where the diffusion coefficient (D) increases exponentially with the ultrasonic intensity, and the rate of mass transfer is accelerated. When the lower ultrasound intensity is applied, the value of D for NaCl is higher than that of D for water, whereas the higher ultrasound intensity led to the reverse result [95].

Tenderization and cooling process improvement for poultry meat can be reached by treating the meat with US [96]. US is used to raise meat tenderness, as shown by Kang et al. Thanks to specific operating conditions, the water-holding capacity and tenderness of beef during curing are enhanced. The former is due to the modest oxidation of myosin that starts polymerization, which helps increase water retention; the latter is confirmed by the enhancement myofibrillar fragmentation index values and proteolysis of desmin and troponin-T [97]. More recently, after 7 and 14 days of storage at 4 °C, the tenderization capacity of US has been experimented on beef *m. Longissimus* dorsi muscle samples with 60 min of sonication. The beef showed a reduction in red color and increased pH, luminosity, fascicle size, and a greater interfibrillary space that results in softer meat [98]. Chang et al. have analyzed the features of intramuscular heat-insoluble collagen as well as the textural properties and meat quality of beef semitendinosus muscle after US treatments of 10, 20, 30, 40, 50, and 60 min. The meat color does not change except for a decrease in yellowness, muscle fiber diameter, and filtering residues, which have been reduced by the treatment, but the content of heat-insoluble collagen was not. In general, it has been seen that US treatment deteriorates the stability of collagen and thus meat textural properties [99].

Tenderization through US has been exploited also for squid meat. This causes the muscle fiber to break and proteins degradation, leading to a softer meat [100].

3.1.3. Application in Cereal Product

For flour dough and bakery products such as bread, crackers, biscuits, wafers, and batters (pancakes, donuts), researchers have experimented with variations in texture, density, and volume; furthermore, ultrasound treatment has brought enhancements in visual (aspects, color), sensory characteristics, and digestibility [101,102]. Ding et al. have evaluated the physicochemical properties of germinated dehulled rice flour and its energy requirement in germination under US treatment. It has been seen that the treatment transforms the surface microstructure of rice, which facilitated moisture transfer during steam cooking, and it enhances starch hydrolysis and the glucose content [103]. For buckwheat grains, the US impact is considerable, since it modifies the functional properties of the resulting flour. Only 15 min of US treatment raises the water absorption index and the swelling power of the flour along with the water solubility index and insoluble polyphenols content. In addition, a redness and yellowish enhancement in all processed samples has been observed [104].

Singla et al. investigated the impact of US on the functional properties and structural characteristics of gluten. They have analyzed the textural and cooking peculiarities of noodles prepared with different amounts of US pretreated gluten. The noodles with less pretreated gluten showed similar cooking and textural characteristics to commercial ones. If treated with an increasing number of ultrasonic frequencies, the solubility, water-holding capacity, and oil-holding capacity of gluten rose substantially [105].

3.1.4. Application in Dairy Products

In the dairy products industry, the use of ultrasounds can be useful for microbial inactivation, fat reduction, product homogenization, and improvement of the organoleptic properties and nutritional value. Moreover, it is a time-saving process, since it reduces the time required for cheese ripening and fermentation [78,106–108]. This treatment has gained much consideration in the last few years in particular for fermented products, since it helps reduce the processing time and enhance the probiotics viability for products with low lactose content. For the latter, US helps to reduce undesirable taste and probiotics or β-galactosidase additions [106].

The longer the US treatment, the better the stabilization of the emulsion and the droplet size reduction [85,107]. The droplets size has been seen to be reduced both for skimmed milk and goat milk, and an increased homogenization has been observed for cream. During the US process, milk deterioration and lipid oxidation can be avoided by reducing the treatment time and temperature. In yogurt, high-intensity US can be used to make a better homogenization and emulsification by reducing the milk fat globule size, and it can also reduce the fermentation time by improving lactose hydrolysis, enhance gel strength and firmness by increasing the coagulation properties of whey proteins, and stimulate probiotic bacteria. In ice cream manufacturing, during the freezing process, US reduces the ice crystal size, freezing time, and block crust on the freezing surface [108–110].

Still considering dairy products, US (>400 kHz) can be applied as a method to fractionate liquids, which arrange themselves in layers. For milk, ultrasonic frequencies of 0.4 MHz and 1.6 MHz are used for 5 min at 35 °C [85].

3.1.5. Application in Emulsified Products

In emulsions such as mayonnaise, mustard, creams, dressings, or oil emulsions, ultrasound is used to increase the stability index, activity index of emulsions, and emulsion capacity [111,112]. Table 2 presents different food types, together with the ultrasound process parameters and effects.

3.2. UV Radiation

Commonly, ultraviolet (UV) light irradiation has been utilized as a disinfectant for surface, water, and air but has also gained attention in the food industry as a fast and inexpensive method for hygenization of the surfaces of solid foods and liquid foods. Being a non-thermal technology, the advantages of it use are multiple: minimal loss of nutrients and sensorial quality of foods, no toxic residues, and low energy consumption compared with other thermal treatment commonly used for food decontamination. The latter is the main purpose of this technique due to its effectiveness in the inactivation of pathogenic microorganisms and spoilages [61,113].

UV light is the part of the electromagnetic spectrum in the range from 200 to 400 nm, and it can be divided into three regions: from 200 to 280 nm, UV short wave (UV-C); from 280 to 320 nm, UV medium wave (UV-B); and from 320 to 400 nm, UV long wave (UV-A). Light is emitted from a gas discharge at wavelengths characteristic of the elements that compose the gas itself as well as the excitation, ionization, and kinetic energy of them. A gas discharge is a mixture of excited atoms, nonexcited atoms, cations, and electrons generated through a high voltage applied across a volume of gas. A schematization of UV lamp is shown in Figure 4.

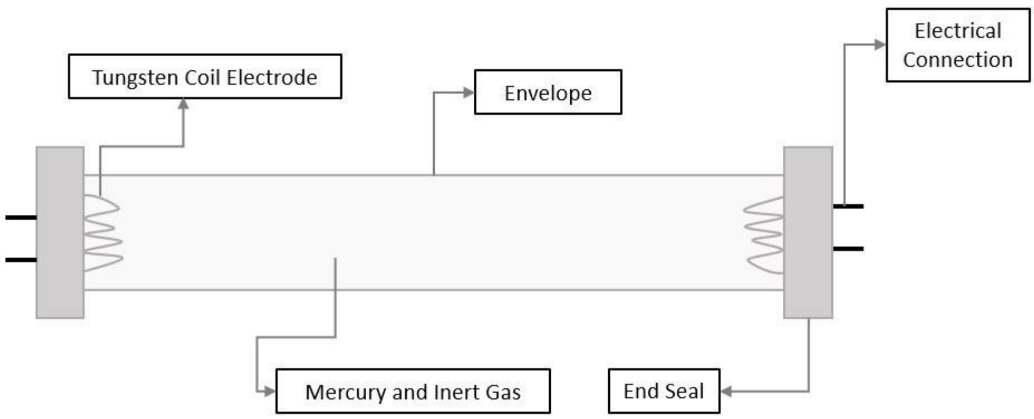

Figure 4. UV lamp.

Table 2. Different food types together with ultrasound process parameters and effects.

Category	Type	Process Parameters (Type/Power/Frequency/Intensity/Time)	Use	Effects	Reference
Fruits and Vegetables	Melon	Water bath/25 kHz/4870 W/m^2/10, 20, and 30 min	Pre-drying treatment	Samples immersed in distilled water present negative water loss values, in sucrose solution, values are positive and are higher when the sonication time increased.	[4]
	Papaya	Water bath/25 kHz/4870 W/m^2/10, 20, and 30 min	Pre-drying treatment	Water loss increased with sonication time.	[4]
	Pineapple	Water bath/25 kHz/55.5 W/L/20 and 40 min	Pre-drying treatment	The moisture content increased with increasing sonication time.	[4]
	Mushrooms	Water bath/25 kHz/154 W/20 and 25 min	Pre-drying treatment	Water gain increased with increasing sonication time.	[4]
	Strawberry	Water bath/480 W/ 40 kHz/5 min	Pesticides removal	Reduction of 91.2% of 16 pesticide residues.	[6]
	Lettuce	Water bath/300 W/20, 40, 60 kHz/8 min	Pesticides removal	Removal of 92.31% of abamectin b1, 89.36% of alphamethrin and 95.25% of emamectin benzoate. No changes in nutritional properties.	[76]
	Oriental sweet melon juice	Ice-water bath/100–500 W/20 kHz/ 20 min	Inhibitory effect on enzymes	65% of inactivation of PPO.	[79]
	Satsuma mandarin	Ice-water bath/400 W/20 kHz/30 min	Inhibitory effect on enzymes	63,7% of inactivation of PPO.	[80]
	Pineapple	Water bath/25–29 W/20, 40, 37 kHz/10–15 min	Inhibitory effect on enzymes	Decrease in PPO and POD activity. Enhancement of phenylalanine ammonia lyase activity.	[81]
	Pineapple juice	Titanium probe/500 W/19 kHz/ 376 W/cm^2/10 min	Inhibitory effect on enzymes	PPO activity reduced; viscosity drop of 75%.	[82]
	Fresh cut potatoes	Water bath/200 W/40 kHz/5 min	Inhibitory effect on enzymes	PPO activity reduced. pH goes down with longer treatments. No change in color. After 10 min, the potatoes' cells are damaged.	[83]

Table 2. *Cont.*

Category	Type	Process Parameters (Type/Power/Frequency/Intensity/Time)	Use	Effects	Reference
	Garlic cloves	Solvent bath/35 kHz/30 min	Aroma extraction	-	[84]
	Grape seeds	33–67% ethanol–water bath/250 W/ 40 kHz/16–34 min	Phenol, antioxidants, anthocyanins extraction	-	[84]
	Grapefruit juice	Probe/28 kHz/30, 60 and 90 min	Microorganism reduction	Enhancement of total antioxidant capacity, ascorbic acid, flavonoids, flavonols, and total phenolics.	[85]
	Apple juice	Probe/25 kHz/2 Wcm^{-2} /30 and 60 min	Microorganism reduction	Rise of total carotenoids, viscosity, minerals such as Na, K, and Ca, and of the concentration of sugar and polyphenolic compounds.	[85]
	Orange, sweet lime, carrot, and spinach juices	Probe/100 W/20 kHz/15 min	Microorganism reduction	Sterilization without loss of nutrients.	[86]
	Cape gooseberry juice	Water bath/240 W/42 kHz/10, 20, 40 min	Post-US process modifications	Decrease in chromaticity, juice yellowing, increased total phenols, RAE value, and carotenoids.	[87]
	Sweet potatoes	Probe/300 W/28 kHz/30 min	Prior to frying treatment	Reduction of 71.47% the oil uptake during the frying step.	[88]
	Potatoes strips	Water bath/160 W/28–40 kHz/240 s	Treatment before drying	Useful to avoid excessive oil uptake during the frying step.	[89]
	Cassava, corn, and yam starch nanoparticles	Probe/20 kHz/30 min	Starch nanoparticles production	-	[90]
Meat and Fish Products	Bovine semitendinosus muscle	Water bath/40 kHz/11 Wcm^{-2}/60–90 s	Post-US process modifications	Improved water-holding capacity, controlled growth of mesophilic and psychrophilic bacteria and total coliforms. Increased meat luminosity and lowers pH without affecting the redness or yellowness.	[91]
	Beef	Probe/150 W/20 kHz/2,39 Wcm^{-2}/ 60–90 s	Meat brining	Rate of mass transfer is accelerated, and the value of D for NaCl is higher than D of water.	[95]

Table 2. *Cont.*

Category	Type	Process Parameters (Type/Power/Frequency/Intensity/Time)	Use	Effects	Reference
	Chicken broilers	US bath/25–130 kHz/28 W/L/5 to 30 min	Tenderization and decontamination	Reduction of about 40% prechiller process time.	[96]
	Beef	Probe/300 W/20 kHz/20–30 min	Curing	Water-holding capacity and tenderness are enhanced.	[97]
	Beef m. Longissimus dorsi muscle	US Bath/40 kHz/11 Wcm^{-2}/60 min	Tenderization	Reduction in red color and increased pH, luminosity, size of fascicle, and greater interfibrillar space.	[98]
	Beef semitendinosus muscle	Water bath/1500 W/40 kHz/10–60 min	Post-US process modifications	US treatment deteriorates the stability of collagen and meat textural properties.	[99]
	Squid	Water bath/186.9 W/25.6 kHz/30.8 min	Tenderization	Broken fiber and proteins degradation create a softer meat.	[100]
Cereal Products	Quinoa (Chenopodium quinoa)	Water bath/250 W/20 kHz/Up to 19 h	Post-US process modifications	Increased water solubility and in vitro starch digestibility, decreased gelatinization temperatures, enthalpy changes in viscosity, gelling capacity, antioxidant activity, and total phenolic content.	[101]
	Flour batters and similar thick liquids	Probe/2.25 MHz	Monitoring the specific gravity	-	[102]
	Dehulled rice flour	Water bath 2000 W/25 kHz/16 W/L/ 5 min	Post-US process modifications	Transformed surface microstructure to facilitate moisture transfer during steam-cooking, enhanced starch hydrolysis, and glucose content.	[103]
	Buckwheat grains	Water bath/100 W/45 kHz/15 min	Post-US process modifications	Rise in the water absorption index, the swelling power of the flour, the water solubility index, and insoluble polyphenols content. Redness and yellowish enhancement.	[104]

Table 2. *Cont.*

Category	Type	Process Parameters (Type/Power/Frequency/Intensity/Time)	Use	Effects	Reference
	Noodles	US reaction tank/67 W/L/ 28–40-80 kHz/10 min	Post-US process modifications	Solubility, water-holding capacity and oil-holding capacity of gluten increased. Particle size reduced. UV absorption and fluorescence intensity of the treated gluten increased. The surface hydrophobicity of gluten increased.	[105]
Dairy Products	Skimmed milk	Probe/28 kHz/100 W/L/30 min	Fermentation	Peptide content and viable cells increased by 49.5% and 43.5%, respectively.	[107]
	Skimmed milk and goat milk	Probe/20–41 W/20 kHz /Up to 60 min	Stabilization and droplet size reduction	Droplets size reduced both for skimmed milk and goat milk. Increased homogenization for cream.	[107]
	Yogurt	Probe/150–750 W/20 kHz /10 min	Homogenization	Reduced milk fat globule size.	[108]
	Yogurt	Probe/100 W/30 kHz/2–15 min	Emulsification	Reduced milk fat globule size.	[109]
	Yogurt	Probe/250 W/20 kHz/20 min	Fermentation	Fermentation time reduced, enhanced gel strength and firmness.	[110]
	Ice cream	Probe/20 kHz/0.21 W/cm^2/5 s	Freezing process support	Reduced ice crystal size, freezing time, and block crust on the freezing surface.	[110]
	Milk	Probe/0.4–1.6 MHz/5 min	Fractionation	Arrangement in layers.	[86]
Emulsified Products	Mustard	Probe/750 W/20 kHz/30 min	Post-US process modifications	Increased stability index.	[111]
	Emulsions with low oil soybean content	Probe/120 W/20 kHz/1 min	Post-US process modifications	Reduced suspension viscosity and size of the biopolymer complexes.	[112]

Microbial inactivation, but also protein damage, is caused by UV light on the DNA genes, in particular by UV-C waves whose maximum germicidal peak is between 260 and 265 nm, the same as the maximum DNA absorption. These types of waves cause the formation of DNA photoproducts, for example pyrimidine 6–4 pyrimidone photoproducts and cyclobutane pyrimidine dimers, which imply DNA mutagenesis and cell death [113,114].

3.2.1. Application in Fruits and Vegetables

UV light has been widely explored for the decontamination of fresh fruits and vegetables. In particular, also UV-assisted TiO_2 photocatalysis (TUV) [115] has been recently investigated for disinfection from *E. coli* on oranges' surface and juice [116]. *L. monocytogenes, Staphylococcus aureus, E. coli* O157:H7, *Salmonella typhimurium*, and *Saccharomyces cerevisiae* have been inactivated in commercial apple juice after treatment with TUV followed by a high hydrostatic pressure process [117]. In addition, Quatrini Corrêa et al. have investigated UV-C light irradiation on apple juice in order to lower the population of *E. coli*, which was reduced after the experiments by (3.2 ± 0.4) and (3.8 ± 0.2) $\log_{10}$ colony-forming units CFU/mL [118].

On the other hand, UV light reduces considerably the vitamin C content in apple juice. Orlowska at al. have analyzed the modifications made on juice by continuous monochromatic low-pressure (LPM) and medium-pressure polychromatic (MPM) mercury UV lamps. Vitamin C reduced by −1.30 ± 0.07% with an LPM UV lamp after about 140 min and by −5.45 ± 0. 27% with an MPM UV lamp after almost 5 min. The pH, of value 3.56 ± 0.01, was not affected [119].

Low-pressure (LP) UV light combined with mild temperatures on freshly squeezed orange juice inactivate part of *E. coli*; the treatment reduces of 16.45% ascorbic acid content and 63.96% the pectinmethylesterase activity but it does not affect acidity, pH and color [120]. Furthermore, *E. coli* and *S. typhimurium* has been inoculated in coconut milk to evaluate UV-C light effects on these bacteria and the consequences on the milk physicochemical, bioactive, microbial and sensory characteristics. UV-C light does not influence pH, acidity and soluble solids; otherwise phenolic compounds are reduced by 26.6%. Regarding bacteria, these are reduced by (4.1 ± 0.1) $\log_{10}$ CFU/mL after 30 min of UV-C treatment [121]. Ilse N. Fredericks et al. have investigated the effectiveness of ultraviolet-C radiation (254 nm) as a substitute process to the SO_2 addition to deactivate microorganisms in grape juices and wine. It has been experimented a $\log_{10}$ CFU/mL bacterial drop of 4.97 and 4.89 in Chardonnay and Pinotage, respectively. In Chenin blanc and Shiraz juice, a $\log_{10}$ CFU/mL decrease of 4.48 and 4.25, respectively [122]. Black peppercorns have been analyzed under UV light emitting diode (UV LED) irradiation. After treatments with 280 nm wavelengths and durations of 20 min, bacillus subtilis concentration decreases to (6.20 ± 0.44) $\log_{10}$ CFU/g [123]. *L. monocytogenes, E. coli, Bacillus subtilis* and *S. typhimurium*, after inoculation in onion powder, garlic powder, cheese and onion powder and chilli powder, have been treated with UVC-LEDs light at wavelengths of 270 nm. A substantial reduction of 0.75 up to 3 $\log_{10}$ CFU/g has been obtained after 40 s of UVC-LED exposure times [124].

UV-light has been studied not only as disinfectant method. In their work, Baenas et al. analyze if UVA light and UVC light pre-treatment (1 kJ/m^2) can enhance the concentration of bioactive compounds such as carotenoids, polyphenols and hydrophilic-lipophilic antioxidant capacity in tomatoes during the post-harvest step. Unfortunately, UV irradiation alone does not considerably influences the carotenoid content, neither phenols or polyphenols concentration [125].

3.2.2. Application in Meat and Fish Products

Corrêa et al. investigated UV-C light irradiation on beef, pork, and chicken meat in order to lower the population of *E. coli*. UV-C lamps reduce the number of bacteria by (1.0 ± 0.2) $\log_{10}$ CFU/mL in beef. Regarding chicken and pork, after 4 and 10 min of irradiation, the bacteria decrease by (1.6 ± 0.7) $\log_{10}$ CFU/mL and (1.6 ± 0.4) $\log_{10}$ CFU/mL, respectively [118].

Lázaro et al. analyzed which is the most suitable UV-C light intensity to inactivate *S. typhimurium* inoculated in chicken breast meat, stored at 4 °C for 9 days, without damaging it. The group of meat treated with the highest UV-C intensity showed extended shelf life and lag phase as well as a decrease in the initial bacterial load. Some intensities revealed a more stable yellowness (b*) value than the other groups; the rise in the biogenic amines, tyramine, cadaverine, and putrescine contents registered for all the analyzed groups should not be considered as an indicator of bacterial growth but as a consequence of the UV treatment [126].

Bacteria and microorganism can also attack fish meat. In this case, UV-light can be an easy method to inactivate these foodborne pathogens. Colejo et al. evaluated the effectiveness of UV-C treatment on vacuum-packaged smoked salmon during refrigerated storage (4 ± 1 °C) against *L. monocytogenes, Listeria innocua, S. typhimurium, Salmonella enterica enteritidis, S. aureus, E. coli* O157:H7, *Aeromonas hydrophila,* and *Plesiomonas shigelloides*. Moreover, after 28 days of storage, the degree of lipid oxidation, color, and external appearance have been evaluated. A precise dosage of UV-C radiation permits inactivation in the range of (−0.5) and (–1.3) $\log_{10}$ CFU units of the microbial population without important variations in the sensory quality properties of the treated products [127].

3.2.3. Application in Cereal Product

UV light irradiation has been tested on cake batters by Konak et al. for different times (0, 1, 2, and 4 h) and subsequently backed applying typical methods or microwaves or a combination of them. The parameters evaluated are chemical composition, water activity, specific volume, crumb and crust color, textural parameters such as hardness, cohesiveness, springiness, and resilience, and sensory characteristics. An increase in UV radiation and time of irradiation leads to an enhancement in browning reactions on the cake. In addition, a rise in specific volume has been observed after 1 or 2 h of UV treatment. Consumers have noticed an unappealing taste and fragrance as the irradiation time increases; on the other hand, the browning reaction on the cake surface, backed only with conventional methods, has made cakes prepared with UV-light more preferable [128].

UV radiation effects on food products containing gluten are documented by Kumar et al., who focused their research on wheat (*Triticum aestivum*) flour and its protein modification after UV-C radiation. They observed a decrease in gluten content as well as a rise in total volatile basic nitrogen content and photo-induced thiol-disulfide bridge exchange [129].

3.2.4. Application in Dairy Products

Used for milk treatments, UV light reduces considerably the vitamin C content. Orlowska et al. analyzed the modifications made on milk by continuous monochromatic low-pressure (LPM) and medium-pressure polychromatic (MPM) mercury UV lamps. Vitamin C reduced by −35.13 ± 1.56% with an LPM UV lamp after 234 min and by −61.67 ± 3.08% with an MPM UV lamp after 11 min. The pH, of value 6.68, was not affected [119]. Vitamin C is not the only one lowered by UV light. A study on cow and goat milk highlights that also vitamins A, B2, and E are damaged by UV irradiation. The most affected after vitamin C is vitamin E, then A, and at last vitamin B2. In cow milk, vitamin A, B2, and E decrease by 8 to 13%, 3 to 10%, and 16 to 33%, respectively, while in goat milk, they were lowered by 1 to 9%, 1 to 2%, and 1 to 48%, respectively [130]. Koca and Öztürk investigated UV light irradiation on the surface of kashar cheese, a kind of pasta-filata cheese, before the packaging step in order to eliminate or control contamination that can happen during the post-processing steps without compromising chemical and sensorial quality. The cheese's surfaces underwent different intensities in a batch UV cabinet system, and the researchers obtained $\log_{10}$ pathogens reductions of 0.34, 0.69, and 2.49 in samples treated with different dosages of radiation. No significant differences in hardness or composition have been found in any of the treated cheeses. In addition, during sensory analysis, no color modifications have been perceived. Unfortunately, lipid oxidation, accelerated by light enhancement, has caused a perception of off-flavor [131]. Ricotta is another cheese potentially exploitable by a wide range of microorganisms as a growth medium. It has been artificially inoculated with *Pseudomonas fluorescens* by Ricciardi et al. and then irradiated with UV-C light. After less than 5 days, the control samples were no more acceptable from the microbiological side, whereas the UV-C irradiated ricotta persisted for more than 6 days without any alteration in sensory properties [132]. Sliced cheese has been inoculated with *E. coli*, *S. typhimurium*, and *L. monocytogenes* and then packaged in order to analyze the effectiveness of UV light irradiation in inactivating these food-borne pathogens living under the plastic packaging. Among the materials used for the packaging (polyethylene terephthalate (PET), polyvinylchloride (PVC), polypropylene (PP), and polyethylene (PE)), the ones that reduced the levels of the pathogens the most are PP and PE films. A thickness of 0.07 mm allows equal reduction in the three bacteria compared to non-packaged UV-treated samples [133].

In Table 3, it is possible to find the studies where UV is investigated and utilized, which are schematized according to the food type, together with process parameters and effects.

3.3. Ozonation

The use of ozone (O_3) in the food industry has become widespread as it acts primarily as a disinfectant against a variety of microorganisms but also as a means of shelf-life extension of many foods. Meat [134,135], poultry [136], eggs [137], seafood [138], fruits [139,140], vegetables [141–145], juices [146], spices and herbs [147,148], dairy and dairy products [149], and dry foods have been treated with ozone for different purposes, among them sanitization and disinfection purposes [150,151]. Ozone as a non-thermal treatment has great antioxidant activity against bacteria, fungi, viruses, protozoa, and vegetative cells [152,153]. Ozone destroys microorganisms by gradually oxidizing vital cellular components, starting first with the sulfhydryl groups and amino acids, contained in proteins and enzymes, and continuing with the oxidation of polyunsaturated fatty acids [154]. Ozone also has significant antioxidant activity against mycotoxins, which are highly toxic substances formed in a variety of agricultural products [155–157], at all stages of their distribution and marketing [158], with the processed products showing little or no chemical residues and pollutants [159]. Ozone has also been shown to modify certain functional properties of foods. Increased shelf life, improved texture, as well as reduced viscosity are some of the effects of ozonation on starch modification in various starch sources such as rice, corn, potato, cassava, and wheat sources [151]. Figure 5 presents the main uses of ozone technology in food processing.

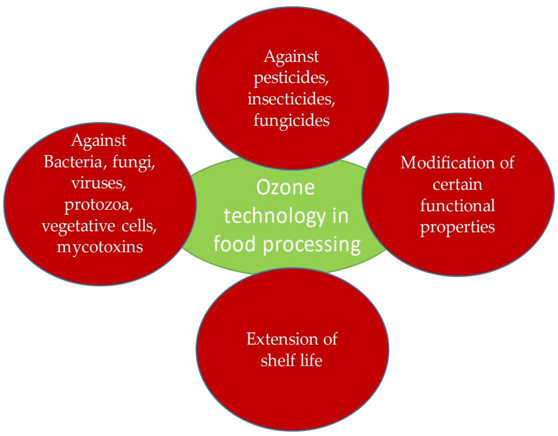

Figure 5. Use of ozone technology in food processing.

Table 3. Different food types, together with UV light process parameters and effects.

Category	Type	Process Parameters (Power/Wavelength/Intensity/Time/Distance from the Sample)	Use	Effects on Microorganism and Properties	Reference
Fruits and Vegetables	Orange surface	TUV 254 nm/35 W/17.2 mW/cm^2/up to 20 min	Disinfection	*E. coli* reduced by 4.3 log_{10} CFU/mL.	[116]
	Orange juice	TUV 254 nm/35 W/17.2 mW/cm^2/ 20 min + HHP 400 MPa 1 min	Disinfection	*E. coli* reduced by 2.4 log_{10} CFU/mL.	[116]
	Apple juice	TUV 254 nm/16 W/8.45 J/cm^2/+ HHP 400–500–600 MPa	Disinfection	*L. monocytogenes*, *S. aureus* totally inactivated. *E. coli* and *S. typhimurium* reduced by 7.1 and 7.2 log_{10} CFU/mL, respectively. *S. cerevisiae* reduced by 6.2 log_{10} CFU/mL.	[117]
	Apple juice	UV-C 254 nm/4 W/13 mW/cm^2/ 5–10 min/1 cm	Disinfection	*E. coli* reduced by (3.2 ± 0.4) and (3.8 ± 0.2) log_{10} CFU/mL.	[118]
	Apple juice	LMP UV 254 nm/20 W/ 10 mJ/cm^2/140 min/30.48 cm MPM UV 245 nm/ 2660 W/10 mJ/cm^2/5 min/45.72 cm	Post-UV irradiation alterations	Vitamin C reduced by −1.30 ± 0.07% with LPM lamp after about 140 min and of −5.45 ± 0. 27% with MPM. pH not affected.	[119]
	Orange juice	LP UV 245 nm/8 W/23.72 J/mL/ 3.6 min at 55 °C	Disinfection	Reduction of 16.45% ascorbic acid content and 63.96% pectinmethylesterase activity. Acidity, pH, and color not affected; 6 log_{10} cycles of inactivation of *E. coli*.	[120]
	Coconut milk	UV-C 254 nm/17 W/ 0.342–1.026 kJ/m^2 /30 min at 4 °C	Disinfection	*E. coli* and *S. typhimurium* reduced by (4.1 ± 0.1) log_{10} CFU/mL. pH, acidity and soluble solids not affected. Phenolic compounds reduced by 26.6%.	[121]
	Grape juice and wine	UV-C 245 nm/30 W/3672 J L^{-1}	Disinfection	Bacterial drop of 4.97 and 4.89 log10 CFU/mL in Chardonnay and Pinotage, respectively. Bacterial drop of 4.48 and 4.25 log_{10} CFU/mL in Chenin blanc and Shiraz juice, respectively.	[122]

Table 3. *Cont.*

Category	Type	Process Parameters (Power/Wavelength/Intensity/Time/Distance from the Sample)	Use	Effects on Microorganism and Properties	Reference
	Black peppercorns	UV-LED 280 nm/20 min/1 cm	Disinfection	*B. subtilis* concentration decreased to (6.20 ± 0.44) $\log_{10}$ CFU/g.	[123]
	Onion, garlic, cheese and onion powders and chilli powder	UV-C-LEDs 270 nm/128 mJ/cm^2/ 40 s/20 mm	Disinfection	*L. monocytogenes*, *E. coli*, *B. subtilis*, and *S. typhimurium* reduced by 0.75 up to 3 $\log_{10}$ CFU/g.	[124]
	Tomatoes	UV-C 254 nm/8 W/1 kJ/m^2/5 h UV-A 366 nm/8 W/1 kJ/m^2/5 h	Compounds enhancement	Carotenoid content, phenols, or polyphenols concentration not considerably influenced.	[125]
Meat and Fish Products	Beef	UV-C 254 nm/4 W/13 mW/cm^2 / 5 min/1 cm	Disinfection	*E. coli* reduced by (1.0 ± 0.2) $\log_{10}$ CFU/mL.	[118]
	Chicken	UV-C 254 nm/4 W/13 mW/cm^2 / 5 min/1 cm	Disinfection	*E. coli* reduced by (1.6 ± 0.7) $\log_{10}$ CFU/mL.	[118]
	Pork	UV-C 254 nm/4 W/13 mW/cm^2 / 5 min/1 cm	Disinfection	*E. coli* reduced by (1.6 ± 0.4) $\log_{10}$ CFU/mL.	[118]
	Chicken breast	UV-C 254 nm/30–55 W/ 1.13–1.95 mW/cm^2/up to 120 s/ 14 cm	Disinfection	Extended shelf life, decrease in bacterial load of (0.6 ± 0.03) $\log_{10}$ CFU/g. Rise in biogenic amines content, tyramine, cadaverine, and putrescine.	[126]
	Smoked salmon	UV-C 254 nm/30–55 W/900 mJ/cm^2	Disinfection	Drop of −0.5 /–1.3 $\log_{10}$ CFU unit/tot unit of bacterial population. No variation in sensory quality after 28 days of storage.	[127]
Cereal Products	Cake batters	UV-C 254 nm/3.636 mJ/m^2/up to 4 h	Post-UV irradiation alterations	Enhancement in browning reactions on the cake. Rise in specific volume. Unappealing taste and fragrance as the irradiation time increases.	[128]
	Wheat flour	UV-C 254 nm/30 W/ 0.568 ± 0.026 mW/cm^2/from 50 up to 250 s	Post-UV irradiation alterations	Decrease in gluten content. Rise in total volatile basic nitrogen content and photo-induced thiol-disulfide bridge exchange. Reduction in pH.	[129]

Table 3. *Cont.*

Category	Type	Process Parameters (Power/Wavelength/Intensity/Time/Distance from the Sample)	Use	Effects on Microorganism and Properties	Reference
Dairy Products	Milk	UV-C LPM 254 nm/20 W/10 mJ/ cm^2 /234 min UV-C MPM 254 nm/2.660 W/ 10 mJ/cm^2/11 min	Post-UV irradiation alterations	Vitamin C reduced by −35.13 ± 1.56% with LPM UV lamp and of −61.67 ± 3.08% with MPM UV lamp. pH not affected.	[119]
	Milk	UV-C 254 nm/28 W/88.2 J/mL	Post-UV irradiation alterations	Vitamin A, B2, and E decrease by 8 to 13%, 3 to 10%, and 16 to 33%, respectively.	[130]
	Goat milk	UV-C 254 nm/28 W/82.04 J/mL	Post-UV irradiation alterations	Vitamin A, B2, and E decrease by 1 to 9%, 1 to 2%, and 1 to 48%, respectively.	[130]
	Kashar cheese	UV-C 254 nm/32.1 W/m^2/ up to 300 s/4 cm	Disinfection	Bacterial reduction of up to (2.49) log_{10}. CFU/g. Lipid oxidation causes a perception of off-flavor. No differences in color and hardness value.	[131]
	Ricotta	UV-C 254 nm/95 W/6.54 J/cm^2/ 30 s/3.5 cm	Disinfection	*P. fluorescens* reduced by (−1.03 ± 0.02) log_{10} CFU/g. Ricotta lasts for 6 days without any alteration in sensory properties.	[132]
	Sliced cheese	UV-C 254 nm/3.04 mW/cm^2/ 1 min/10 cm	Disinfection	PP and PE films reduced the most the levels of the pathogens. A thickness of 0,07 mm allows equal reduction in the three bacteria compared to non-packaged UV-treated samples.	[133]

The application of ozone is a bio-friendly technique and commercially feasible technology, making it a promising agent in the food industry. Moreover, there is no need for transportation, and all the treatments with ozone have lower running costs except for the first high cost for installation [160–162]. In addition, there is no need for management facilities of possible waste as there are none, nor are cleaning facilities of the required equipment necessary. However, its use can be dangerous for people who use this technology, as it can show significant toxicological effects at certain concentrations [151].

In 1997, the US-FDA (United States Food and Drug Administration) included ozone in GRAS (Generally Recognized as Safe) additives and officially in 2001 began to be allowed for direct contact with food [162]. Ozone can act as a sterilizing agent in either gaseous or aqueous form [162]. Decomposition caused by the aqueous form of ozone is faster than that caused by its gaseous form [163]. Oxygen cylinders or oxygen concentrators are mainly used for ozone production, but the atmospheric source of oxygen through the ambient air can be also used for the same purpose [162]. Ozone is a triatomic gas that does not require storage in a container, as it can be produced on site [163], and it spontaneously decomposes into oxygen [164]. Ozone production begins with the passage of air or oxygen through a high-energy electric field. Along with ozone, some free radicals are also produced [159], such as hydroxyperoxy ($HO_2\cdot$), free hydroxyl ($HO\cdot$), and superoxide ($O_2\cdot$), which also acts against microorganisms [150]. Table 4 presents recent studies of applications of ozone in different food categories.

3.3.1. Application of Ozone in Fruits and Vegetables

The application of ozone to fruits and vegetables focuses mainly on their preservation in combination with their microbiological safety, mycotoxins, and chemical residues. Many researchers have widely studied its use in a variety of fruits and vegetables, and what can basically emerge from their studies is that the effectiveness of using ozone in these food categories is achieved by applying a relatively low concentration of ozone in combination with short exposure time. Regarding their maintenance, it is very well established that ozone is extremely effective in controlling ethylene in storage areas. Although most research highlights the beneficial effects of ozone, there are several research papers that also report adverse effects on quality characteristics that vary from product to product. For example, the degradation of anthocyanin and the color of many fruits has been reported in fruits and juices derived from strawberries and blackberries [161,164], which is caused by the oxidizing power of this triatomic molecule, which reacts and degrades certain organic compounds [159].

For the production of fruits and vegetables, several pesticides are used, such as insecticides and fungicides in order to prevent infestations by insects and fungi. This use carries the risk of the presence of serious residues in fruits and vegetables. The combination of ozone use and ultrasound treatments has been shown to be effective against both pathogens. E. coli, Salmonella, and Listeria, as well as pesticides including thiamethoxam, imidacloprid, and acetamiprid, have been detected in freshly harvested spinach [167]. Application for 5 min was sufficient to extend the shelf life of minimally treated pepper for 14 days, which was packaged in polypropylene bags and stored at temperature 5 ± 0.5 °C and RH 85% $\pm$ 5 % [168].

Table 4. Recent studies of applications of ozone in different food categories.

Food Category	Product	Ozone Form and Concentration	Exposure Time	Effect	Reference
Fruits and Vegetables	Fresh-cut lettuce	Ozonated water, 2 mg L^{-1}	5 min	2.57 log reductions against *S. Typhimurium* color properties and sensory quality without any effect	[165]
			15 min	3.47 log reductions against *E. coli* color properties and sensory quality without any effect	
	Spinach	Gaseous ozone, 1 ppm	10 min	1 log reduction in *E. coli* and *Listeria* spp.	[166]
	Spinach	Combination of ozone 3.33 g min^{-1} and ultrasound 40 kHz	10 min	1.46 log reduction in *E. coli*, *Salmonella*, and *Listeria*	[167]
	Fresh-cut green bell peppers	Aqueous ozone, 2.4 mg L^{-1}	5 min	3.71 log reduction in total plate count	[168]
	Strawberry	Aqueous ozone, 0.1 ppm	2 min	Retention the fruit quality and extension the storage life	[169]
	Strawberry	Aqueous ozone, 3.5 mg L^{-1}	5 min	Reduced decay caused by *B. cinerea* almost 17%	[170]
	Fresh-cut cabbage	Aqueous ozone, 1.4 mg L^{-1}	5 min	Significantly inhibited aerobic bacteria, coliforms, and yeasts, reduced ethylene production	[171]
	Fresh-cut onions	Aqueous ozone, 1.4 mg L^{-1}	5 min	Significantly inhibited aerobic bacteria, coliforms, and yeasts, reduced respiration rate, reduced residual levels of five tested pesticides	[172]
Fish Products	White shrimp	Ozonated water, 1 ppm	10 min	Increased shelf life (up to 24 days), maintained acceptable sensorial attributes	[173]
	Sea bream	Aqueous ozone, 640 ppm	15 min	0.29 log reductions in *Enterobacteriaceae*	[174]
	Oyster	0.6 mg/L/	6 h	1.3 log reductions in *E. coli*	[175]
Mushrooms	*Agaricus bisporus*	Gaseous ozone, 2.0 mg/L	30 and 60 min	Increased firmness	[176]

Table 4. *Cont.*

Food Category	Product	Ozone Form and Concentration	Exposure Time	Effect	Reference
Meat Products	Turkey breast meat	Gaseous ozone, 1×10^{-2} kg m^{-3}	up to 8 h	2.9 log reductions in the counts of total aerobic mesophilic bacteria, 2.3 log reductions in *enterobacteriaceae*, 1.9 log reductions in yeast–mold, significant changes in color and pH, acceptable sensory properties	[177]
	Beef	Gaseous ozone, 280 mg m^{-3}	5 and 10 min every 30 min for 5 h	1 log reductions in lactic acid bacteria, mesophilic and *enterobacteriaceae*	[178]
	Goat meat	Ozonated water, 0.68 mg/L	6 min	0.50 log reductions in *E. coli*	[179]
Juices and Beverages	Peach juice	Gaseous ozone, 0.11 mg O_3 min^1 mL	12 min	99.5% decreased POD activities 93.9% decreased PPO activities	[180]
		Gaseous ozone, 0.20 mg O_3 min^1 mL		99.8% decreased POD activities 97.3% decreased PPO activities	
	Apple juice	Gaseous ozone, 33–40 µg/mL	8 min	Increased shelf life in 34 days at 8 °C storage	[181]
Table Olives	Nocellara Etnea	Ozonated water, 6.5 ppm	10 min	1 log reductions for mesophilic aerobic bacteria and 1.47 log reductions for yeasts and mold	[182]

3.3.2. Application of Ozone in Juices and Beverages

Consumers' demands for fresh juices are growing without all these negative effects that thermal pasteurization has on juices. However, ozone leaves no residue when applied to juices, and a concentration limit of 0.4 mgL^{-1} has been set. Factors related to the effectiveness of ozone against pathogenic microorganisms are the pH of the juice, the concentration, the temperature, and the additives as well as the exposure time and the ozone concentration [164]. The ozonation of juices usually takes place in cylinders with the formation of bubbles [180].

Sánchez et al. reported enzyme peroxidase (POD) and polyphenoloxidase (PPO) activities which were reduced due to treatments with gaseous ozone in peach juice. The researchers exposed peach juice to ozone with different concentrations. Maximum enzyme activities reductions after 12 min of treatment were achieved through the effect of higher ozone concentration [180].

Low concentrations of ozone have been found not to completely inactivate pathogenic microorganisms in juices, whereas high concentrations of ozone degrade some of their quality characteristics such as phenolic content and color. García-Mateos et al. reported that a combination of low ozone concentration (24 mg L^{-1}) with high hydrostatic pressure (179–321 MPa, 5 min) was efficient for the stabilization of refrigerated pitaya juice [152].

3.3.3. Application of Ozone in Meat Products

The microbial disinfection caused by the use of ozone in meat products is the main goal of this treatment, but sometimes, it also brings some negative effects. The oxidation of myoglobin and oxymyoglobin to methyoglobin is the main reason that ozone treatment in meat leads to discoloration [159]. Particular care should also be taken in the application of high-ozone concentrations, as they can cause the oxidation of lipids and proteins, which are also important quality indicators [183].

Meat is one of the most vulnerable foods and substrates for the growth of a variety of microorganisms including Pseudomonas spp, lactic acid bacteria, Clostridium spp, Aspergillus, and Penicillium. Ozone is used for a wide variety of meats and meat products that are not only fresh but also processed. Among the various types of meat available on the market, chicken meat is of great interest, as it is widely consumed with a significant degree of vulnerability [184]. Muhlisin et al. evaluated the effects of gaseous ozone exposure on the bacterial counts and oxidative properties in chicken breast meat. Coliform and total aerobic and anaerobic bacteria were effectively inhibited by the application of ozone gas at 10×10^{-6} kg $O_3/m^3/h$ [185].

Werlang et al. studied the application of 5 ppm gaseous ozone on the microbial and quality attributes of pig carcasses. From the results of the study, two 4 h treatments with ozone gas proved to be effective not only against total aerobic mesophilic bacteria but also for maintaining its quality [183].

3.4. High-Pressure Processing

High-pressure processing (HPP) (also called as high pressure (HP) or high hydrostatic pressure (HHP) or ultra-high pressure (UHP)) is a novel, emerging, and promising non-thermal pasteurization technology, the use of which has steadily increased in food processing since the beginning of the twenty-first century [186–188]. In fact, the application of high-pressure technologies in the food industry is following an exponential growth over the last few years [189]. HPP technology acts as a cold pasteurization process and takes place at pressures ranging between 100 and 1000 MPa and at temperatures from −20 to 60 °C, to solid, liquid, packaged, or unpackaged foods, for several seconds or minutes [190]. A liquid, which is water, is usually used as a means of pressure transfer [8], due to safety and cost considerations [191]. Figure 6 displays a high-pressure processing (HPP) vessel.

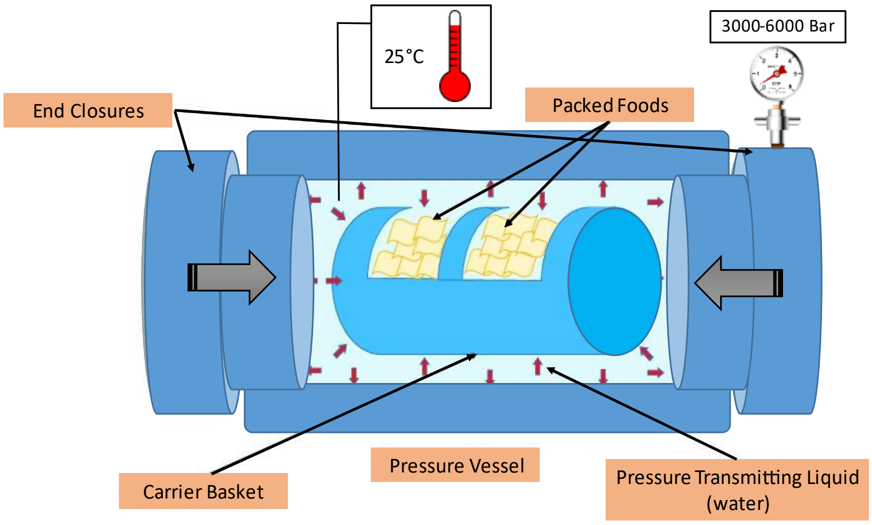

Figure 6. Schematic display of a high-pressure processing (HPP) vessel. Adapted from [192].

The most suitable foods to be processed with the HPP technique are those that have a satisfactory concentration in water and a lack of air gaps. Today, this technique has found wide application, mainly in fruits and vegetables, seafood and shellfish, dairy products, juices and beverages, ready-to-eat meals, and meat products [186]. This technique is unsuitable for the production of low acidity foods, as they require high pressures of 800–1700 MPa in order to inactivate their bacterial spores [193].

Food safety, food quality, and extending the shelf life of high-value refrigerated foods have been the main focus of HPP technology in recent years [194,195]. All these can be achieved, as a variety of pathogenic and spoilage vegetative bacteria, yeasts, molds, viruses, and also spores can be inactivated with HPP treatment [196]. Applying the PP technique has been also shown to enhance healthy attributes in foods. It has been found that the immunoglobulin of dairy products is preserved, the content of resistant starch in cereals is increased, and the glycemic index of fruits is reduced. In addition, this technique promotes the extraction of bioactive compounds from food waste [197].

Key process parameters for this technology include pressure, temperature, and exposure time, but water activity, types of enzymes and/or microorganisms, and the cell growth phase are some extraordinary factors that critically influence the process [198]. The application of pressure can be performed both directly and indirectly [199]. In direct application, a piston moves and causes a change in volume inside the pressure vessel, while in indirect application, the pressure setting in the container varies according to the amount of pressure fluid [186].

The application of this technology disrupts cell walls and membranes, inactivates enzymes, denatures proteins, and causes gel formation [190]. HPP has been officially approved as a food pasteurization alternative to traditional pasteurization by the U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) [200]. Isostatic pressure above 300 MPa is applied to hermetically sealed containers containing food [190]. In HHP technology, pressure is uniform and simultaneous in all directions of the container, so the pasteurization effect of HPP is not affected by the size, shape, product composition, and nutrient content of the food [201].

3.4.1. Application of HPP in Fruits and Vegetables

The extension of shelf life of fresh and minimally processed fruits and vegetables is a key priority at their post-harvest storage [202]. Due to their very high vulnerability, many fruits and vegetables show a relatively short post-harvest life and degraded quality over time [203]. The food industry has turned its attention to the production of minimally processed fruits and vegetables through techniques aimed at maintaining safety and reducing their contamination from foodborne pathogens, which are inevitable microorganisms. The HPP technique can help significantly in the processing of minimally processed fruits and vegetables, causing minimal losses in natural aromas and colors and maintaining their high quality [204]. Actually, the effect of HPP treatment on the covalent bonds of low molecular weight compounds of fruits and vegetables is limited, and therefore, the nutrients and sensory properties are well preserved. Since the success of the technique is due not only to the parameters of the treatment but also to factors related to the integrity and texture of the fruit, there may be conflicting results for the same product [205].

The wounding stress caused by the various changes that occur in the membranes of fruits and vegetables is the main effect of the treatment with the HPP technique [206]. The exposure of whole fruits and vegetables to treatment with the HPP technique has caused an increase in their bioactive components [207], such as polyphenols, isothiocyanates, fatty acids, and essential oils [208]. For example, HPP enhanced the extraction of carotenoids, phenolics, and ascorbic acid in whole mangoes [209], free and bound phenolics in whole carrots [206], and total phenolics in strawberries [210]. To date, the accumulation of nutraceuticals caused by the application of the HPP technique has not been fully elucidated, and it is not known whether it is a result of the time of application of the pressure or increases as the pressure increases [206].

The HPP technique has also been used for the extraction of valuable compounds from plant sources, such as anthocyanins from grapes [211], pectin from tomato peel [199,212], carotenoid from tomato peel [213], and pectin from potato waste peel [214].

3.4.2. Application of HPP in Meat and Fish Products

Fish and seafood are among the most vulnerable foods, and they pose a major threat to public health, especially when eaten raw or undercooked. Foodborne bacterial pathogens, such as L. monocytogenes and S. enterica, significantly affect the quality, and the HPP technology can contribute to effective microbiological safety [215]. In a very recent study, Boziaris et al. applied the HHP technique in frozen fish fillets and caused a reduction in L. monocytogenes and S. enterica without significant effect on the quality [215].

A total of 500,000 tons of HPP product are traded annually on the planet with ready-to-eat meat products occupying the largest share in this market [200]. The HPP technique has caused the inactivation of pathogens such as Campylobacter jejuni [216], E. coli [217], L. monocytogenes [218,219], and S. enterica [220]. Although HPP is effective against spoilage and pathogenic microorganisms in meat, it can cause some unpleasant effects on its quality, related to color, appearance, and texture completely dependent on the intensity of the pressure to be exerted [221–223].

The application of the HPP technology begins with the sealing of meat samples in flexible plastic containers in vacuum conditions. These containers are placed in vessels/chambers, which are filled with the pressure transmitter medium. The pressure transmission is independent of direct or indirect contact with the sample and takes place in a uniform manner [222].

The HPP technique may have a synergistic effect with essential oils in the treatment of foodborne pathogens such a Salmonella and Listeria. Chuang et al. (2020), reported 5.25 log reduction against L. monocytogenes and 6.01 log reduction against S. enterica in fresh ground chicken meat after HPP treatment at 350 MPa for 10 min and 4°C with 0.60% carvacrol treatment [221].

3.4.3. Application of HPP in Juices and Beverages

HPP technology has been used primarily to reduce pathogens and spoilage enzymes in juices [191,200]. In addition, through this technique, the shelf life of the juices is extended, while it seems to be effective in maintaining the sensory and nutritional quality [224]. Enzymes such as ascorbic acid oxidase (AAO), polyphenol oxidases (PPO), and peroxidase (POD) are found naturally in fruit and vegetables and modify quality characteristics related to texture, taste, color, and nutritional value [225]. The enzymatic browning of juices is a result of high enzymatic activity, which causes the degradation of valuable bioactive compounds [226]. Both pasteurization and inactivation of these enzymes can be performed through the HPP treatment, although studies have shown that in relation to heat treatment, this technique is not as effective in the degradation of enzymes [227,228].

3.4.4. Application of HPP in Dairy Products

Dairy products are generally characterized as vulnerable foods with neutral pH levels and high water activity (>0.9), and their shelf life is short. Through the HPP technique, quality characteristics of milk, such as texture and taste, remain unchanged and at the same time, their shelf life is extended [6]. The several classes of immunoglobulins present in dairy products have positive effects on human health, and the treatment with the HPP technique against the traditional thermal pasteurization can maintain its content [197]. Sousa et al. (2014) found that in human colostrum, immunoglobulin A (IgA), immunoglobulin M (IgM), and immunoglobulin G (IgG) were not significantly affected when treated at 200 MPa for 2.5, 15, and 30 min in 8 °C [229].

3.4.5. Application of HPP in Emulsified Product

The HPP technique has been used successfully in the processing of mayonnaise, spreadable dressings, sauces, and other emulsified foods, as it is a technique without the use of chemicals and also without causing a deterioration in their sensory quality. Sethi et al. (2017) evaluated the quality and stability of mayonnaise enriched with green mango after treatment with high pressure. The optimum conditions for high oxidative and emulsion stability of mayonnaise were the application of 435 MPa pressure for 5 min and the addition of green mango pulp at the rate of 28% [230]. Recently, Pallarés et al. used HPP technology (600 MPa for 5 min at room temperature) for the decontamination of different juice models from alternariol and aflatoxin B1, achieving a reduction of 24% for AFB1 and 37% for AOH [231]. Table 5 presents recent studies of applications of high-pressure processing in different food categories.

Table 5. Recent studies of applications of high-pressure processing in different food categories.

Food Category	Product	Pressure	Exposure Time	Temperature	Effect	Reference
Fruits and Vegetables	Dried strawberry	400 MPa	10 min	5 °C	Increased total phenolic content, same content in vitamin C	[232]
	Grapes	200–550 MPa	10 min	<30 °C	+80% extraction of anthocyanins	[211]
Fish Products	Frozen pink salmon fillets	250 MPa	3 min	−22 °C	3 log reduction against *L. monocytogenes* and *S. enterica*	[215]
Meat Products	Frozen chicken breast	500 MPa	1 min	5 °C	*Salmonella spp* inactivation and preserve color parameters	[233]
	Chicken fille	500 MPa	10 min	20 °C	*S. Enteritidis* inactivation and increased shelf life	[220]
	Poultry- and pork-based semidried fermented sausage	600 MPa	960 s	5 °C	*L. monocytogenes* and *C. perfringens* were below LOQ[3]	[234]
Juices and Beverages	Sugarcane based mixed beverage	300–500 MPa	10–20 min	40–60 °C	Inactivation in PPO[1] (79%) and POD[2] (72%) activity	[235]
	Pawpaw pulp	600 MPa	76 s	4 °C	Significantly decreased PPO	[236]
	Cloudy carrot juice	300 MPa	5 min	22 °C	Inactivation in POD (31%)	[236]
		600 MPa			Inactivation in PPO (57%)	
Dairy Products	Raw milk	600 MPa	5 min	18 °C	5 log reductions for *E. coli*, *Salmonella* and *L. monocytogenes*	[237]
	Cow and goat milk	450 MPa	7 min	15 °C	Increased shelf life (up to 22 days to 8 °C)	[238]

[1] PPO, polyphenol oxidase; [2] POD, peroxidase; [3] LOQ, limit of quantification.

4. Microfluidization

As in the previous described non-thermal technologies, microfluidizer is a modern process that produces strong changes in the food matrix as well. The aim of this technology is to transform two immiscible liquids into a very stable emulsion thanks to very high pressures up to 200 MPa.

It can be exploited in many field such as cosmetic and pharmaceutical industries but also in the case of food processing and agricultural sectors [239]. The most important advantage is that it can solve problems related with emulsion instability such as sedimentation, creaming, or turbidity in beverages [240]. Microfluidizers are able to modify proteins, starch, and fiber structures as well as deactivate enzymes and potential pathogens [241,242].

Despite these many advantages, its application in industrial processing is rarely reported, and research on microfluidization technology, also in the case of food field, is still at the laboratory stage [243].

5. Membrane Technology

Differently from microfluidizers, membrane technology is widely used in the food industry, becoming one of the most exploited non-thermal techniques over the last few decades [244]. Usually, membrane processes are categorized in more specific groups: microfiltration, ultrafiltration, nanofiltration, reverse osmosis, and electrodialysis [245].

These processes utilized membranes usually classified taking into account the average pore sizes and, according to the latter, are capable of retaining species of different molecular weights. The product flows throughout the membrane thanks to an external applied pressure or exploiting a pressure gradient.

This technology finds application for many kinds of fruit juices since permits it the clarification, concentration, and deacidification of the juice itself; clarification and stabilization are guaranteed with this method also for wines and beer.

During sugar processing, purification and demineralization are achieved by membrane operations.

In the dairy industry, membrane technology is extensively used due to its versatility; it is possible to eliminate bacteria and spores from milk, separate casein micelles, fractionate fats from whole milk, and concentrate and demineralize milk [244].

6. Discussion

Traditional food preservation methods can reduce the number of pathogenic microorganisms to safe levels. However, these methods lead to the loss of organoleptic characteristics such as heat-sensitive vitamins, aromatic compounds, and color pigments. Recently, non-thermal technologies have attracted increased attention [203]. High hydrostatic pressure, cold plasma, UV light, pulsed electric field, and ultrasound (US) can effectively destroy microorganisms with almost zero adverse effects on the nutritional value and sensory properties of food materials. These methods apply mild temperature conditions and shorter processing times, which retain the flavor, enhance the shelf life, and inactivate enzymes [18,19,22]. This makes them attractive for producing high-quality and fresh products.

Ultrasound offers many advantages such as a decrease in the use of fossil fuels to provide energy during food processing, including drying and heating; decreases in the amount of water consumed; enhancement of productivity, and retaining the nutrients of the product [18,46]. Ultrasound waves (frequency >20 kHz) with specific intensity and amplitude are used for inactivation of microorganisms in foods. The cavitation phenomenon is responsible for microbial destruction [46], since cavitation bubbles are formed through cycles of pressure created by high-intensity ultrasound. The bubbles grow over several compression/rarefaction cycles, reaching an unstable size, and then they collapse, leading to the release of energy. Very high shear forces are induced, creating high-temperature and pressure conditions (5000 K and 5000 atm) and leading to the structural destruction of many microorganisms [33,48]. Furthermore, their benefits go beyond the inactivation of microorganisms: enhancement of compounds [85], meat tenderization [98], mass transfer acceleration [95], improved emulsification and homogenization [109], and so on.

UV, as a physical preservation technology, is surely a fast and handy way to reduce or eliminate pathogens; in particular, it has been revealed as a promising alternative to traditional thermal treatment for liquid foods, post-processing treatment for cheese and meat, and shelf-life extension of fresh products [114], while still maintaining low energy demands. On the other side, UV radiation is less effective with turbid liquids with particulates, due to strong light absorption, scattering, or reflection effects. In addition, it is necessary to be careful about some compounds that can be damaged by the radiation [119,128,129], generating a reaction that can ruin the flavor and the food itself [88]. Similarly, also, ultrasounds occasionally can provoke color [71], antioxidants [72] and polysaccharides modifications [73], degradation of fats, radicals formation and oxidation [74] in high content lipid foods, due to the strong effects of cavitation phenomena.

Ozone is a potent oxidant and disinfecting agent that does not require thermal energy, so this technology should be considered suitable for heat-sensitive foods [160]. The bactericidal effect of ozone has been proved on a wide variety of organisms, including Gram-positive and Gram-negative bacteria, vegetative cells, and spores. The exposure to fruits and vegetables with ozone increases the shelf life of the products, and it leaves no residues, since it decomposes quickly [246]. However, this treatment is not advised for meat decontamination since it oxidized myoglobin and oxymyoglobin to methyoglobin, leading to meat discoloration [159].

High hydrostatic pressure processing has potential in the development of health foods and at the same time can enhance or retain the nutritional value of raw material and food products. The color, taste, quality, and nutritional content of food are not affected by HPP technology and remain at their original prices [247]. Moreover, HPP can be exploited as a method in combination with existing technologies to reduce extraction time while extracting functional components and developing and improving low-sodium food products while still maintaining microbial safety [156]. High-pressure processing has a high cost: an average of 1 million euros. The machinery for HPP equipment can range in price anywhere from $500,000 to more than $3 million dollars per machine [248]. Bhargava et al. (2021) demonstrate that ultrasounds have low cost [52]. The cost for UV is also low, according to Koutchma (2009) [249].

7. Conclusions

The development of novel and emerging non-thermal treatment technologies, replacing thermal technologies, has resulted from the food industry's effort to find solutions to produce healthy, safe, highly nutritious, and long shelf life foods. Non-thermal processes in relation to thermal processes have significant advantages as they require less processing time, use low temperatures and energy, increase the quality of food with improved characteristics such as color, taste, and nutrient retention, enhance their functionality, are more environmentally friendly, and lead to products with a longer shelf life. HHP has been characterized as the most successfully commercialized non-thermal processing technology, although the high cost of installation is a significant limiting factor for greater adoption of this technology by the food industry. As all processing technologies have advantages and disadvantages, the adoption of one of them in the food industry should be thoroughly considered in order to optimize all the involved parameters.

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