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REVIEW

Non-thermal physical methods to sanitize produce after harvest

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Abstract – Non-thermal physical treatments on ready-to-eat produce are receiving extensive attention because chemicals are facing increasing consumer restrictions concerning the presence of residues with eventual negative health effects. The growing demand for fresh-like and handy foods contrasts with perishability and inherent sensitivity to handling procedures that may result in quality losses. The industry is required to address food security as the numbers of foodborne outbreaks are rising prompting increased attention of health authorities on food safety issues. Expansion of food supply chains has led to spiraling of health risks. To overcome the challenges to reduce microbial loads several disinfection alternatives were developed. Some have advantages over others in terms of quality traits maintenance, ease of application or generation of noxious waste.

Keywords: Alternative treatments. Food safety. Microbiological contamination. Non-heat treatment.

Métodos físicos não térmicos para higienizar produtos hortícolas após a colheita

Resumo – Tratamentos físicos sem aplicação de calor em alimentos prontos para consumo estão recebendo uma maior atenção porquanto os agroquímicos estão enfrentando restrições de parte dos consumidores por eventuais efeitos negativos na saúde por presença de resíduos. O aumento da demanda por produtos frescos e prontos para consumo contrasta com a perecibilidade e a inerente sensibilidade ao manuseio que resultam em perdas de qualidade. Da indústria requer-se a adequação aos parâmetros de alimentos seguros de vez que surtos de contaminantes estão em ascensão incitando uma maior atenção das autoridades sanitárias nos temas alimentos seguros. A expansão das cadeias de suprimento de alimentos tem ampliado os riscos à saúde dos consumidores. Para superar os desafios na redução da carga microbiana, diversas alternativas de desinfecção foram desenvolvidas. Algumas apresentam vantagens sobre outras em termos de manutenção de características de qualidade, facilidade de aplicação ou geração de resíduos nocivos.

Palavras-chave: Tratamentos alternativos. Alimentos seguros. Contaminação microbiológica. Tratamentos não-térmicos.

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Introduction

Historically, the first cleaning approaches of produce were washing with water to remove dirt, foreign materials and tissue fluids on cut surfaces. Soap was added to reduce microorganisms (Castro-Ibáñez; Gil; Allende, 2017). Thereafter, for many decades, postharvest treatments based on molecules of chemical synthesis were almost the only choice to control after harvest produce microbial loads in a speedy and easy straightforward procedure. Nowadays, however, consumers perceive these molecules negatively because of information on health risks and harm to the environment (Pinela; Ferreira, 2017).

Horticultural crops consumed fresh require handling procedures to maintain its visual and internal quality. Any damages by either mechanical forces or temperature abuse devalue tissue freshness appearance. On the other hand, fresh produce naturally may be carriers of high microbial contaminants deriving from field cultural practices and after harvest handling (Gindri; Laporta; Santos, 2012). The microbiological quality of produce often exceeds the internationally accepted indices of contamination (Souza; Lionzo; Petrovick, 2006). Moreover, some food items traverse numerous national borderlines internationalizing and multiplying health risks.

Batz, Hoffmann and Morris Junior (2012) list *Escherichia coli* 0157:H7*, Salmonella* spp. and *Listeria* spp. as the most frequent bacteria species linked to produce-related outbreaks. Ramos *et al.* (2013) indicate that 53.0 % of foodborne disease outbreaks are related to bacteria, while 42.5 % and 4.5 % may be ascribed to viruses and parasites, respectively. According to Todd (2020), approximately 600 million people fall ill every year because of the ingestion of contaminated food and children below 5 years of age sum up about 40 % of those numbers. The most common illnesses are diarrheal diseases affecting about 550 million individuals yearly, mostly children under the age of 9 years (WHO, 2024).

According to the EFSA and ECDC (2021), *Salmonella spp.*, norovirus, *Listeria monocytogenes*, *Campylobacter jejuni* and *Escherichia coli* are the most common contaminants responsible for foodborne outbreaks. All of which occur on uncut and minimally processed vegetables and fruit and should be of public health concern.

Increases in the consumption rates all over the world of minimally processed fruits and vegetables has risen and, concomitantly, food transmitted illnesses. The most common cause of those illnesses is the microbiological contamination that may occur as a result of underestimates of the risk of contaminants presence, lack of knowledge and deficient hygiene and neglected equipment cleaning at the working stations (Schlundt, 2002).

Apart the risk of the presence of microorganisms and their toxic compounds on produce an additional challenge is the capability of microorganisms to form biofilms, though, markedly not all species. Biofilms are complex extracellular polymeric networks of proteins, nucleic acids, lipids, and polysaccharides (Yuan *et al.*, 2019) embedding bacterial clusters attached to surfaces or to each other as part of a survival mechanism turning into more resistant to antimicrobial treatments (Vestby *et al.*, 2020). Limoli, Jones and Wozniak (2015) emphasize that after microorganisms have settled on tissue surfaces they start developing biofilms and become more difficult to get rid of.

Food safety has become a top priority to both the private and public sectors (Santos *et al.*, 2023). Concerns about efficacy of the available sanitizing procedures have instigated the industry and academia to investigate technologies to appropriately deal with food-borne diseases and with some extra undesirable consequences of the sanitizing treatment. The fact is that no sanitizing technology can be applied universally to reduce microbial loads and, at the same time, should not impart undesirable outcomes on product quality.

In many research papers are references to the formation of carcinogenic by-products with an excessive use of chlorine as sanitizer. Trihalomethanes, chloramines, haloketones, chloropicrins, and haloacetic acids derive from reactions of residual chlorine with soil and organic matter from fruit and vegetables in the wash waters (Bilek; Turantaş, 2013). Because of the inherent risk with the use of chlorine some European countries forbid its use in the food industry. By eliminating chlorine compounds, other technologies are being investigated as replacements for chlorination (Issa-Zacharia *et al*., 2010).

In the present paper non-thermal physical methods as alternatives for chlorine-based compounds were gathered through a literature search and described to provide understanding on mode of action, effectiveness and advantages and disadvantages. And by that, eventually, assist in the selection of a single method or a combination of methods to reduce microbial loads on produce.

Non-thermal technologies

Artés *et al.* (2009) indicate that the major preservation techniques applied to prevent or delay spoilage on whole or fresh-cut produce are cold storage and modified atmosphere packaging. Atop of storage temperature and atmosphere modification, sanitation procedures might be combined with either chemical treatments such as antimicrobial solutions, acidulants or antioxidants or moderate heat treatments (Leistner; Gould, 2002).

The industry is investigating non-thermal physical treatments because chemical sanitizers are perceived by consumers as detrimental to human health and harmful to the environment. Furthermore, conventional thermal treatments may negatively affect nutraceutical attributes and cause visual quality damages of highly perishable food items driving increasing attention to non-thermal technologies (Chen *et al*., 2015).

Several methods have been developed as non-thermal treatments in which heat is not the main element for microorganism inactivation. Ionizing and ultraviolet radiation, cold plasma, dense phase carbon dioxide, high hydrostatic pressure, high-power ultrasound, non-conventional atmospheres, ozone, pulsed light, pulsed electric field and pulsed magnetic field as well as possible combinations between them are alternatives either already in use or under development.

Ionizing radiation

Ionizing radiation, including nuclear radiation consists of subatomic particles or electromagnetic waves with sufficiently high energy to ionize atoms*, i. e.,* enough energy to remove tightly bound electrons from the orbit of an atom resulting in a charged (=ionized) atom.

There are several forms of electromagnetic radiation that differ only in frequency and wavelength: heat waves, radio waves, infrared, ultraviolet and visible light, X and gamma (γ) rays (Fig. 1). Longer wavelengths with lower frequency waves have less energy than shorter wavelengths and with higher frequency. Not all electromagnetic radiation is ionizing. Only the high frequency portion of the electromagnetic spectrum, including X rays and gamma rays are ionizing radiation.

Gamma rays were discovered in 1900 by Paul Ulrich Villard (1860 – 1934), a French chemist and physicist after his studies on radiation emanating from radium salts (^{233}Ra). Ernest Rutherford (1871 – 1937), also a chemist and physicist of New Zealand that had

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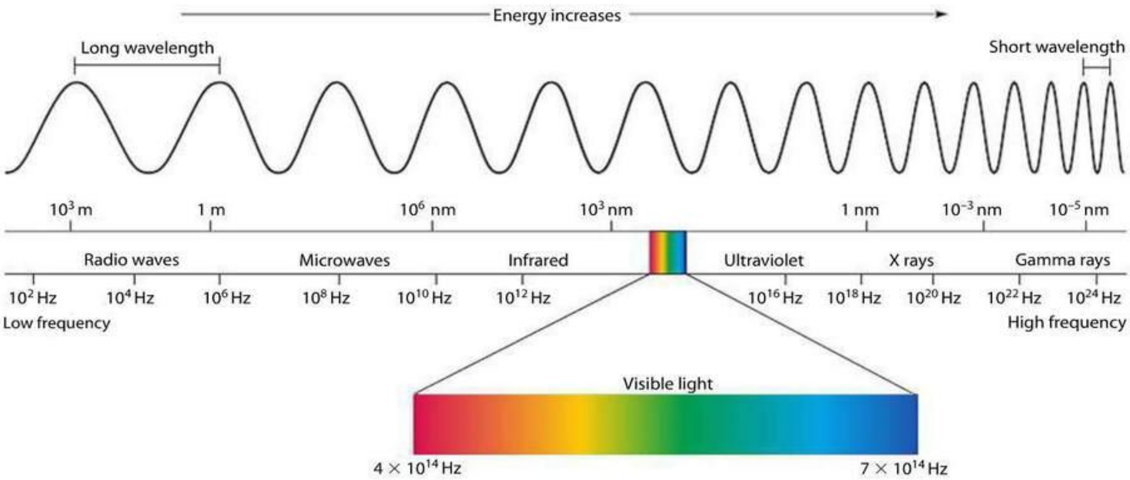
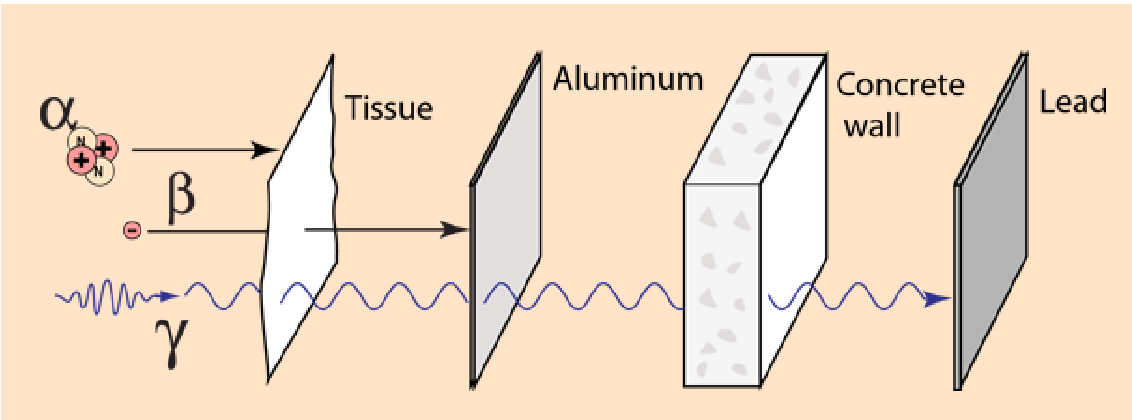
moved to McGill University/Canada, studying uranium (^{238}U) in 1899 determined the existence of a radiation that could be easily blocked by a thin metal layer. The particles were named alfa (α) rays. Rutherford also determined beta (β) rays, which are more penetrating and require thicker metal layers to be blocked (Fig. 2). Rutherford together with Edward Andrade (1887-1971), an English physicist, determined in 1914 that gamma rays are an electromagnetic radiation without mass that is emitted by the radioactive decay of some radioactive materials (radionucleotides).

Figure 1. The electromagnetic spectrum.



Source: https://www.cdc.gov/nceh/radiation/ionizing_radiation.htm

Figure 2. Penetrating capacity of alfa (α), beta (β) and gamma rays (γ).



Source: Alfa, beta, gamma radiation penetration.svg.

There are a number of sources of gamma rays. The most common are solar eruptions and the natural radiation decay of some elements such as uranium (^{238}U), thorium (^{232}Th) and actinium (^{227}Ac). The isotopes cesium (^{132}Cs), cobalt ($^{58.9}Co$), technecium (^{98}Tc) and americium (^{243}Am) are also sources of gamma rays.

Gamma rays have direct effects by breaking down the molecular structure of the DNA. Gamma rays may also have indirect effects via the generation of hydroxyl (•OH) and alkoxy (•OR) radicals that also react with the DNA resulting in permanent damages to the genome (Ashraf *et al.*, 2019). Gamma radiation is a very versatile

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decontamination method for processed food items and, moreover, is regarded as safe, effective, environmentally clean and an energy efficient process (Spoto *et al*., 2000).

The World Health Organization (WHO) stated in 1994 that irradiated food is safe and nutritionally adequate as long as it is produced in accordance to established good manufacturing practices (Marin-Huachaca *et al*., 2002). There have been, however, preceding concerns on the formation of cyclic ketones, for example 2-alkylcyclobutanones as a result of the irradiation process. The review by an expert committee of FAO/IAEA/WHO of all available data concluded that `… *irradiation of any food commodity up to an overall dose of 10 kGy presents no toxicological hazard*…` (Stefanova; Vasilev; Spassov, 2010).

The first regulations for food irradiation in Brazil date back to the sixties. Nowadays food irradiation is regulated by the resolution RDC Nº. 21 of January 26, 2001 (Levy; Sordi; Villavicencio, 2020).

Practical applications of food irradiation can be divided based on the radiation doses into three categories: low dose applications of up to 1 kiloGray (kGy), medium dose applications are in the range of 1 kGy to 10 kGy and high dose applications are above 10 kGy (Haider *et al*., 2023). High doses of ionizing radiation may induce blemishes in host tissues such as color, texture, flavor or aroma changes (Reisz *et al*., 2014; Jeong; Jeong, 2018).

One Gray (Gy), in honor of the British physicist Louis Harold Gray (1905-1965), corresponds to 100 RAD, which means radiation absorbed dose. One RAD is equivalent to 1 Joule.kg^{-1} mass or 0.239 calories.

Gamma irradiation was initially recommended for the extension of shelf life of fresh fruit, including papaya, by Ernest Akamine and James Moy in 1983 using a semi-commercial irradiator in Hawaii (Paull, 1996). Gamma rays for pathogen control is authorized for food irradiation in more than 50 countries worldwide and estimates of yearly irradiated volumes of produce exceed 500 thousand metric tons (Kumar *et al*., 2014). More recently, the interest on food irradiation technologies has been directed towards shelf life increases of fruits and vegetables (Baldık; Aytekin; Erer, 2011).

Besides the very positive effects of gamma irradiation on postharvest pathogen control and quality maintenance on several commodities in many papers there are also mentions to negative effects of the technology that shall not be overlooked (Hallman, 2011). Radiation induces the formation of reactive oxygen species exhausting tissue antioxidant capacity that might lead to an oxidative stress triggering biochemical and morphological changes (Moller *et al*., 2013).

X-rays were discovered by the German physicist and mechanical engineer Wilhelm Conrad Roentgen (1845-1923). X-rays, also called Roentgen rays, are an ionizing radiation located between gamma rays and the ultraviolet portion of the electromagnetic spectrum (Fig. 1) and have wavelengths varying from 0.01 to 10 nanometers (nm). X-rays were discovered in investigations of fluorescence produced in vacuum tubes. As their nature, at that time was rather unknown, Roentgen named them as X-rays (Tubiana, 1996).

X-rays present a much higher penetration power in comparison to high-energy electrons from radioactive isotopes and, therefore, large size commodities or pallet loads can be more easily treated (Hallman, 1999). Irradiation treatments are well known as effective against pests of quarantine importance but some detrimental effects on visual quality have been reported in some products (Alonso *et al*., 2007). According to the authors, the quality of irradiated produce might be influenced by the species itself such as cultivar and physiological condition and handling and storage procedures.

Challenges for future application of irradiation in fresh produce are the cost, lack of irradiation facilities, lack of knowledge about optimal conditions for different commodities, and consumer denial of acceptance of irradiated fresh produce (Jeong; Jeong, 2018).

Ultraviolet radiation

Ultraviolet (UV) radiation was discovered, in 1801, by the German physicist Johann W. Ritter (1776-1810) while conducting experiments to investigate the existence of energy beyond the violet wavelengths of the visible spectrum presented in Fig. 1. UV radiation of the electromagnetic spectrum is in between the end of visible light at about 400 nm and the X-ray wavelengths. Based on substantial variations in biological effects, UV radiation is classified, according to Diffey (2002), into three primary types: ultraviolet A (UVA – 315-399 nm), ultraviolet B (UVB – 280-314 nm), and ultraviolet C (UVC – 100-279 nm).

Antibacterial activity of UV radiation has been known for a long time. According to Artés and Allende (2005) the use of UV to preserve foods dates back to the 1930´s. Efficacy of UV against bacteria, rests on parameters such as wavelength, radiation intensity, exposure duration and microorganism species and concentration (Sandri *et al*., 2023). UVC radiation with wavelengths varying from 100 nm to 280 nm, according to the same authors, is a potent sanitizer but also presents severe human health risks. UV effectiveness as antimicrobial treatment is almost exclusively attributable to photochemical reactions within the microorganisms.

Primarily UV radiation induces the formation of covalent bonds in between adjacent pyrimidine nucleotides forming thymine dimers blocking DNA transcriptions and replications affecting microorganism viability (MacLean *et al.*, 2008). UV–C by activating defense mechanisms is an indirect sanitizing effect. However, UV–C can change cell permeability in leafy vegetables increasing electrolyte, aminoacid and carbohydrate leakage that could favor microorganism development (Artés *et al.*, 2009). Therefore, it is essential to determine a dose to impair pathogen growth without damaging the product.

The effectiveness of UV–C seems to be independent of the temperature in the range of 5–37 °C, an advantage in comparison to conventional thermal and chemical disinfectants. The bactericidal action is more effective at room temperature and is advantageous since radiation facilities eliminate the need for large volumes of sanitizers, there is no impact on processed products and the procedures satisfy environmental safety requirements (Tiganov, 2007).

The UVC wavelengths from 250 nm to 270 nm are designated as the germicidal spectrum being 262 nm the peak germicidal wavelength. This range of UVC radiation is most lethal to microorganisms as these wavelengths are strongly absorbed by microorganism nucleic acids (Gurzadyan; Görner; Schulte-Frohlinde, 1995). Coohill and Sagripanti (2008) reported effective microbial inactivation of UV-C at 253.7 nm wavelength. Within the germicidal spectrum, 254 nm is easily produced from mercury low-pressure vapor lamps and has been shown to be close to the optimal wavelength lethal to microorganisms (Dai *et al.*, 2012). A disadvantage of UV light is the poor penetration depth and the fact that more opaque matrices limit as well penetrating potential of UV-C (Tchonkouang *et al.*, 2023).

The resolution RDC Nº. 21/2001 of the Brazilian Sanitary Vigilance Agency (Anvisa) sets the rules for food sanitation using UV light. The NR-09 (regulatory norm) of the Brazilian Ministry of Labor and Employment recommends exposure limits to non-ionizing UV based on the references of the American Conference of Governmental Industrial Hygienists (ACGIH). In fact, there are no established specific legal

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exposure values and, according to ACGIH, the threshold limit value (TLV) for workers safety at 254 nm UV-C is of 6 $mJ.cm^{-2}$.

Cold plasma

Plasma is defined as the fourth state of matter that can be created by applying electrical discharges to a gas in which electrons are removed from atoms generating highly reactive species: hydrogen peroxide (H_2O_2), nitrite (NO_2^-) or nitrate (NO_3^-) ions, superoxide anions ($.0_2^-$) and hydroxyl radicals (-OH) (Zhou *et al.*, 2020). Irving Langmuir (1881-1957), a North American physicist, first proposed the term plasma in a publication in the Proceedings of the National Academy of Science/USA in 1928 (Franklin; Braithwaite, 2009). The fundamentals of plasma science, however, were established much earlier by the British chemist and physicist William Crookes (1832-1919). Crookes, in 1879, ionized gas experimentally in an electrical discharge tube applying high voltages and the ionized gas was named as radiant matter (Braný *et al.*, 2020).

There are two types of plasma: thermal and non-thermal. Non-thermal plasma is also named cold atmospheric plasma. In thermal plasma, electrons and the heavy particles (neutrons and ions) are in equilibrium at the same range of high temperatures. The gas temperature of thermal plasma is too extreme for treating living organisms (Sakudo; Yagyu; Onodera, 2019). In contrast, in cold atmospheric plasma the electrons are at higher temperatures than the heavy particles, which are at room temperature (Hoffmann; Berganza; Zhang, 2013).

Cold atmospheric plasma efficacy is affected by a number of factors such as the target microorganisms, processing parameters and the treatment surface (Brun *et al.*, 2018). Cold plasma is also known as a surface modification technique for altering the chemical properties and morphology of treated materials oxidizing proteins, carbohydrates and fats modifying its characteristics (Wenske *et al.*, 2020). That potential effect raises concerns on possible modifications in the composition of food products with eventual impacts on food safety with the migration of trace chemicals to the treatment target (Wang; Lavoine; Salvi, 2023).

Nonetheless, the effects of cold plasma on surfaces have shown promising results in disinfection processes in the food industry where conveyor belts, equipment and other food contact surfaces require speedy sanitation methods. Niemira, Boyd and Sites (2014) observed a 2.13 log reduction of *Salmonella* on contaminated food-contact surfaces by short cold plasma treatments. Kim *et al.* (2015) indicate a 3 to 4 log $CFU.cm^{-2}$ reduction in biofilms of *Escherichia coli* O157:H7, *Salmonella typhimurium,* and *Listeria monocytogenes* present on food after a 10-minute atmospheric plasma treatment.

Plasmas have the unique ability to disrupt covalent bonds at ambient temperatures, which makes low-temperature plasma suitable technique for thermally sensitive materials (Shalaby; Nagatomi; Powell, 2013). Cold plasma generated reactive species may penetrate and rupture bacterial cells, although there is a difference in sensitivity to plasma between gram-positive, typically more resistant, and gram-negative bacteria. Cold plasma is also associated as a potential treatment of bacteria in biofilms. Yet for a complete removal more exposure time is required (Mai-Prochnow *et al.*, 2014).

There is no specific regulation for cold plasma use in the food industry. The actual standings related to food additives in the USA and the `Novel Foods Regulation` in the European Union could help out in setting a regulatory route to establish a normative for cold plasma use (Anu; Xavier; Prakash, 2025).

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Dense phase carbon dioxide

The term dense phase refers to the fact that supercritical carbon dioxide (CO_2) in a fluid state presents higher density than gaseous CO_2. Therefore, its use in food systems is known as dense phase carbon dioxide (DPCD). Moreover, the other widespread term used is 'cold pasteurization'. A technology with negligible or no changes in nutritional, physical and sensory properties of the treated product unlike conventionally thermal pasteurization methods (Arbal *et al.*, 2024). DPCD is a non-thermal sanitizing method developed for heat sensitive foods to preserve quality and nutrients alongside with inactivation of microorganisms and enzymes in liquid foods, juices and beverages (Damar; Balaban, 2006).

Antimicrobial effects of DPCD on microorganisms were first referenced by D. Fraser in a publication in Nature in 1951 (Liao *et al.*, 2009). For more than 100 years, CO_2 is known for its inhibitory effects on microorganism development (Garcia-Gonzalez *et al.*, 2007).

DPCD is highly compressed fluid with physical properties of both liquids and gases: density similar to liquids and diffusivity capability like gases (Garcia-Gonzalez *et al.*, 2007). According to the authors, these physical properties allow penetration into more complex tissue structures enabling internalized pathogen control. However, DPCD bacterial inactivation is not completely understood, yet bacterial cell wall destabilization and pH decreases altering intracellular balance have been identified as the main inactivation phenomena (Balaban; Duong, 2014).

Microbial inactivation by DPCD is dependent on different parameters: exposure time, pressure, temperature, pressure cycling, initial pH of the medium, water activity, cell growth phase or age, species of microorganisms, food matrices and type of treatment system (Arreola *et al.*, 1991). The application at mild temperatures of DPCD, in the range of 30 °C to 50 °C, is an advantage to retain quality attributes and nutraceutical components. Pressures of less than 50 MPa (mega Pascal) are about one tenth of the pressures applied in high hydrostatic pressure systems.

The various bacteria species respond differently to pressurized CO_2. Aerobic psychrophilic microorganisms (*Pseudomonas* spp., for example) are more sensitive than aerobic mesophilic bacteria (*Escherichia coli*, for example). Furthermore, *Listeria monocytogenes* is more sensitive that *E. coli* (Yu; Niu; Iwahashi, 2020).

Balaban and Duong (2014) report some barriers to treat solid products with DPCD. The diffusion of CO_2 into the mass of more solid samples is slower rendering concerns of possible cellular damages resulting in texture and quality changes. Another dissuading point for the application of the dense phase technology is that reduced presence of free water at the surface limits the solubility of CO_2 and further tissue penetration. DPCD interacts with moisture to form carbonic acid that dissociates to form bicarbonate ions by liberating H^+ ions rising acidity and decreasing pH (Khan *et al.*, 2017).

DPCD use has some disadvantages. A main issue is a higher initial capital expenditure compared to other technologies such as thermal pasteurization. For that reason, a high throughput commercial equipment is not available (Balaban; Duong, 2014) contrasting with the inexpensiveness of CO_2 in industrial quantities. Additionally, CO_2 is recognized as GRAS compound (generally recognized as safe) non-flammable and non-toxic compound (Arbal *et al.*, 2024).

Alike cold plasma there is no single national or international regulation ordained for DPCD and the same is true for high hydrostatic pressure treatments.

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High hydrostatic pressure

Prof. Percy W. Bridgman (1882 - 1961), a North American physicist, was first to study the effects of high pressure technology in the beginnings of the 1900's on microbial contamination of fruits and vegetables (Yamamoto, 2017). Though, application of high-pressure technology experienced an exponential growth with improved microbiological quality of treated foodstuff only since the beginnings of the 2000's (Bermúdez-Aguirre; Barbosa-Cánovas, 2011).

High hydrostatic pressure technology is categorized as a non-thermal process in which pressures of 100 MPa or higher are applied to food products at room temperatures. However, high hydrostatic pressure results in some heating by adiabatic compression and, thereafter, cooling occurs via adiabatic decompression (Yamamoto, 2017). High hydrostatic pressure, also named cold pasteurization, high pressure processing (HPP) or ultra high pressure (UHP) requires less energy usage entailing less environmental impacts when compared to thermal treatments (Huang *et al.*, 2017b).

The products to be sanitized need to be hermetically sealed in flexible containers while pressure is applied equally in all directions of the products using water or another liquid as pressure transfer medium in a high-pressure vessel (Aganovic *et al.*, 2021). Packaging, in addition, assist in preventing cross contamination as the treated product is not in contact with processing devices (Balasubramaniam; Martínez-Monteagudo; Gupta, 2015).

In the literature, there are many references on the effectiveness of high hydrostatic pressure treatments in the control of pathogenic bacteria (*Listeria monocytogenes*, *Escherichia coli*, *Salmonella* spp and *Vibrio* spp), yeasts, molds and other deteriorative microorganisms (Balasubramaniam; Martínez-Monteagudo; Gupta, 2015). High pressure affects the structural arrangement of proteins, enzymes for example, cellular transport phenomena, membrane selectivity and other non-covalent interactions damaging cellular functionality and crucial metabolic routes deterring microorganism survival (Wang *et al.*, 2016).

High power ultrasound

Ultrasonic technology can be an effective method in the process of replacing traditional sanitation treatments applying intense sound waves with frequencies ranging from 20 kHz to 100 kHz (kilo Hertz) that may cause cavitation generating locally high temperatures and pressures with effects on the contaminant microorganisms (Kobus *et al.*, 2023). Ultrasound as additional to thermal processing for bacterial inactivation was first introduced by Juan A. Ordonez and his coworkers in 1987 (Zenker; Heinz; Knorr, 2003).

Based on the intensity and frequency ultrasound waves may be categorized in low and high-intensity ultrasound. Intensities below 1 $W.cm^{-2}$ and frequencies beyond 100 kHz are mostly used for conformational evaluations of shape, size or dimensions (Arvanitoyannis; Kotsanopoulos; Savva, 2017). High intensity and low-frequency ultrasound is characterized by the induction of acoustic cavitation and, as such, is more disruptive ending up in physical, biochemical and mechanical changes on food products and sudden collapse of contaminants as result of liberation of high amounts of energy (Bhargava *et al.*, 2021). Ultrasound involves generation of acoustic longitudinal waves whose frequencies are higher than the threshold of human auditory detection, which is about 20 kHz (Wereski, 2015).

Ultrasound technology is often combined with other decontaminating procedures for sanitization purposes of produce because the

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antimicrobial efficiency of ultrasound is low under some conditions (Bilek; Turantaş, 2013). Huang *et al.* (2017a) reviewed the biological effects of ultrasound on microbial growth and enzyme activity on food products. The authors concluded that in most reports the results are encouraging towards the use of ultrasound technology, though, they do, as well, indicate that the precise mechanisms of the observed effects remain to be elucidated as the numerous species of food contaminants differ widely in susceptibility to ultrasound waves.

Chemat, Huma and Khan (2011) indicate that ultrasound treatments despite beneficial effects such as preservation of sensory characteristics of processed fruit and vegetables might, as well, result in faster degradation of primary and secondary metabolites. Ultrasound effects on enzyme inactivation and chemical outcomes are dependent on the type of enzyme, its amino acid composition and conformational structure (Kadkhodaee; Povey, 2008).

Tahi *et al.* (2021) observed positive control effects on *Staphylococcus aureus* in orange juice with the combination of ultrasound and heat treatments. Scanning Electron Microscopic images demonstrated bacteria membrane damages, collapsed and disrupted cells after exposure to sonication. Ultrasound might be applied with temperature that is then called thermosonication or with pressure called manosonication resulting in a synergistic effect enhancing efficacy of the ultrasound technology (Condón-Abanto *et al.*, 2016).

The application of high power ultrasound has to follow the general regulations expressed in the RDC´s Nº. 275 of 2002 and RDC Nº. 216 of 2004. The resolutions imply that the technology does not pose risks to food security and quality. At the international as well as at the national level there is no specific regulation governing high power ultrasound for fresh produce sanitation.

Non-conventional atmospheres

Modified atmospheres have been widely used to prolong shelf life of a diversity of fruits and vegetables. The procedure relies on the increases in the CO_2 and decreases of oxygen (O_2) concentrations with a positive effect in phasing down metabolic activity. Non-conventional atmospheres is a technology in which original partial atmosphere pressures are replaced with noble gases: helium (He), argon (Ar) or xenon (Xe), nitrous oxide (N_2O) or superatmospheric oxygen (Artés *et al.*, 2009).

Microorganism growth inhibition by compressed noble gases was demonstrated by Claude Bernard at about the beginning of 1900´s (Thom; Marquis, 1984).

Noble gases exert an effect on the metabolic activity of various vegetable products through different and some unknown mechanisms. Generally, it is accepted that noble gases act distorting the hydrophobic nature of cell membranes as they are, as well, very hydrophobic. Another possible mechanism of action are alterations of hydrophobic interactions between proteins (Thom; Marquis, 1984).

Argon reduces microbial growth and improves the quality retention of fresh produce because it interferes with oxygen receptor sites. Argon does not directly affect the metabolism of plant tissues by reducing the activity of enzymes, but rather, it enhances the diffusion of gases such as CO_2 and ethylene (C_2H_4) from plant tissues because it is denser than N_2 (Gorny; Agar, 1998).

Increases in He concentrations in modified atmosphere packaging could enhance O_2 diffusion through tissues, which, at the end, may assist in a reduction of the oxygen gradient in between the inside and outside of cells. A procedure to minimize the risk of fermentation due to low O_2 concentration (Silveira *et al.*, 2014). Noble gases are not widely used even after attested as potent microbial growth inhibitors mainly

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because of cost. He, N_2 and Ar at high pressures inhibit growth, but it is also necessary to distinguish the effect of the gases themselves from the effects of hydrostatic pressures as some microorganisms are sensitive to hydrostatic pressure (Thom; Marquis, 1984).

Superatmospheric O_2 at concentrations above 21 kPa around and inside a commodity influences aerobic and anaerobic microbial growth and may result in higher levels of free radicals with eventual damages to plant tissues (Kader; Ben-Yehoshua, 2000). A warning, according to the authors, is that superatmospheric O_2 concentrations may accelerate combustion of materials and, therefore, machinery design and gas-flushing systems to avoid ignition sources at super atmospheric O_2 concentrations are indispensable.

Elevated O_2 concentrations in the range of 80 to 90 kPa caused some growth reductions of *Salmonella enteritidis* and *S. typhimurum* associated with vegetables and fruits (Amanatidou; Smid; Gorris, 1999). When the authors combined 10 kPa or 20 kPa CO_2 with those hyperbaric O_2 concentrations on all of some ten evaluated microorganisms a significant growth reduction was determined.

Another gas that has attracted research interest is nitrous oxide (N_2O), which is widely used in medicine and has a chemical structure similar to that of CO_2, providing advantageous physical properties, such as high solubility (Gouble; Fath; Soudain, 1995). N_2O partially inhibits respiration by affecting cytochrome oxidase C activity in the mitochondria, a phenomenon observed in isolated seeds, leaves or cell suspensions decreasing metabolism of the product and increasing storage life (Sowa; Towill, 1991).

Trials conducted by Thom and Marquis (1984) concluded that N_2O at a pressure of 2.72 MPa almost completely inhibited growth of *Escherichia coli*, *Saccharomyces cerevisiae* (a yeast species used in alcoholic fermentations) and *Tetrahymena thermophila* (free living protozoon that occurs in fresh water and is largely used in biological studies).

Ozone

The German chemist Christian Friedrich Schönbein (1799 – 1868) in 1839 discovered the presence of a pronounced smell in his laboratory when working electrolysis of water. He then named that gas: ozone (Carletti *et al.*, 2013). Ozone was applied as early as 1893 in Europe for drinking water disinfection (Gray, 2014). Experimental plants had been established the year before (Kinman; Rempel, 1975). Ozone is the triatomic molecule of oxygen, with an estimated average half-life of roughly 20 to 30 min in distilled water (Khadre; Yousef; Kim, 2001). Half-life of ozone has been reported by McClurkin, Maier and Ileleji (2013), however, dependent on temperature, humidity and air flow. A higher sanitation capability of ozone is affected by temperature. With higher temperatures, ozone becomes less soluble and less stable increasing its decomposition rates (Sarron; Gadonna-Widehem; Aussenac, 2021).

Ozone is a highly unstable gas with excellent germicidal effects because of its strong oxidative strength. Ozone reacts with other molecules by adding an atom of oxygen to molecular structures and altering, for example, double bonds of unsaturated lipids and breaking apart large molecules (Brodowska; Nowak; Śmigielski, 2018; Shezi *et al.*, 2020). Ozone is a potent sanitizer for a wide array of food contaminants and its use expanded considerably in the food industry after being recognized as safe (GRAS) in the United States in 1997 (Botondi *et al.*, 2015).

Ozone treatments may be applied to produce in the form of gas or in water containing dissolved ozone. Because of its instability, ozone has to be generated on-site, which is a drawback (Sarron; Gadonna-Widehem;

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Aussenac, 2021). Ozone has the second-highest oxidation potential, lower only than fluorine and higher than chlorine. Ozone decomposes rapidly to oxygen leaving no residues in food neither altering internal quality and appearance (Brodowska; Nowak; Śmigielski, 2018). Ozone oxidizes the bacterial cell components such as proteins, unsaturated lipids, and respiratory enzymes. Shezi and collaborators (2020) extensively reviewed the changes in the biochemistry of fresh produce after ozone treatment. The authors report that microbial inactivation is mainly due to changes in double bonds of unsaturated membrane lipids. The authors did also state that the type of product, ripeness stage, exposure time and if in the form of gas or water-dissolved ozone might affect treatment effectiveness. Gaseous ozone is more effective than ozone in liquid systems because gaseous ozone is pure, highly reactive, and has a longer half-life. Aqueous ozone might be influenced by the quality of the water used to generate ozonized water since the presence of impurities such as organic and inorganic elements could affect its effectiveness (Fijołek; Świetlik; Frankowski, 2024).

Lone *et al.* (2019) reported a 6 log CFU mL^{-1} bacterial reduction in kiwi after ozone treatment at 19.8 mg mL^{-1} and a 60 min exposure. Another study has shown an *E. coli* O157:H7 reduction at 3.5 log CFU g^{-1} in blueberries by applying 1.5 mg L^{-1} ozone for 5 min (Pangloli; Hung, 2013).

Continuous exposure to ozone in indoor environments is recognized as leading to health effects, mainly respiratory illnesses. All the medical evidences indicate that short-term exposures to ozone may lead to respiratory effects based on a comprehensive evaluation performed by the Environmental Protection Agency (EPA) of the USA (Grignani *et al.*, 2021). The Brazilian legislation indicates that safe limits for ozone at workstations have to be in accordance to the NR Nº. 15-Annex 11. That normative indicates a maximum ambient concentration of 0.08 ppm or 0.16 g m^{-3} for a workshift of 48 hours a week. As of 2005, the California Air Resources Board established an eight-hour standard of 0.07 ppm for ozone. In most European countries, occupational exposure limit values for eight-hour workshifts have been set at 0.1 ppm or 0.2 mg m^{-3} (Grignani *et al.*, 2021).

Pulsed electric field

Pulsed electric field (PEF) is a technology in its early development stages for produce sanitation. Even though as early as 1879, Cohn and Mendelsohn reported microorganism inactivation by channeling a DC-current (direct current in which the flow of electric charge is in a single direction, which differs from alternating current) through a nutrient solution that could be considered as the initial stages of the development of that sanitation procedure (Morren; Roodenburg; De Haan, 2003). PEF involves the application of pulses within an electric field intensity range of 0.1–100 kV cm^{-1} in an insulated chamber containing the targeted food in between electrodes: one on high voltage and the other on ground potential. The generation of the electric field depends on the electrode type, the distance amongst them, the configuration of the treatment chamber and the conductivity of the product (Puértolas; Koubaa; Barba, 2016). The generated electric field charges membrane components forming pores or expanding the existing pores in cell membranes, a phenomenon called electroporation (Brito; Silva, 2024).

Electroporation was initially designed as a gene transfer technique by applying high-voltage pulses to cells in the range of nano- to microseconds of defined magnitude and intervals in an electroporation buffer (Young; Dean, 2015). PEF results in micropores in cell membranes increasing its permeability via disruption of

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the physical structure triggered by an increase in the cellular transmembrane potential from 0.07 V and 0.2 V up to 0.5 V (Campelo *et al.*, 2023). The damages and morphology changes of cell membranes leading to ion leakage, losses of cytoplasmic content were suggested as causes of microbial inactivation (Kinosita Junior; Tsong, 1997).

Different microorganisms react distinctively to PEF. The membrane constituents and arrangements are an appointed reason for that variety of responses. Overall, gram-positive organisms seem to be less sensitive (Toepfl; Heinz; Knorr, 2005). According to the authors, it is also striking that resistance to PEF does not correlate well to other sanitizing treatments: either heat or non-heat. The genus *Listeria*, for example, highly sensitive to heat is, on contrary, highly resistant to PEF treatments.

That variability in microorganism response emphasizes the fact that there is a need to identify the resistant microorganisms and, additionally, specific strains to evaluate and prove PEF efficacy. Besides, the PEF technology holds some limitations: the high initial investment and, according to Capodaglio (2021), only a few literature sources allude to commercial PEF units built for the food industry.

Pulsed light

Pulsed light (PL), as a sterilization solution, was patented by Hiramoto in Japan in 1984 (Chen *et al.*, 2015). Pulsed light are high energy ultrashort pulses of light in the range of picoseconds to femtoseconds (Santamera *et al.*, 2020). PL comprises the visible light spectrum and portions of UV and near infrared light spectra (Barbosa-Canovas *et al.*, 2000). The light flashes reach the surface of a food product with an energy density of 0.01 to 50 $J.cm^{-2}$ and the sanitation achieved by pulsed light is generally credited to DNA damages triggered by UV irradiation. Pulsed light technologies are also designated by terms such as pulsed ultraviolet light, intense light pulse, high intensity broad spectrum pulsed light, high-intensity pulsed UV light or pulsed white light (Krishnamurthy *et al.*, 2010)

Pulsed light sanitation is regarded as more advantageous in comparison to other non-heat processes as it is possible to succeed in fast and effective inactivation of microorganisms on produce surfaces, equipment and packaging materials (Salehi, 2022). PL lamps produce broad light spectrum at wavelengths ranging from ultraviolet (UV) to near infrared (NIR, 100 nm to 1000 nm). The light used for food processing applications typically pulsed at 1–20 flashes per second and an energy density in the range of 0.01–50 $J.cm^{-2}$ at the surface (Condón; Álvarez; Gayán, 2014). Remembering that one $Joule.cm^{-2}$ is equivalent to 0.239 calories.

Microorganisms were demonstrated by Levy *et al.* (2012) to have variable susceptibility to pulsed light flashes: bacterial and fungal spores and gram-negative bacteria are the most susceptible to PL. Gram-positive bacteria are more resistant. Esbelin *et al.* (2013) report also that the surface color may have a significant effect on the susceptibility of the microorganism. According to the authors, that effect is attributable to the presence of dark pigments (melanins) in cell wall layers absorbing more light in UV-C region of the light spectrum rendering the organism more resistant to light pulses in comparison to less pigmented strains.

The FDA (Food and Drug Administration of the USA) certified the PL to apply as decontaminant in the food industry (Waghmare *et al.*, 2024). The Brazilian legislation only indicates that sanitation procedures using PL has to follow good manufacturing practices (GMP) as described in the RDC Nº. 216/2004 to prove its efficacy as sanitizer.

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Pulsed magnetic field

Toepfl, Heinz and Knorr (2005) indicate that pulsed electric field technology was developed by the German engineer Karl-Heinz Doevenspeck (1939 – 2019). In 1960, he patented the technology in which PEF could be used for cell disruption in foodstuffs. The main target at that time were meat products and in 1961 an industrial plant was built with a capacity to process 2,500 $kg.h^{-1}$ of meat. Later on, liquid foods did benefit from the PEF technology

Pulsed magnetic fields generate impulses of a duration in between 10 microseconds and several milliseconds. The frequencies are at maximum of 500 MHz and at that level, temperature rises are usually of less than 5 ºC, consequently preserving heat sensitive nutrients in the food matrix. However, above that 500 MHz frequency limit, food matrices may warm up significantly (Guo *et al.*, 2022).

Application of a constant magnetic field over a period to a food matrix is described as a static magnetic field (SMF). When the magnetic field is applied to the food matrix in the form of pulses, it is described as a pulsed magnetic field (PMF). The two major process parameters of PMF are the magnetic field intensity and the pulse number (Basak, 2023). Butz and Tauscher (2002) indicate that SMF of 5 up 50 Tesla has the potential to inactivate vegetative micro-organisms. Tesla, in honor to the Austrian physicist Nikola Tesla (1856 – 1943) is the SI (International System of Units) unit to measure magnetic fields. For comparison, the Earth´s magnetic field at surface is of 3.1×10^{-5} up to 5.8^{-5} T.

PMF is an emerging technology for the food industry with advantages in microorganism inactivation by magnetoporation and electromagnetic effects. Magnetoporation, an increase in cell membrane permeability, induced by PMF leads to a loss of cytosol and nucleic acid content. Another effect of PMF is the possibility of increases in intracellular calcium (Ca^{2+}) content that could lead to microorganism collapse (Basak, 2023). According to the author, enzyme inactivation is attributable to the loss of tertiary structure. Moreover, enzymes and other macromolecules are charged components in cells and under exposure to magnetic fields become distorted with atypical movements altering activity and the normal physiological activities of the cell (Guo *et al.*, 2022).

PMF has some advantages over other non-thermal technologies. Static or pulsed magnetic fields present a deeper penetration capability into food matrices and there is no contact of the electrodes with the treated product. Another great advantage is the low energy consumption in the range of 50 to 100 W and its almost instantaneous sterilization (Guo *et al.*, 2022). The authors do, however, describe some disadvantages of the magnetic pulses: discharge voltages are high which could lead to concerns in terms of workers safety performance of the technology.

Conclusion

Vegetables and fruits are blamed worldwide as a major cause of foodborne illnesses as a result of negligent hygiene and, occasionally, excessive manipulation. Therefore, it is important that, from farm to fork, good agricultural practices, good handling practices and, at consumer level, hygienic manipulation are implemented to reduce food transmitted diseases. In the present review, all the available non-heat sanitizing procedures are described to hand to either small or big possible users. A compilation to assist in the selection of the most appropriate handling procedure for practical implementation. The reference list is extensive and, as such, is an additional source to search for more information on any of the described sanitizers.

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Conflict of Interest

The author declares that the research was conducted in the absence of any potential conflicts of interest.

Ethical Statements

The author confirms that the ethical guidelines adopted by the journal were followed by this work, and agrees with the submission, content and transfer of the publication rights of the article to the journal. The author also declares that the work has not been previously published nor is it being considered for publication in another journal.

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References

AGANOVIC, K. *et al*. Aspects of high hydrostatic pressure food processing: Perspectives on technology and food safety. **Comprehensive Reviews in Food Science and Food Safety**, v. 20, n. 4, p. 3225-3266, 2021. https://doi.org/10.1111/1541-4337.12763.

ALONSO, M., *et al*. Effect of X-ray irradiation on fruit quality of clementine mandarin cv. 'Clemenules'. **Radiation Physics and Chemistry**, v. 76, n. 10, p. 1631-1635, 2007. https://doi.org/10.1016/j.radphyschem.2006.11.015.

AMANATIDOU, A.; SMID, E. J.; GORRIS, L. G. M. Effect of elevated oxygen and carbon dioxide on the surface growth of vegetable-associated micro-organisms. **Journal of Applied Microbiology**, v. 86, n. 3, p. 429-438, 1999. https://doi.org/10.1046/j.1365-2672.1999.00682.x.

ANU, C., XAVIER, J. R.; PRAKASH, C. O. Use of Cold Plasma for Phytosanitation and Decontamination of Food Products: A Review. **Future Postharvest and Food**, v. 2, n. 4, p. 390-410, 2025. https://doi.org/10.1002/fpf2.70017.

ARBAL, A. *et al.* Dense phase carbon dioxide (DPCD) inactivation of microorganisms and enzymes, and its application in food: A review. **Food Chemistry Advances**, v. 5, p. 100782, 2024. https://doi.org/10.1016/j.focha.2024.100782.

ARREOLA, A. G. *et al.* Effect of supercritical carbon dioxide on microbial populations in single strength orange juice. **Journal of Food Quality**, v. 14, p. 275-284, 1991.https://doi.org/10.1111/j.1745-4557.1991.tb00068.x.

ARTÉS, F.; ALLENDE, A. Processing Lines and Alternative Preservation Techniques to Prolong the Shelf-life of Minimally Fresh Processed Leafy Vegetables. **European Journal of Horticultural Science**, v. 70, n. 5, p. 231-245, 2005. https://doi.org/10.1079/ejhs.2005/34006.

ARTÉS, F. *et al.* Sustainable sanitation techniques for keeping quality and safety of fresh-cut plant

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Received: 16 Jun, 2025. Accepted: 02 Dec., 2025.

commodities. **Postharvest Biology and Technology**, v. 51, n. 3, p. 287-296, 2009. https://doi.org/10.1016/j.postharvbio.2008.10.003.

ARVANITOYANNIS, I. S.; KOTSANOPOULOS, K. V.; SAVVA, A. G. Use of ultrasounds in the food industry–methods and effects on quality, safety, and organoleptic characteristics of foods: a review. **Critical Reviews in Food Science and Nutrition**, v. 57, n. 1, p. 109-128, 2017. https://doi.org/10.1080/10408398.2013.860514.

ASHRAF, S. *et al*. Food irradiation: A review. **International Journal of Chemical Studies**, v. 7, n. 2, p. 131-136, 2019. Available from: https://www.chemijournal.com/archives/?year=2019&vol=7&issue=2&ArticleId=5139. Accessed: May 27, 2025.

BALABAN, M. O.; DUONG, T. Dense Phase Carbon Dioxide Research: Current Focus and Directions. **Agriculture and Agricultural Science Procedia**, v. 2, p. 2-9, 2014. https://doi.org/10.1016/j.aaspro.2014.11.002.

BALASUBRAMANIAM, V. M.; MARTÍNEZ-MONTEAGUDO, S. I.; GUPTA, R. Principles and Application of High Pressure–Based Technologies in the Food Industry. **Annual Review of Food Science and Technology**, v. 6, p. 435-462, 2015. https://doi.org/10.1146/annurev-food-022814-015539.

BALDIK, R.; AYTEKIN, H.; ERER, M. Radioactivity measurements and radiation dose assessments due to natural radiation in Karabük (Turkey). **Journal Radioanalytical and Nuclear Chemistry**, v. 289, p. 297-302, 2011. https://doi.org/10.1007/s10967-011-1077-z.

BARBOSA-CANOVAS, G. V. *et al*. Pulsed Light Technology. **Journal of Food Science**, v. 65, n. s8, p. 82-85, 2000. https://doi.org/10.1111/j.1750-3841.2000.tb00621.x.

BASAK, S. The potential of pulsed magnetic field to achieve microbial inactivation and enzymatic stability in foods: a concise critical review. **Future Foods**, v. 7, 100230, 2023. https://doi.org/10.1016/j.fufo.2023.100230.

BATZ, M. B.; HOFFMANN, S.; MORRIS JUNIOR, J. G. Ranking the Disease Burden of 14 Pathogens in Food Sources in the United States Using Attribution Data from Outbreak Investigations and Expert Elicitation. **Journal of Food Protection**, v. 75, n. 7, p. 1278-1291, 2012. https://doi.org/10.4315/0362-028X.JFP-11-418.

BERMÚDEZ-AGUIRRE, D.; BARBOSA-CÁNOVAS, G. V. An Update on High Hydrostatic Pressure, from the Laboratory to Industrial Applications. **Food Engineering Reviews**, v. 3, p. 44-61, 2011. https://doi.org/10.1007/s12393-010-9030-4.

BHARGAVA, N. *et al*. Advances in application of ultrasound in food processing: A review. **Ultrasonics Sonochemistry**, v. 70, p. 105293, 2021. https://doi.org/10.1016/j.ultsonch.2020.105293.

BILEK, S. E.; TURANTAŞ, F. Decontamination efficiency of high power ultrasound in the fruit and vegetable industry, a review. **International Jou/rnal of Food Microbiology**, v. 166, n. 1, p. 155-162, 2013. https://doi.org/10.1016/j.ijfoodmicro.2013.06.028.

BOTONDI, R. *et al.* Ozone fumigation for safety and quality of wine grapes in postharvest dehydration. **Food Chemistry**, v. 188, n. 1, p. 641-647, 2015. http://dx.doi.org/10.1016/j.foodchem.2015.05.029.

BRANÝ, D. *et al*. Cold Atmospheric Plasma: A Powerful Tool for Modern Medicine. **International Journal Molecular Sciences**, v. 21, n. 8, p. 2932, 2020. https://doi.org/doi.org/10.3390/ijms21082932.

BRITO, I. P. C.; SILVA, E. K. Pulsed electric field technology in vegetable and fruit juice processing: A review. **Food Research International,** v. 184, p. 114207, 2024. https://doi.org/10.1016/j.foodres.2024.114207.

BRODOWSKA, A. J.; NOWAK, A.; ŚMIGIELSKI, K. Ozone in the Food Industry: Principles of Ozone Treatment, Mechanisms of Action, and Applications: An Overview. **Critical Reviews in Food Science and Nutrition**, v. 58, n. 13, p. 2176-2201, 2018. https://doi.org/10.1080/10408398.2017.1308313.

BRUN, P. *et al.* Antibacterial efficacy and mechanisms of action of low power atmospheric pressure cold plasma: Membrane permeability, biofilm penetration and antimicrobial sensitization. **Journal of Applied Microbiology**, v. 125**,** n. 2, p. 398-408, 2018. https://doi.org/10.1111/jam.13780.

BUTZ, P.; TAUSCHER, B. Emerging technologies: chemical aspects. **Food Research International**, v. 35, n. 2-3, p. 279-284, 2002. https://doi.org/10.1016/S0963-9969(01)00197-1.

CAMPELO, S. N. *et al.* Annual Review of Biomedical Engineering Recent Advancements in Electroporation Technologies: From Bench to Clinic. **Annual Review of Biomedical Engineering**, v. 25, p. 77-100, 2023. https://doi.org/10.1146/annurev-bioeng-110220-023800.

CAPODAGLIO, A. G. Pulse Electric Field Technology for Wastewater and Biomass Residues Improved Valorization. **Processes**, v. 9, n. 5, p. 736, 2021. https://doi.org/10.3390/pr9050736.

CARLETTI, L. *et al*. Use of ozone in sanitation and storage of fresh fruits and vegetables. **Journal of Food, Agriculture & Environment,** v. 11, n. 3&4, p. 585-589, 2013. Available from: https://www.wflpublisher.com/Abstract/4710. Accessed: May 26, 2025.

CASTRO-IBÁÑEZ, I.; GIL, M. I.; ALLENDE, A. Ready-to-eat vegetables: Current problems and potential solutions to reduce microbial risk in the production chain. **LWT – Food Science and Technology**, v. 85, part B, p. 284-292, 2017. https://doi.org/10.1016/j.lwt.2016.11.073.

CHEMAT, F.; HUMA, Z. E.; KHAN, M. K. Applications of ultrasound in food technology: Processing, preservation and extraction. **Ultrasonics Sonochemistry**, v. 18, n. 4 p. 813-835, 2011. https://doi.org/10.1016/j.ultsonch.2010.11.023.

CHEN, B.-Y. *et al*. Pulsed light sterilization of packaging materials. **Food Packaging and Shelf Life,** v. 5, n. 1-9, 2015. https://doi.org/10.1016/j.fpsl.2015.04.002.

CONDÓN, S.; ÁLVAREZ, I.; GAYÁN, E. Non-thermal processing | Pulsed UV light. *In*: BATT, C. A.; TORTORELLO, M. L. (ed.). **Encyclopedia of Food Microbiology**. 2. Ed. Cambridge: Academic Press, 2014.

P. 974-981. https://doi.org/10.1016/B978-0-12-384730-0.00398-0.

CONDÓN-ABANTO, S. *et al*. Application of ultrasound in combination with heat and pressure for the inactivation of spore forming bacteria isolated from edible crab (*Cancer pagurus*). **International Journal of Food Microbiology**, v. 223, p. 9-16, 2016. https://doi.org/10.1016/j.ijfoodmicro.2016.02.001.

COOHILL, T. P.; SAGRIPANTI, J.-L. Overview of the Inactivation by 254 nm Ultraviolet Radiation of Bacteria with Particular Relevance to Biodefense. **Photochemistry and Photobiology**, v. 84, n. 5, p. 1084-1090, 2008. https://doi.org/10.1111/j.1751-1097.2008.00387.x.

DAI, T. *et al.* Ultraviolet C irradiation: an alternative antimicrobial approach to localized infections? **Expert Review of Anti-Infective Therapy**, v. 10, n. 2, p. 185-195, 2012. https://doi.org/10.1586/eri.11.166.

DAMAR, S.; BALABAN, M. O. Review of Dense Phase CO2 Technology: Microbial and Enzyme Inactivation, and Effects on Food Quality. **Journal of Food Science**, v. 71, n. 1, R1-R11, 2006. https://doi.org/10.1111/j.1365-2621.2006.tb12397.x.

DIFFEY, B. L. Sources and measurement of ultraviolet radiation. **Methods**, v. 28, n. 1, p. 4-13, 2002. https://doi.org/10.1016/S1046-2023(02)00204-9.

ESBELIN, J. *et al.* Role of Pigmentation in Protecting *Aspergillus niger* Conidiospores Against Pulsed Light Radiation. **Photochemistry and Photobiology**, v. 89, n. 3, p. 758-761, 2013. https://doi.org/10.1111/php.12037.

EFSA; ECDC. The European Union One Health 2021 Zoonoses Report. **EFSA Journal**, v. 20, n. 12, p. e07666, 2022. https://doi.org/10.2903/j.efsa.2022.7666.

FIJOŁEK, L.; ŚWIETLIK, J.; FRANKOWSKI, M. Ozonation and catalytic ozonation – Sources of error. What do we need to know? **Journal of Environmental Management**, v. 370, p. 123031, 2024. https://doi.org/10.1016/j.jenvman.2024.123031.

FRANKLIN, R. N.; BRAITHWAITE, N. S. J. 80 Years of Plasma. **Plasma Sources Science and Technology**, v. 18, n. 1, p. 010201, 2009. https://doi.org/10.1088/0963-0252/18/1/010201.

GARCIA-GONZALEZ, L. *et al.* High-pressure carbon dioxide inactivation of microorganisms in foods: The past, the present and the future. **International Journal of Food Microbiology**, v. 117, n. 1, p. 1-28, 2007. https://doi.org/10.1016/j.ijfoodmicro.2007.02.018.

GORNY, J. R.; AGAR, I. T. Are Argon-enriched Atmospheres Beneficial? **Perishables Handling Quarterly**, n. 94, p. 7-8, 1998. Available from: https://web.archive.org/web/20240603062918/http://ucanr.edu/datastoreFiles/234-197.pdf Accessed: June. 02, 2025

GINDRI, A. L.; LAPORTA, L. V.; SANTOS, M. R. Microbiological 18ontrolo f medicinal drugs commercialized in the central region of Rio Grande do Sul, Brazil. **Revista Brasileira de Plantas Medicinais**, Botucatu, v. 14, n. 3, p. 563-570, 2012. https://doi.org/10.1590/S1516-05722012000300020.

GOUBLE, B.; FATH, D.; SOUDAIN, P. Nitrous oxide inhibition of ethylene production in ripening and senescing climacteric fruits. **Postharvest Biology and Technology**, v. 5, n. 4, p. 311-321, 1995. https://doi.org/10.1016/0925-5214(94)00030-V.

GRAY, N. F. Ozone Disinfection. *In*: PERCIVAL, S. L. *et al*. (ed.). **Microbiology of Waterborne Diseases**. Cambridge: Academic Press, 2014. ch. 33, p. 599-615. https://doi.org/10.1016/B978-0-12-415846-7.00033-0.

GRIGNANI, E. *et al.* Safe and effective use of ozone as air and surface disinfectant in the conjuncture of Covid-19. **Gases**, v. 1, n. 1, p. 19-32, 2021. https://doi.org/10.3390/gases1010002.

GUO, L. *et al*. Germicidal efficacy of the pulsed magnetic field against pathogens and spoilage microorganisms in food processing: An overview. **Food Control**, v. 136, p. 108496, 2022. https://doi.org/10.1016/j.foodcont.2021.108496.
https://www.sciencedirect.com/science/article/abs/pii/S0956713521006344?via%3Dihub. Accessed: May 27, 2025.

GURZADYAN, G. G.; GÖRNER, H.; SCHULTE-FROHLINDE, D. Ultraviolet (193, 216 and 254 nm) photoinactivation of *Escherichia coli* strains with different repair deficiencies. **Radiation Research**, v. 141, n. 3, p. 244-251, 1995. https://doi.org/10.2307/3579001.

HAIDER, S. T.-A. *et al*. Postharvest application of gamma irradiation affects fruit quality and antioxidant enzymes activities of 'kinnow' mandarin fruits during cold storage. **Food Science and Technology**, Campinas, v. 43, p. e113122, 2023. https://doi.org/10.1590/fst.113122.

HALLMAN, G. J. Ionizing radiation quarantine treatments against tephritid fruit flies. **Postharvest Biology and Technology**, v. 16, n. 2, p. 93-106, 1999. https://doi.org/10.1016/S0925-5214(99)00012-5.

HALLMAN, G. J. Phytosanitary applications of irradiation. **Comprehensive Reviews in Food Science and Food Safety**, v. 10, n. 2, p. 143-151, 2011. https://doi.org/10.1111/j.1541-4337.2010.00144.x.

HOFFMANN, C.; BERGANZA, C.; ZHANG, J. Cold Atmospheric Plasma: methods of production and application in dentistry and oncology. **Medical Gas Research**, v. 3, n. 21, 2013. https://doi.org/10.1186/2045-9912-3-21.

HUANG, G. *et al*. Effects of ultrasound on microbial growth and enzyme activity. **Ultrasonics Sonochemistry**, v. 37, p. 144-149, 2017a. https://doi.org/10.1016/j.ultsonch.2016.12.018.

HUANG, H.-W. *et al*. Current status and future trends of high-pressure processing in food industry. **Food Control**, v. 72, part A, p. 1-8, 2017b. https://doi.org/10.1016/j.foodcont.2016.07.019.

ISSA-ZACHARIA, A. *et al*. A review of microbiological safety of fruits and vegetables and the introduction of electrolyzed water as an alternative to sodium hypochlorite solution. **African Journal of Food Science**, v. 4, n. 13, p. 778-789, 2010. Available from: https://academicjournals.org/journal/AJFS/article-abstract/2A5B72826270. Accessed: May 26, 2025.

JEONG, M.-A.; JEONG, R.-D. Applications of ionizing radiation for the control of postharvest diseases in fresh produce: recent advances. **Plant Pathology**, v. 67, n. 1,

p. 18-29, 2018. https://doi.org/10.1111/ppa.12739.

KADER, A. A.; BEN-YEHOSHUA, S. Effects of superatmospheric oxygen levels on postharvest physiology and quality of fresh fruits and vegetables. **Postharvest Biology and Technology**, v. 20, n. 1, p. 1-13, 2000. https://doi.org/10.1016/S0925-5214(00)00122-8.

KHAN, S. *et al*. Dense phase carbon dioxide: An emerging non-thermal technology in food processing. **Physical Science International Journal**, v. 16, n. 1, p. 1-7, 2017. https://doi.org/10.9734/PSIJ/2017/35518 .

KHADRE, M. A.; YOUSEF, A. E.; KIM, J.-G. Microbial aspects of ozone applications in food: A review. **Journal of Food Science**, v. 66, n. 9, p. 1242-1252, 2001. https://doi.org/10.1111/j.1365-2621.2001.tb15196.x.

KADKHODAEE, R.; POVEY, M. J. W. Ultrasonic inactivation of Bacillus a-amylase. I. effect of gas content and emitting face of probe. **Ultrasonics Sonochemistry**, v. 15, n. 2, p. 133-142, 2008. https://doi.org/10.1016/j.ultsonch.2007.02.005.

KIM, H.-J. *et al.* Effect of atmospheric pressure plasma jet on the foodborne pathogens attached to commercial food containers. **Journal of Food Science and Technology**, v. 52, p. 8410-8415, 2015. https://doi.org/10.1007/s13197-015-2003-0.

KINMAN, R. N.; REMPEL, G. Water and wastewater disinfection with ozone: A critical review. **Critical Reviews in Environmental Control**, v. 5, n. 1, p. 141-152, 1975. https://doi.org/10.1080/10643387509381625.

KINOSITA JUNIOR, K.; TSONG, T. Y. Voltage induced pore formation and hemolysis of human erythrocyte membranes. **Biochimica et Biophysica Acta – Biomembranes**, v. 471, n. 2, p. 227-242, 1997. https://doi.org/10.1016/0005-2736(77)90252-8.

KOBUS, Z. *et al*. Effect of High-Powered Ultrasound on Bioactive Compounds and Microbiological Stability of Juices—Review. **Applied Sciences**, v. 13, n. 19, p. 10961, 2023. https://doi.org/10.3390/app131910961.

KRISHNAMURTHY, K. *et al.* Microscopic and spectroscopic evaluation of inactivation of *Staphylococcus aureus* by pulsed UV light and infrared heating. **Food and Bioprocess Technology**, v. 3, p. 93-104, 2010. https://doi.org/10.1007/s11947-008-0084-8.

KUMAR, M. *et al.* Gamma radiation protects fruit quality in tomato by inhibiting the production of reactive oxygen species (ROS) and ethylene. **Journal of Radioanalytical and Nuclear Chemistry**, v. 301, p. 871-880, 2014. https://doi.org/10.1007/s10967-014-3234-7.

LEISTNER, L.; GOULD, G. W. **Hurdle Technologies**: Combination Treatments for Food Stability, Safety and Quality. New York: Springer Science+Business Media, 2002. 194 p. (Food Engineering Series). https://doi.org/10.1007/978-1-4615-0743-7.

LEVY, C. *et al*. Relevant factors affecting microbial surface decontamination by pulsed light. **International Journal of Food Microbiology**, v. 152, n. 3, p. 168-174, 2012. https://doi.org/10.1016/j.ijfoodmicro.2011.08.022.

LEVY, D.; SORDI, G. M. A. A.; VILLAVICENCIO, A. L. C. H. Irradiação de alimentos no Brasil: revisão histórica, situação atual e desafios futuros. **Brazilian**

Journal of Radiation Sciences, v. 8, n. 3, p. 1-16, 2020. https://doi.org/10.15392/bjrs.v8i3.1241.

LIAO, X. *et al*. Alterations of molecular properties of lipoxygenase induced by dense phase carbon dioxide. **Innovative Food Science & Emerging Technologies**, v. 10, n. 1, p. 47-53, 2009. https://doi.org/10.1016/j.ifset.2008.06.007.

LIMOLI, D. H.; JONES, C. J.; WOZNIAK, D. J. Bacterial extracellular polysaccharides in biofilm formation and function. **Microbiology Spectrum**, v. 3, n. 3, p. 1-19, 2015. https://doi.org/10.1128/microbiolspec.mb-0011-2014.

LONE, S. A. *et al*. An investigation on the sterilization of berry fruit using ozone: An option to preservation and long-term storage. **Biocatalysis and Agricultural Biotechnology**, v. 20, p. 101212, 2019. https://doi.org/10.1016/j.bcab.2019.101212.

MACLEAN, M. *et al*. Photoinactivation and Photoreactivation Responses by Bacterial Pathogens after Exposure to Pulsed UV-Light. *In*: IEEE INTERNATIONAL POWER MODULATORS AND HIGH-VOLTAGE CONFERENCE, 2008, Las Vegas. **Proceedings** [...]. Las Vegas: IEEE, 2008. p. 326-329. https://doi.org/10.1109/IPMC.2008.4743649.

McCLURKIN, J. D.; MAIER, D. E.; ILELEJI, K. E. Half-life time of ozone as a function of air movement and conditions in a sealed container. **Journal of Stored Products Research,** v. 55, p. 41-47, 2013. https://doi.org/10.1016/j.jspr.2013.07.006.

MARIN-HUACHACA, N. S. *et al.* Detection of irradiated fresh fruits treated by e-beam or gamma rays. **Radiation Physics and Chemistry**, v. 63, n. 3-6, p. 419-422, 2002. https://doi.org/10.1016/S0969-806X(01)00618-1.

MAI-PROCHNOW, A. *et al.* Atmospheric pressure plasmas: infection control and bacterial responses. **International Journal of Antimicrobial Agents**, v. 43, n. 6, p. 508-517, 2014. https://doi.org/10.1016/j.ijantimicag.2014.01.025.

MOLLER, A. P. *et al.* Differences in effects of radiation on abundance of animals in Fukushima and Chernobyl. **Ecological Indicators**, v. 24, p. 75-81, 2013. https://doi.org/10.1016/j.ecolind.2012.06.001.

MORREN, J.; ROODENBURG, B.; DE HAAN, S. W. H. Electrochemical reactions and electrode corrosion in pulsed electric field (PEF) treatment chambers. **Innovative Food Science & Emerging Technologies,** v. 4, n. 3, p. 285-295, 2003. https://doi.org/10.1016/S1466-8564(03)00041-9.

NIEMIRA, B. A.; BOYD, G.; SITES, J. Cold Plasma Rapid Decontamination of Food Contact Surfaces Contaminated with *Salmonella* Biofilms. **Journal of Food Science**, v. 79, n. 5, p. M917-M922, 2014, https://doi.org/10.1111/1750-3841.12379.

PANGLOLI, P.; HUNG, Y.-C. Reducing microbiological safety risk on blueberries through innovative washing technologies. **Food Control**, v. 32, n. 2, p. 621-625, 2013. https://doi.org/10.1016/j.foodcont.2013.01.052.

PAULL, R. E. Ripening behavior of papaya (*Carica papaya* L.) exposed to gamma irradiation. **Postharvest**

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Biology and Technology, v. 7, n. 4, p. 359-370, 1996. https://doi.org/10.1016/0925-5214(95)00049-6.

PINELA, J.; FERREIRA, I. C. F. R. Nonthermal physical Technologies to decontaminate and extend the shelf-life of fruits and vegetables; trends aiming at quality and safety. **Critical Reviews in Food Science and Nutrition**, v. 57, n. 10, p. 2095-2111, 2017. https://doi.org/10.1080/10408398.2015.1046547.

PUÉRTOLAS, E.; KOUBAA, M.; BARBA, F. J. An overview of the impact of electrotechnologies for the recovery of oil and high-value compounds from vegetable oil industry: Energy and economic cost implications. **Food Research International**, v. 80, p. 19-26, 2016. https://doi.org/10.1016/j.foodres.2015.12.009.

RAMOS, B. *et al*. Fresh fruits and vegetables - an overview on applied methodologies to improve its quality and safety. **Innovative Food Science & Emerging Technologies**, v. 20, p. 1-15, 2013. https://doi.org/10.1016/j.ifset.2013.07.002.

REISZ, J. A. *et al.* Effects of ionizing radiation on biological molecules—mechanisms of damage and emerging methods of detection. **Antioxidants & Redox Signaling**, v. 21, n. 2, p. 260-292, 2014. https://doi.org/10.1089/ars.2013.5489.

SALEHI, F. Application of pulsed light technology for fruits and vegetables disinfection: A review. **Journal of Applied Microbiology**, v. 132, n. 4, p. 2521-2530, 2022. https://doi.org/10.1111/jam.15389.

SANTOS, M. I. *et al.* One health perspectives on food safety in minimally processed vegetables and fruits: from farm to fork. **Microorganisms**, v. 11, n. 12, p. 2990, 2023. https://doi.org/10.3390/microorganisms11122990.

SAKUDO, A.; YAGYU, Y.; ONODERA, T. Disinfection and Sterilization Using Plasma Technology: Fundamentals and Future Perspectives for Biological Applications. **International Journal of Molecular Sciences**, v. 20, n. 20, p. 5216, 2019. https:doi.org/10.3390/ijms20205216.

SANDRI, A. *et al*. New Method to Easily Assess Bacteriostatic and Bactericidal Activity of Ultraviolet Radiation Using Quantitative Image Analysis. **Photochemistry and Photobiology**, v. 99, n. 6, p. 1476-1482, 2023. https://doi.org/10.1111/php.13796.

SANTAMERA, A. *et al.* Pulsed Light: Challenges of a Non-Thermal Sanitation Technology in the Winemaking Industry. **Beverages**, v. 6, n. 3, p. 45, 2020. https://doi.org/10.3390/beverages6030045.

SARRON, E.; GADONNA-WIDEHEM, P.; AUSSENAC, T. Ozone treatments for preserving fresh vegetables quality: a critical review. **Foods**, v. 10, n. 3, p. 605, 2021. https://doi.org/10.3390/foods10030605.

SCHLUNDT, J. New direction in foodborne disease prevention. **International Journal of Food Microbiology**, v. 78, n. 1-2, p. 3-17, 2002. https://doi.org/10.1016/s0168-1605(02)002349.

SHALABY, S. W.; NAGATOMI, S. D.; POWELL, E. F. Sterilization techniques for biotextiles for medical applications. *In*: KING, M. W.; GUPTA, B. S.; GUIDOIN, R. (ed.). **Biotextiles as Medical Implants**. Sawston: Woodhead Publishing, 2013. ch. 6, p. 157-168.

ISSN: 0104-9070. ISSN ONLINE: 2595-7686.
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CC BY NC SA

(Woodhead Publishing Series in Textiles). https://doi.org/10.1533/9780857095602.1.157.

SHEZI, S. *et al.* Changes in biochemistry of fresh produce in response to ozone postharvest treatment. **Scientia Horticulturae**, v. 269, p. 109397, 2020. https://doi.org/10.1016/j.scienta.2020.109397.

SILVEIRA, A. C. *et al.* Effect of non-conventional modified atmosphere packaging on fresh cut watercress (*Nasturtium officinale* R. Br.) quality. **Postharvest Biology and Technology**, v. 92, p. 114-120, 2014. https://doi.org/10.1016/j.postharvbio.2013.12.012.

SOUZA, T. P.; LIONZO, M. I. Z.; PETROVICK, P. R. Evaluation of microbial contamination reduction on plants through technological process of decoction and spray dry. **Revista Brasileira de Farmacognosia**, v. 16, n. 1, p. 94-98, 2006. https://doi.org/10.1590/S0102-695X2006000100017.

SOWA, S.; TOWILL, L. E. Effects of nitrous oxide on mitochondrial and cell respiration and growth in *Distichlis spicata* suspension cultures. **Plant Cell, Tissue and Organ Culture**, v. 27, p. 197-201, 1991. https://doi.org/10.1007/BF00041290.

SPOTO, M. H. F. *et al*. Gamma irradiation in the control of pathogenic bacteria in refrigerated ground chicken meat. **Scientia Agricola**, v. 57, n. 3, p. 389-394, 2000. https://doi.org/10.1590/S0103-90162000000300003.

STEFANOVA, R.; VASILEV, N. V.; SPASSOV, S. L. Irradiation of Food, Current Legislation Framework, and Detection of Irradiated Foods. **Food Analytical Methods**, v. 3, p. 225-252. 2010. https://doi.org/10.1007/s12161-009-9118-8.

TAHI, A. A. *et al*. Ultrasound and heat treatment effects on Staphylococcus aureus cell viability in orange juice. **Ultrasonics Sonochemistry**, v. 78, p. 105743, 2021. https://doi.org/10.1016/j.ultsonch.2021.105743.

TCHONKOUANG, R. D. *et al.* UV-C Light: A Promising Preservation Technology for Vegetable-Based Nonsolid Food Products. **Foods**, v. 12, n. 17, p. 3227, 2023. https://doi.org/10.3390/foods12173227.

THOM, S. R.; MARQUIS, R. E. Microbial Growth Modification by Compressed Gases and Hydrostatic Pressure. **Applied and Environmental Microbiology**, v. 47, n. 4, p. 780-787, 1984. https://doi.rg/10.1128/aem.47.4.780-787.1984.

TIGANOV, V. S. Ultraviolet technologies for sanitation of veterinary supervision's objects. **Veterinary Pathology**, v. 2, p. 96-100, 2007. Available from: http://elibrary.ru/download/elibrary_16861293_54313027.pdf. Accessed: May 27, 2025.

TODD, E. Food-Borne Disease Prevention and Risk Assessment. **International Journal of Environmental Research and Public Health**, v. 17, n. 14, p. 5129, 2020. https://doi.org/10.3390/ijerph17145129.

TOEPFL, S.; HEINZ, V.; KNORR, D. Overview of Pulsed Electric Field Processing for Food. *In*: SUN, D.-W. (ed.). **Emerging Technologies for Food Processing.** Cambridge: Academic Press, 2005. ch. 4, p. 69-97. https://doi.org/10.1016/B978-012676757-5/50006-2.

TUBIANA, M. Wilhelm Conrad Röntgen and the discovery of X-rays. **Bulletin de l´Academie Nationale**

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de Medecine, v. 180, n. 1, p. 97-108, 1996. Available from: https://pubmed.ncbi.nlm.nih.gov/8696882. Accessed: May 26, 2025.

VESTBY, L. K. *et al.* Bacterial biofilms and its role in the pathogenesis of disease. **Antibiotics**, v. 9, n. 2, p. 59, 2020. https://doi.org/10.3390/antibiotics9020059.

WAGHMARE, R. *et al.* Pulsed light: Innovative non-thermal technology for preservation of fruits and vegetables. **Food Physics**, v. 1, p. 100022, 2024. https://doi.org/10.1016/j.foodp.2024.100022.

WANG, C.-Y. *et al.* Recent Advances in Food Processing Using High Hydrostatic Pressure Technology. **Critical Reviews in Food Science and Nutrition**, v. 56, n. 4, p. 527-540, 2016. https://doi.org/10.1080/10408398.2012.745479.

WANG, Q.; LAVOINE, N.; SALVI, D. Cold atmospheric pressure plasma for the sanitation of conveyor belt materials: Decontamination efficacy against adherent bacteria and biofilms of *Escherichia coli* and effect on surface properties. **Innovative Food Science & Emerging Technologies**, v. 84, p. 103260, 2023. https://doi.org/10.1016/j.ifset.2022.103260.

WENSKE, S. *et al.* Nonenzymatic post-translational modifications in peptides by cold plasma-derived reactive oxygen and nitrogen species. **Biointerphases**, v. 15, n. 6, p. 061008, 2020. https://doi.org/10.1116/6.0000529.

WERESKI, M. The Threshold of Hearing. **The Transdisciplinary STEAM+ Journal**, v. 2, n. 1, art. 20, 2015. https://doi.org/10.5642/steam.20150201.20.

WHO. **Diarrheal disease**. [Geneva], 2024. Available from: https://www.who.int/news-room/fact-sheets/detail/diarrhoeal-disease. Accessed: April 10, 2025.

YAMAMOTO, K. Food processing by high hydrostatic pressure. **Bioscience, Biotechnology, and Biochemistry**, v. 81, n. 4, p. 672-679, 2017. https://doi.org/10.1080/09168451.2017.1281723.

YUAN, Y. *et al.* Isolation and characterization of a bacteriophage and its potential to disrupt multi-drug resistant Pseudomonas aeruginosa biofilms. **Microbial Pathogenesis**, v. 128, p. 329-336, 2019. https://doi.org/10.1016/j.micpath.2019.01.032.

YOUNG, J. L.; DEAN, D. A. Electroporation-mediated gene delivery. **Advances in Genetics**, v. 89, p. 49-88, 2015. https://doi.org/10.1016/bs.adgen.2014.10.003.

YU, T.; NIU, L.; IWAHASHI, H. High-pressure carbon dioxide used for pasteurization in food industry. **Food Engineering Reviews**, v. 12, p. 364-380, 2020. https://doi.org/10.1007/s12393-020-09240-1.

ZENKER, M.; HEINZ, V,; KNORR, D. Application of Ultrasound-Assisted Thermal Processing for Preservation and Quality Retention of Liquid Foods. **Journal of Food Protection**, v. 66, n. 9, p. 1642-1649, 2003. https://doi.org/10.4315/0362-028X-66.9.1642.

ZHOU, R. *et al.* Plasma-activated water: generation, origin of reactive species and biological applications. **Journal of Physics D: Applied Physics**, v. 53, p. 303001, 2020. https://doi.org/10.1088/1361-6463/ab81cf.