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Gentle Preservation Technologies

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Editor: Lilia Ahré,Professor in Dairy Technologies, Department of Food Science (UCPH Food)

Authors:

Lilia Ahrné Professor in Dairy Process Technology at Department of Food Science (UCPH Food)

Markus Walking Ribeiro Assistant Professor in Dairy processing at Department of Food Science (UCPH Food)

Signe Knigge Hylleberg MSc in Dairy Technology, research assistant (UCPH Food)

The report was reviewed by Aberham Hailu Feyissa Associate Professor at DTU-Food

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1. Introduction

Processing of food has evolved over centuries enabling to preserve products for a longer period of time and far away from their original production site. Associated to preservation, processing technologies have contributed to transform, in many case inedible raw materials, into a large variety safe food products that satisfy a diversity of consumer demands.

As environmental and nutritional issues are becoming more relevant to protecting the planet's resources and the health of its inhabitants, raw materials should be gently processed in a sustainable manner. The transformation and preservation of inedible raw materials into tasty and convenient food requires energy and water, and generates side streams, Therefore it is of major importance that technologies, processes and production strategies are selected taking in account minimal use of energy, water and product waste, while retaining or even enhancing food quality attributes, such as sensory characteristics and nutritional value.

Gentle processing technologies include techniques, which have minimal impact on food quality, i.e. minimal degradation of nutritional or functional value, and carbon footprint. Other terms such as *minimal* and *careful* processing have also been used for describing gentle processing. *Minimal processing* is widely used in the literature, and was first reported in the 90's (Ohlsson (1994)). It is a requirement to maintain a sufficient level of food safety in order to protect the health of consumers. New technologies are therefore only deemed competitive to existing technologies, if they can achieve the destruction of pathogenic bacteria found in food such as listeria, salmonella, and coliforms, as well as inactivation of enzymes and food spoilage microorganisms during storage that will both affect food quality adversely. In addition, to succeed, new technologies must overcome cost and reliability constrains (Ohlsson 2002).

Conventional processing technologies which, amongst others, include pasteurization, sterilization, drying and evaporation, are common practices. However, the thermal process required to achieve safety may degrade thermo-sensitive compounds which affect the sensory and nutritional quality of the food. Microwave (MW) and radio frequency (RF) technology are examples of so-called advanced thermal treatments, which have emerged as potentially more gentle alternatives to traditional thermal treatments, as heat can be rapidly transferred to the food. Additionally, a group of non-thermal technologies have been on the rise for a number of years that are characterized by the absence of heat as the primary mode of action to inactivate microorganisms. Albeit non-thermal technologies can be heat-assisted to increase their microbial inactivation efficacy, or produce heat to a certain extent, they are applied at lower temperatures and/or shorter treatment times than conventional thermal processes. This group of technologies includes ultrasound (US), high hydrostatic pressure (HHP), and pulsed electric fields (PEF), amongst others, which can inactivate microorganisms at near-ambient temperatures, thereby, avoiding thermal degradation of the food components, and, consequently, preserving the sensory and nutritional quality in 'fresh-like' food products. Besides the use for preservation, most of these next-generation techniques display specific advantages that can be utilized for production of novel, innovative products with tailored properties. The versatility of emerging technologies furthermore makes it possible to design highly specialized production lines. Furthermore, most of these technologies have shorter process times and may be driven by renewable electricity sources, which has clearly advantages in terms of carbon footprint.

Some of these processing technologies are already applied in food, pharmaceutical, and other industries, e.g., for surface disinfection and sterilization purposes, or in combination with traditional processing units. The new technologies are found in most sectors of the food industry, including meat, dairy, fresh produce (including fruit and vegetables), beverages, seafood products and complement both ready-to-eat and non-ready-to-eat product manufacturing (Jermann et al., 2015).

The objective of this report is to summarize the latest knowledge about gentle preservation technologies including thermal and non-thermal technologies based on ongoing activities at KU FOOD. The focus is on technologies that can inactivate microorganisms, thus cooling, freezing, drying, and modified atmosphere that preserve foods by hindering microbial growth were not described.

2. Thermal Technologies

Preserving food using thermal treatment is well-established and the go-to technology to reduce or eliminate the microbial flora present in food products. More gentle approaches for food preservation have been investigated for a long time as thermal treatment is not exclusively beneficial, but also results in undesirable, heat-induced degradation of product quality.

Only mild preservation techniques are needed as long the quality of the raw materials is relatively high (this means fresh, not contaminated), and the 'fresh-like' product quality can be more easily maintained from production, along the supply chain until the consumer is reached. However, in some cases, more severe heat treatment is needed. Choice of heat treatment depends on the product properties and the subsequent conditions under which the product is intended to be stored, e.g., refrigerated, frozen, at ambient temperatures etc. In the following, the conventional thermal methods High-temperature-short-time (HTST), Extended-Shelf-Life (ESL) and Ultra-High-Temperature (UHT) treatment will be reviewed. Optimal storage stability also includes choosing suitable filling and packaging technology, where aseptic filling and canning/retort processing will be touched upon further down in this section.

2.1 Conventional heating processes

2.1.1 High-temperature short-time pasteurization (HTST)

Thermal treatment has been the established preservation method for many years and for this reason, the use of heat has therefore been continuously developed and highly specified over the years. High-temperature short-time pasteurization (HTST), being the most applied pasteurization method especially for liquid/pumpable foods, has not yet been matched by other technologies in terms of operation cost and energy efficiency. The HTST treatment can be in batch and continuous and makes use of energy regeneration.

Principle

HTST treatment is typically carried out in plate, tubular or scraped surface heat exchangers, in which the product and the heating streams are separated from each other by the heat exchanger wall. The heat transfer takes place at different processing conditions, depending on the product characteristics and the desired degree of microbial and enzymatic inactivation. Heat exchangers are widely used for

HTST and recognized for having very high capacities (50,000 L/h), high regeneration efficiencies (>95%) and the run times between cleaning can be up to 20 hours (Lewis, 2010). Plate heat exchangers are limited to products with a relatively low viscosity as heat transfer takes place over the area of layers of thin stainless steel plates. The incoming, untreated product can be pre-heated by the warmer, outgoing product that has been treated, and hot water or steam is used to reach the pasteurization temperature. Strict time-temperature control is essential with HTST starting at a minimum temperature-time combination of 72°C for 15 s to make it safe for consumption in line with the food legislation.

High temperatures used for HTST may increase the risk of fouling and produce cooked or other off flavors. Hence, time, temperature, and flow rate should be adjusted according to product characteristics such as viscosity, fat content, protein content, etc. If over-processing is avoided the quality of heat-pasteurized products will meet consumer acceptability and not deteriorate noticeably. In addition, the products will exhibit a good shelf-life stability, provided that post-pasteurization contamination is prevented, and low temperature storage conditions are maintained at all times (Lewis, 2010).

Effect on microorganisms

As pasteurization of products such as milk and juices is usually performed at 72°C for 15 s and above (using higher temperature levels and/or longer treatment times) the treatment destroys vegetative cells but not thermophilic spores. HTST is therefore suitable for products that require only short-term storage stability and furthermore, it depends on additional preserving factors, for instance, storage under refrigeration or low product pH.

Effect on micro and macro components

Thermal treatment will always have some effect on the product. It is primarily the residence time duration that causes the changes, minimal holding time is therefore the best practice to reduce the quality changes (Ohlsson 1980). This is particularly challenging, when processing highly viscous products, and careful control of the processing conditions it required as small changes in the temperature-time ratio can damage the product. Loss of vitamins and other micronutrients is an issue observed after thermal treatments and, consequently, this can be compensated by adding supplements of the lost micronutrients to the final product.

Fouling at heat exchanger walls that transfers the heat and are in direct contact with the product, affects not the quality negatively if burned protein and fat components build-up, but fouling furthermore lowers the heat transfer rate and extends equipment cleaning, thereby, increasing the cost of operation. Finally, fouling may promote the formation of biofilms and, thus, increase the risk that microbial contamination of the processed products occurs.

Main applications

Heat exchangers are especially used in the beverage and dairy industries for pasteurization of fruit juices, milk, dairy, and plant based products for refrigerated distribution and storage.

2.1.2. ESL (Extended shelf-life)

Shelf-life represents the storage time in which a product is still safe for consumption, and maintains a product quality, that is in line with consumer acceptability. This means, that a shelf stable product is microbially safe and offers a product quality with regard to sensory attributes (e.g., appearance/color, odor, texture/mouthfeel, and flavor) that meets consumer expectations, if it has been stored accordingly. ESL treatment produces good quality products with extended shelf-life compared to HTST products.

Principle

ESL is not a standardized treatment but is typically a thermal treatment combined with other technologies, also known as hurdles, to achieve microbial inactivation and prolonged shelf-life. Possible hurdles for integration in ESL include bactofugation, high-temperature heat treatment, and microfiltration, but also non-thermal technologies, as will be discussed later, can be used for so-called hurdle technology.

The thermal process intensity of ESL treatment varies and is found in between pasteurization and sterilization processing conditions and may extend the shelf-life of ESL products up until between 30 to 60 days. As pasteurized products have a relatively shorter shelf-life, which offers less convenience to consumers and may lead to food waste, ESL has emerged as an alternative processing method for obtaining longer shelf-life than traditional pasteurization with less of a quality compromise compared to more intense sterilization treatments. A typical thermal ESL treatment of liquid food is conducted in batch mode at 90°C for 10 minutes or, alternatively, in continuous mode 125-138°C for 2-4 sec. ESL treatment is generally combined with aseptic filling and refrigerated storage (Tetra Pak, 2015).

Effect on microorganisms

Conventional ESL treatment at 90℃ for 10 minutes destroys vegetative cells and spores of psychrotrophic bacteria. The log cycle reduction is higher compared to pasteurization as a higher temperature is applied, but since the process does not eliminate all bacterial groups, products treated with ESL should be kept under refrigeration. Sodium nitrite is added to seafood and meat products to control growth of psychrotrophic clostridia, including non-proteolytic *C. botulinum*, but the use of additives can be avoided by using ESL treatment in conjunction with an intact cold chain after product processing.

Effect on micro and macro components

The effect of ESL on the food product is comparable to that of HTST and other commercial/traditional thermal treatments, but with a slightly higher heat load, that for some products may alter sensory product properties.

Main applications

Extending the shelf life of food products is beneficial from both economic and environmental viewpoints. ESL is of commercial importance especially with regards to milk (ESL and UHT milk) as well as beverages like fruit and vegetable juices. The former, also known as ultra-pasteurized (UP) milk, has a shelf-life from a few up to 28 days or longer when stored under refrigeration. In contrast to UHT milk that may have a shelf life up to approximately six months, the fresh product qualities is better preserved in UP milk, still with a shelf life more than four times that of pasteurized milk.

2.1.3. Ultra-high-temperature treatment (UHT)

As an effective sterilization treatment, UHT quickly gained traction, offering direct and indirect heating options, while oftentimes remaining the only suitable processing method from a product safety and quality perspective in countries with challenging climate, hygienic conditions, and poor cold chains.

Principle

Ultra-high temperature treatment, also known as ultra-heat treatment (UHT), is carried out with indirect or direct (steam injection/infusion) heating systems. The former system is based on a plate- or a tubular heat exchanger, where the heat exchanger type and the operation time/temperature combinations depends on the type of product and food properties such as viscosity and acidity. The latter are characterized by direct contact between the product and the heating medium (hot steam). Compared to indirect heating, steam injection/infusion allows fast heating and very short holding times (in the range of a few seconds) at a specific temperature (usually ranging between 135°C and 150°C). The short holding time, during which the product is in direct contact with the steam, will tend to minimise product changes.

Effect on microorganisms

UHT treatment creates commercial sterile products, where microorganisms and heat-resistant enzymes are completely inactivated, making an unrefrigerated shelf-life between six and nine months possible for UHT-treated food products. As sterilization destroys all forms of microorganisms it can provide long-term preservation without need of further hurdle factors, such as refrigeration, if recontamination is prevented and by using adequate packaging solutions. For recombined products, where a liquid is mixed with a dry raw material, such as in the case of chocolate milk, the sterilization temperature is often higher than that used for plain liquids like milk as spore-forming microorganisms may be present in the dry material or be shielded by small, undispersed particles in the mix. UHT systems offer processing conditions from 140°C to 142°C for 6 s and up to 145°C for 15 s.

Effect on micro and macro components

The heat load on the product can affect sensory properties in a positive and a negative way, depending on the food product. For chocolate-based products, a high heat load can be used to enhance the chocolate flavour, whereas in the case of plain milk, a cooked flavour, resulting from an exposure to high heat, is an undesirable product attribute, although accepted as trade-off for convenience. Colour degradation and loss of vitamins are often limiting factors for the shelf-life of fruit juices.

Applications

UHT is applied in the dairy industry for the treatment of a large variety of products, including drinking milk, cream, and flavoured dairy products. Besides dairy products, UHT treatment is also widely used for preservation of fruit and vegetable juices, smoothies, nectars, still drinks, and for prepared foods such as desserts, liquid nutritionals, dressings, spreads, soups, and cooking sauces for both chilled and ambient temperature storage and distribution. The long shelf stability of these products at ambient temperatures enables longer distribution chains.

2.1.4 Canning/in-container/retort processing

Canning of foods was invented by Nicolas Appert of France in 1809 for preserving food for army consumption. Thus, long shelf-life could be achieved in a process that simultaneously cooked the foods. Canning allows for food transport, storage and consumption at challenging sanitary conditions and ambient temperatures and for years, as long as the can integrity remains intact.

Principle

Sterilization of canned products is implemented by using aseptic filling or in-container sterilization, also referred to as retort processing. It is noteworthy, that sterilization takes place after the product is hermetically sealed in an airtight container, thus, eliminates the need for aseptic handling. Retort systems vary from still batch type retorts to complex continuous retorts, supporting different heating mediums for processing. Batch systems are based on loading the pressure vessel of the retort with cans and then heating to the sterilization temperature, the holding time, and subsequent cooling to ambient temperature prior to unloading are all done in the same place. In continuous mode the sealed containers are commonly transported through a large, tunnel-like pressure chamber consisting of a pre-heating part, a sterilization part, and a cooling part. The heating sources are only water, only steam or a mixture of both and for the cooling, usually water or sometimes air is used. In addition to the use of static retorts for some products, rotating retorts have shown to be more advantageous as the forced convection will increase the heat transfer and make the process more efficient.

Effect on microorganisms

Commercial sterilization has a lethal effect on all microorganisms, providing long-term preservation. Retort processing offers great advantages over aseptic filling as the process is simple, and the risk of post-sterilization of the product or cans is eliminated. Spores e.g., from the thermophilic bacterium

Clostridium botulinum may cause a risk of food poisoning in low-acid products with a pH above 4.6. These products require sterilization treatment to be commercial acceptable for distribution, storage and safe consumption under ambient conditions. High-acid products have a pH lower than 4.6, which inhibits the germination of *C. botulinum* spores, and thermal treatment of these products does not require to be at sterilization level to meet the safety standards for commercialization.

Effect on micro and macro nutrients

In-container canning requires longer processing times in comparison to aseptic filling, where the product and can/containers are sterilized prior to filling. Longer cooking times have a negative effect on the nutritional quality, including loss of heat-sensitive vitamins and minerals. The same is true for sensory properties, which are also adversely affected by longer exposure to high treatment temperature levels. Retort processing under agitation not only improves the heat transfer, but it also reduces the possibility of fouling at can walls, which can lead to a more significant loss in product nutrient quality (Holdsworth & Simpson, 2016).

Main applications

Modern retorts have the capabilities to thermally process jars, cans, pouches, cartons, trays, and bowls, and in-container sterilization can thus be applied for preservation of a huge variety of products, including vegetables and fruits, meat, fish, dairy products, and ready-to-eat-meals.

2.2 Electro-magnetic and -conductive heating processes

Electro-magnetic technologies generate heat volumetrically inside the food product, because of the electric resistance properties of the food. Most of the sources of radiation seen in the electromagnetic spectrum in Figure 1 have been applied to food and they can be applied for various purposes. The lethal effect of electro-magnetic technologies is due to the formation of heat, which builds up when dipoles (water molecules), free charges, ions and electrons in the food are stimulated and oscillated, trying to follow the direction of the applied electric field.

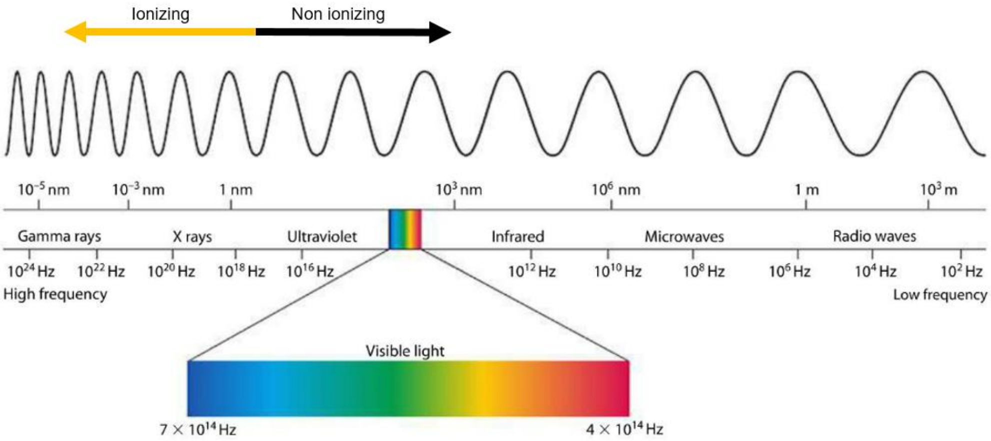

Figure 1. The electromagnetic spectrum (source: miniphysics.com).

The electromagnetic spectrum can be subdivided into ionizing and non-ionizing radiation. X-rays and gamma rays are ionizing radiation technologies with extremely high frequency and penetration power. At a high enough dosage, they cause damage to living tissue and change (ionize) the molecular structure of matter. Non-ionizing frequencies found, for example, in microwaves and radio frequency waves have reduced energy and cause only vibration and not structural changes of the molecules. The following subsections will go through: microwaves, radiofrequency, and infrared heating, whereas ultraviolet light waves, Gamma, X-ray, and electron beams will be presented under section 3.2 and 3.3 respectively, as the mode of action of those technologies is not heat, as is the case for the technologies in this section.

2.2.1. Microwave (MW) and Radiofrequency Heating

While microwave treatment (MW) of food has been established in households and food industry, radio frequency treatment (RF) emerged more recently as an electro-magnetic technology for food preservation.

Principle

When food is subjected to electromagnetic waves, the water molecules inside the product align with the waves. Thermal energy is then generated inside the food instead of being transferred from the surface by convection or conduction as during conventional thermal treatments.

MW can provide relatively uniform heating if the setup is optimized and adjusted, the wavelength frequencies are inferior to those of RF. Preservation of larger sized products is not carried out with MW as the penetration depth is limited, so that the center of a product may not be processed sufficiently or requiring a longer processing time. Too long exposure to MW though results in more intensely or even over-treated areas of the food, still while other parts of the food just reach the minimum required for safe consumption. Compared to MW, RF has a higher penetration depth, and it is also the more energy efficient technology, making it more suitable for in-depth heating of larger food specimens. However, it is a less researched technology compared to MW and optimizing a RF setup is usually more labor-intensive. RF radiation has higher frequencies than MW but as for MW, inactivation of microorganisms also happens due to heat generation inside the food.

Effect on microorganisms

The microbial inactivation by MF and RF application is similar to other traditional thermal processing methods, achieving the same level of microbial inactivation to produce food that is safe for consumption. However, the type of food, the food volume as well as the design of the MW and RF ovens (e.g., magnetron positioning, forced convection due to turning plates) are important processing parameters that need to be considered to ensure sufficient process efficacy. Tendency to hot and cold spots and inhomogeneous heating needs to be controlled for an efficient microbial inactivation. Based on the heating principle by electro-magnetic waves, both technologies are particularly useful for pasteurizing or sterilizing already packaged food, thereby, preventing contamination with pathogenic or spoilage microorganisms after processing.

Effect on micro and macro components

Overall, MF and RF have not been found to damage fats, protein, and carbohydrates adversely, although extended exposure at intense settings (leading to higher temperatures) can cause protein denaturation. The latter is known to occur for all thermal pasteurization methods though. Cooking times are shorter in MW and RF ovens compared to conventional thermal processes, so that vitamins are depleted to a slightly lesser extent than by using traditional thermal processing methods.

Main applications

The main industrial applications of both MW and RF - sometimes in the role of an assisting technology - are thawing and tempering of meat and fish, pre-cooking of meat, heat pasteurization of pre-cooked meals and their use for food dehydration. Energy efficiency in combination with the product quality, that can be achieved, will remain a key criterion for the fields of application of either MW or RF.

2.2.2. Infrared

Infrared radiation (IR) is mainly regarded as a so-called surface treatment method, comparable to other radiation techniques (e.g., pulsed high intensity light, ultraviolet light), and it has been successfully applied for pasteurization, drying and/or other heating purposes.

Principle

IR heating is generated with one or a series of IR emitters that generate electro-magnetic waves with wavelengths in the range between 10^3 nm and 10^6 nm. The wavelength determines the radiation power, where short waves exhibit the highest radiation power and long waves emit the lowest radiation power and consequently the lowest temperature (~ 900°C). IR treatment is typically conducted by means of IR heating ovens or ovens combining IR heating with convection air heating. The highest IR intensity is found on the surface of the food and heat is then conducted through the food material.

Effect on microorganisms

IR heating is suitable for inactivation of bacteria, yeast, and molds specially in solid foods. The penetration depth of the radiation is limited, so that IR is an effective technique for surface pasteurization. To achieve incenter pasteurization, the application of IR can be assisted with other heating sources. Microbial inactivation efficacy is influenced by parameters such as IR power level related to processing temperature, penetration depth, moisture content, and type of food material, wavelength, and types of microorganisms. (Krishnamurthy et al., 2008).

Effect on micro and macro components

Food components absorb IR radiation at different intensities dependent on the wavelength as can be seen in Table 1. The radiation will induce changes in the vibrational state of the food molecules and, consequently, lead to generation of heat. Surface coloration is unavoidable using IR heating as the applied radiation will be most intense on the surface of the food material.

Table 1.The chemical groups involved and IR absorption wavelengths of main food components.

Chemical group	Absorption wavelengths	Relevant food components
Hydroxyl group	2.7-3.3	Water, sugars
Aliphatic carbon-hydrogen bond	3.3-3.7	Lipids, sugar, proteins
Carbonyl group (C=O) (ester)	5.7-5.8	Lipids
Carbonyl group (C=O) (amide)	5.92	Proteins
Nitrogen–hydrogen group (-NH-)	2.8-3.3	Proteins
Carbon–carbon double bond (C=C)	4.4-4.8	Unsaturated lipids

(Adapted from Krishnamurthy et al., 2008*).*

Main applications

IR has been applied in drying, baking, roasting, blanching, and for pasteurization and sterilization of food products. Moreover, it has successfully been combined with convective air heating. Drying in oven (e.g., part baked bread) with an air circulation at a high velocity in combination with IR can reduce the treatment time considerably, compared to traditional, separate drying and impingement treatment. With IR only a thin crust is obtainable as the penetration depth is limited, and the temperature in the center of the food will therefore not reach a sufficient heating temperature before the crust e.g., will take damage from the radiation.

2.2.3 Ohmic heating (OH)

Ohmic heating (OH), also known as Joule heating, provides microbiologically safe products through so-called direct resistance heating, where electrical energy is converted to thermal energy inside the food product. Rapid heating, high energy efficiency, and minimal impact on the food quality are some of the benefits of the OH technology (Demirci et al., 2020).

Principle

Treatment using OH utilizes, that components naturally present in food such as water, salt, and minerals are capable of electric conductivity. Alternating electric currents of low (50–60 Hz) or high (25–30 kHz) frequencies are applied to a food material with electrodes directly attached to the food or connected through a conductive media. During OH the electric current will encounter the specific resistance of the food product, which results in a rise in temperature. The heating effect is generated directly inside the food and is not transferred from the surface as the case in traditional, conductive heating. Ohmic heating can be performed as a batch process or in a continuous flow system (Demirci et al., 2020). The cooking time can be highly reduced for several products compared to traditional heating, more uniform treatment of different particles sizes (reduced the temperature gradient) (Pedersen et al., 2016) and the energy efficiency is increased by up to 90% (Jaeger et al., 2016a). The effect of ohmic heating is dependent on the conductivity of the food product, which is determined by its water content, salt, pulp, fats and oils, temperature, and the electric field applied. Viscosity, electrical conductivity, and fouling deposits are possible limitations for the application of OH, but a higher particle density in the food product enables a faster, more effective, and gentle heating with this technology.

Effect on microorganisms

OH is used for pasteurization and sterilization purposes, especially of high viscous, particulate foods. The lethal effect is mainly derived from the heat generated in the food. The efficacy against microorganisms is dependent on the strength of electric field applied, microorganism species present, and the type of food, and the corresponding holding time (Jaeger et al., 2016b). The microbial load is reduced with increased electric field strengths and longer treatment time with some microbial inactivation also attributed to non-thermal effects caused by the electric current (Tian et al., 2018).

Effect on micro and macro components

As heat is generated directly inside the food and without a temperature gradient, this allows for an equally distributed heating of the food material, and minimal thermal damage. However, some hot spots will still arise, which can be ascribed to factors such as product geometry, if the food contains aqueous oil or particulate fractions, as well as other product properties influencing the electrical conductivity inside the food material. The impact of thermal damage is though still dramatically reduced compared to traditional thermal treatment methods (Jaeger et al., 2016b).

Main applications

OH is particularly suited for processing high viscosity products such as jam and fruits puree, particulate products (stews, soups vegetables mixture with sauce), and solid food such as ham and fruits. OH systems must be adjusted according to type of product to be processed and for optimal use of OH, the rheological properties and electrical conductivity of food needs to be better understood.

3. Non-thermal technologies

The drawback of thermal processing techniques, especially the ones relying on heat transfer by conduction or convection, is the considerable dissipation of heat. Thereby, the transfer of energy from the equipment to the food may not be very effective, and consequently the time required to inactivate microorganisms cause thermal damage on heat sensitive products. The latter has a major influence on the sensory quality of a product, for instance, color changes, off-flavors or loss of flavor compounds, and undesired degradation of textural properties. Non-thermal technologies, where the preservation effect is by the action of other means that heat, have been successfully applied for preservation of a variety of foods.

3.1 Pressure driven technologies

3.1.1 High Hydrostatic Pressure (HHP)

High Hydrostatic Pressure (HHP) processing, or isostatic pressure, uses pressure rather than heat to achieve a pasteurization-equivalent treatment without adverse thermal effect on food quality. This universally applicable technology is currently of much interest as an alternative to conventional thermal processing in the food manufacturing industry. The technology is consistent with the demand for minimally treated products and additionally, HHP has been found to modify the protein structure which, amongst others, can be used for improvement of textual properties and product stability e.g., in dairy products and beverages.

Principle

HHP can be performed on both packed and unpacked products, with the former making the technology suitable for non-thermal, post-packaging pasteurization. For packed food, the product is transferred to a pressure vessel containing a pressure-transmitting medium (usually water). When the area in the vessel is decreased, the following compression of the pressure-transmitting medium causes a rise in pressure inside the vessel. The applied pressure typically ranges from 100 MPa to 700 MPa (for comparison, the pressure at the bottom of the deepest location in the Earth's oceans, the Marianna trench, is approximately 110 MPa). The holding time of HHP treatments is usually set between a few seconds and 20 minutes and the temperature range varies from -20°C to 60°C, unless the objective is high pressure sterilization for which higher temperature might be necessary. HHP is based on the isostatic principle, which states that pressure is volume-independent and means, that an amount of s heat will develop in the system during the compression process (estimated to be approximately 2℃ to 3℃ per 100 MPa applied pressure), though to such small extent, that HHP may still be considered a non-thermal process (Barba et al., 2018).

Effects on microorganisms

Microbial inactivation during HHP treatment occurs in the pressure range of 300 MPa 800 MPa. Conditions required for obtaining a similar effect as thermal pasteurization are e.g., 400 MPa for 15 minutes or 600 MPa for 3 minutes. The treatment efficacy is based on a synergetic effect of pressure and a rise in temperature, involving pressure induced structural changes to the microbial membrane and enzymatic systems inside the cell combined with heat- induced stress due to the increased temperature (Knorr et al., 2011). Opposite to the effect of moderate to high pressure ranges, HHP treatment in the lower pressure range (100 MPa to 200 MPa) have shown to strengthen microbial cells as a pressure-induced stress response, and thus, the technology has also been investigated as a pre-treatment of starter cultures before drying or freezing takes place (Knorr et al., 2011).

Pressure gradients inside the food should not be present due to the isostatic principle, which is a main advantage of HHP for ensuring homogenous treatment of the food. However, pressure gradients may occur in heterogeneous foods and result in non-uniform temperature distribution, which may cause local differences in the efficacy of microbial inactivation within the food. The inactivation effect of HHP varies with food composition, type of microorganism, and processing parameters such as time, temperature, and pressure levels (Barba et al., 2017). Stand-alone HHP does not reduce spores effectively as they have pressure tolerances of 1,200 MPa and above. For this reason, HHP is limited to pasteurization processes, unless it is heat-assisted in a combined process for the purpose of high-pressure sterilization, and, thus, HHP-treated products are stored generally under refrigeration.

Effects on macro and micro components

High pressure processing affects the structure of macro molecules such as proteins, whereas micro molecules including amino acids, vitamins and flavour and aroma components that contribute to the sensory and nutritional quality, remain unaffected. Salts and mineral solubility increase under high pressure, but the effect has also been shown to reverse upon release of pressure and, has been suggested to have a negligible effect on the food quality (Datta & Tomasula, 2015). HHP has little to no effect on the primary structure of proteins as the strength of the covalent bonds between the amino acids are strong enough to remain unaffected. The hydrophobic interactions, stabilizing the secondary and tertiary structure are on the other hand impacted by the pressure. These pressure-induced changes are thought to be reversible between 100 MPa to 300 MPa, whereas pressure levels above 330 MPa to 400 MPa are thought to cause denaturation resulting in irreversible unfolding of the protein structure. The effects on protein structure at higher pressures have, for example, shown to improve the melt-down resistance and even improve sensory characteristics such as mouthfeel and creaminess of ice cream (at treatment levels from 400 to500 MPa for a short time). The effect on protein structure can furthermore modify the rheological properties of liquids and inactivation of enzymes, with the latter representing an important aspect for preservation. In addition to the effect on proteins, HHP has shown to induce gelation and swelling of starch, similar to the changes that can be induced by heat and may therefore have great potential for using HHP to customize texture (Knorr et al., 2011). Fat is also influenced by HHP, yet, to a smaller extent than proteins and carbohydrates. The main advantages of HHP for fat processing relates to homogenization, which is further described in section 2.4.2.

Main applications

Products treated with HHP include dairy, meat, seafood, fruit and vegetables, juices and other beverages. with possible applications such as microbial and enzymatic inactivation to enhance product preservation, structural modification, and ingredient extraction. In addition, the technology has been widely applied to process ready-to-eat meals. Relatively high investment costs and the fact, that the technology is only applicable in semi-continuous, or batch mode has limited the use of HHP to a comparably low production volume of premium food products, favouring functional ingredients more than bulk production to date (Datta & Tomasula, 2015).

3.1.2 High Pressure Homogenisation (HPH)

Homogenization is a technology used for establishing emulsions in liquid products composed of two immiscible phases, a continuous phase, and a suspended phase e.g., fat droplets suspended in water (o/w emulsion) like in milk or water in oil (w/o) as the case for butter. The interfacial layer between the two phases is stabilized by surface-active molecules, which reduce the surface tension and stabilize the mixture and, thus, prevent undesired effects such as sedimentation, creaming and aggregation, impairing the product shelf stability and quality. Following homogenization, the emulsion stability is increased by reducing the droplet size and, consequently, minimizing the interfacial surface tension and/or by mixing the immiscible phases in the presence of emulsifiers and surfactants. Utilizing multiple product passages through the homogenizing equipment and/or more than one pressure stage will in most cases further improve the homogenization effect.

Principle

HPH involves forcing a liquid under high pressure through a narrow gap, called the homogenization nozzle, by means of a piston pump, or by passing the liquid through a system of micro-channels in split streams for collision, which is also known as microfluidzation and less common. The pressure gradient between the inlet and outlet of the nozzle or, alternatively, the channeled and colliding high pressure liquid streams, results in high shear, cavitation, turbulent flow conditions, and local short-time heat generation in the fluid. After exposure to these effects, the size of the dispersed droplets is decreased and distributed in the continuous phase. Upon addition of emulsifiers the droplet surface is adsorbed to them, preventing the smaller droplets to merge into larger droplets (Tetra Pak, 2015).

Effect on microorganisms

Pressure, shear, cavitation, and temperature are processing effects known to determine the inactivation of microorganisms, including bacterial spores to some extent (also depending on the added thermal load, which may even enable product sterilization). The treatment efficacy is related to the physical damage that the above-described processing effects cause in the microbial cells. It is also worth mentioning, that HPH has been suggested for combined pasteurization and homogenization treatment of liquid food products (Patrignani & Lanciotti, 2016).

Effects on macro and micro components

Smaller molecules like aroma compounds are not affected by pressure, but pressure above 400 MPa is known to cause protein unfolding and inactivation/activation of enzymes, which highly affect the chemical and physical properties and, ultimately, the sensory quality. HPH treatment is though mostly applied with the aim of stabilizing emulsions by increasing the surface area of fat globules and, thereby, making more space for emulsifying compounds to stabilize the food system over a longer period. HPH is particularly used in the dairy industry, where it has become a standard industrial process for stabilizing the fat emulsion against gravity separation. The disruption of the fat globules has many advantages, including whiter color, reduced sensitivity to fat oxidation, more full-bodied flavor, and mouthfeel (Tetra Pak, 2015).

Main applications

HPH is used for liquid products to provide better stability of emulsions, reduce the microbial load, and thereby increase the product safety considerably. Moreover, the (micro-)structure of the product can also be altered intentionally, depending on the processing conditions (e.g., pressure level, processing temperature and time, and type of equipment), to engineer products with tailored functional properties.

3.1.3. Membrane Filtration

The use of membrane filtration technologies is widespread in the food industry e.g., for fractionation, concentration, demineralization, as well as removal of somatic cells, and microorganisms. This chapter focus on mainly on microfiltration (MF) as gentle preservation technology to remove of microorganisms, although it is relevant to mention in the context of gentle preservation processes that membranes filtration has a low energy consumption compared to evaporators, offering advantages as pre-processing before drying.

Principle

Membrane filtration is a physical separation process, in which a liquid is passed through a semi-permeable membrane, separating the feed into two streams. The permeability is determined by the pore size and properties of the membrane, and the product components passing the membrane are called permeate, while the retained components of the liquid are called retentate. Two types of filtration systems exist, either dead-end filtration or crossflow filtration. In dead-end filtration, the feed is loaded from the top of a vessel and passed through a membrane by gravity similar to a coffee filter. Crossflow filtration is, however, the type mainly used in the food industry and offers many benefits over dead-end filtration, as the feed can flow continuously and parallel to the membrane and thus, less concentration polarization, and reduced filter cake build-up for longer operating times without cleaning. The crossflow is driven by pressure gradient, which is usually applied by means of a centrifugal or positive-displacement pump. Membranes can be made from ceramic or polymeric materials and the exchangeable cartridges or modules consist of one or more membranes tubes stacked or arranged in different ways, dependent on the processing scale and specific to the application. Ceramic membranes are mostly used in the food industry as they are more resistant to heat, chemicals, and frequent cleaning. The different types of membrane systems used in the food industry are listed in Table 2.

Table 2. Membrane types, including pore-size and operating pressure range and retained food components.

Membrane type/ range	Pressure range (kPa)	Components
Microfiltration 0.1µm-10µm	10-350	Somatic cells, fat, bacteria/spores, yeasts, moulds, suspended solids
Ultrafiltration 0.001µm - 0.1µm (1-500 kDa)	30-1050	Proteins, enzymes, fat, polysaccharides
Nanofiltration 0.2 kDa - 2 kDa	1000-4000	Salts, vitamins, sugars, organic acids, and smaller peptides
Reverse Osmosis	1300-8000	Water, ions

(Adapted from Datta, N., & Tomasula, P. M. 2015).

Effects on microorganisms

Microfiltration (MF) covers the largest pore size range from 0.1 µm to10 µm and is thereby able of retaining bacteria (typically, at pore sizes between 1.2 µm and 1.44 µm at commercial scale) and their spores. Hence, MF is considered a valid, alternative to bacterial decontamination treatment by centrifugation, e.g., bactofugation, that is used for pre-treatment of cheese milk. Fat particles (0.1 µm to 15 µm) are found in the same size range as bacteria, and MF is therefore much more suitable and established for non-fat products such as skimmed milk. The temperatures during separation processes based on membranes usually does not exceed 55°C and it is not high enough to have a noticeable killing effect on microorganisms. MF for pasteurization purposes is therefore usually combined with mild thermal treatment and can assist to significantly extend product shelf life e.g., as part of an ESL strategy, whereas cream and retentate are subjected to more intense thermal processes.

Effects on macro and micro components

Microfiltration serves as a gentle product treatment because only moderate temperature changes occur during processing. Since the technology separates the food components solely based on their size, there are no structural or chemical changes of the food components during the treatment.

Main Applications

MF is mainly used for reduction of microorganisms, clarification of liquids such as fruit juices, beer, and wine as well as in water sanitation. Introducing membrane technology can reduce the processing impact on products and they can be used for production of natural products and contribute to a minimal processing approach for sufficient safety and premium quality products or maximum product safety and shelf-life with acceptable quality. For example, reverse osmosis can be implemented as a great supplement in evaporation processes for concentration of juices and other liquids. If applied prior to evaporation reverse osmosis can remove 50% or more of the water before subsequent evaporation and allows for savings of up to 40% in energy consumption compared with direct evaporation processes. Ultrafiltration is widely applied in the dairy industry for concentration of proteins in milk used for yogurt and for other concentration purposes involving proteins.

3.2. Electrical driven technologies

3.2.1. Pulsed Electric Fields

Pulsed electric fields (PEF) has been investigated by researchers over almost the last century as one of the most promising, non-thermal technologies for microbial inactivation, and recently the technology has also gained interest in the industrial sector. Focus of research has mainly been related to preservation, however, PEF has furthermore lately been found applicable in other areas of food processing, such as for pre-treatment prior to freezing, canning, and drying, and for extraction purposes.

Principle

Pulsed Electric Field (PEF) is based on the generation of an electric field at high voltage typically between 10 kV and 80 kV to which the food product is subjected by passing it or placing it between a set of charged and a grounded electrode. For batch mode PEF processing, which is used for extraction or dehydration pre-treatment applications, the solid food product is placed between the two electrodes of a treatment chamber and then electropermeabilized with a high voltage current, released from a set of capacitors that were previously charged by a high voltage generator. During PEF processing a rise in temperature occurs, but as the product subjected to the electric field is only applied for up to few milliseconds, the elevated temperature has a very limited effect on the quality of the product. By contrast, for continuous mode PEF processing a liquid food product is pumped at a specific flow rate through piping to a set of electrodes in a treatment chamber, where it gets electroporated. The application of the latter setup is for preservation of liquid foods. PEF treatment chamber designs differ in the electrode configuration, where electrodes are arranged in parallel, co-axially or in a co-current layout (Taha et al., 2022).

Effect on microorganisms

The technology is suitable for preservation as a result of irreversible electroporation of the cell membrane predominantly in vegetative microorganisms, leading to damage and leakage of cellular content, thus, rendering it non-viable. Furthermore, PEF can also reduce the activity of enzymes significantly and due to processing conditions in the micro- to millisecond range at sub-pasteurization temperatures, it enables gentle food processing (Krishnamurthy, 2020).

The efficacy of PEF treatments against microorganisms depends on various factors such as the electric field strength applied, the processing time (which in turn also depends on the pulsed frequency or number of pulses and the pulse width), the pulse polarity (i.e., either monopolar or bipolar) and type (i.e., square wave shaped or exponential decay) and the processing temperature reached as well as the specific food product and the type of microorganism treated. Current guidelines developed by the United States Food and Drug Administration (FDA) require a 5-log reduction of target foodborne pathogens in fruit juices prior to distribution, which, for commercial exploration of PEF for this type and similar products, requires long treatment times ($>100\mu s$) and high electric field strengths (i.e., > 30 kV/cm). If the intensity of the PEF treatment is not intense enough to achieve irreversible pore formation by electroporation of a microbial membrane, only a sub-lethal injury occurs, and the PEF-treated microorganism will be able to repair the inflicted, but reversible membrane damage, and completely recover from the treatment (Krishnamurthy, 2020). As PEF, per se, like HHP, does not inactivate bacterial spores, it is considered as a non-thermal technology that is an alternative to thermal pasteurization, unless it is further enhanced by combination with other processes using a different mode of action.

Effects on macro and micro components

Optimized application of PEF can modify the structure of solid food (e.g., softening potato tissue) and liquid (e.g., electroporation of milk fat globules) without adverse effects on macronutrients and, consequently, product quality. The technology has furthermore recently gained interest within the field of protein functionality (Taha et al., 2022). The impact of PEF on vitamins and other micronutrients is also very gentle, making PEF one of the gentlest of all non-thermal processing technologies if substantial additional heating is avoided.

Main applications

Pasteurisation of juices is a common application. Gentle preservation is possible for all kinds of liquid food, but the treatment efficacy and shelf-life decrease in more complex products, for instance, with high and insulating fat content such as whole milk and cream or in liquid food containing particulate matter that can shadow and protect microorganisms. Furthermore, PEF treatment can increase mass and heat transfer in solid foods by electroporation, for instance, accelerating drying of solid foods, e.g., bell peppers and apple slices. Moreover, the extraction yield, for example, during the production of juice or wine, can be enhanced over that of some of conventional methods or PEF can also be used as an additional, complementary extraction method.

3.2. Acoustic technologies

3.2.1. Ultrasound (US)

The interest in ultrasound (US) for food processing is growing, as synergetic treatment effects have been shown when the technology is combined with other processing techniques. Due to their versatility, US-assisted processes have been proposed for nearly every aspect of food production, amongst others inactivation of microorganisms and enzymes, homogenization, extraction, drying processes and for stimulation of living cells.

Principle

US penetrates food media in waves characterized as power (W), acoustic intensity (W/m^2), or energy density (W/cm^3), creating series of compression and rarefaction. The main treatment parameters are amplitude and frequency at a given power level as well as the time of the treatment. Growing cavitation bubbles formed by ultrasonication, which eventually will collapse due to reaching a critical size, interacting with the local media, and neighbouring cavitation bubbles, can be further intensified by combination with moderate concurrent heating, pressure, and both heating and pressure, known as thermos-sonication, mano-sonication, and mano-thermo-sonication, respectively. These heat and/or pressure-assisted US process significantly enhance the range of applications and various types of equipment, including sonication baths, ultrasonic probes, and vibrating systems can be used to apply US to continuous process lines (Barba et al., 2018).

Effect on microorganisms

The energy released from the collapsed bubbles leads to chemical, mechanical, and physical changes in the food including pressure and temperature changes, shear, cavitation, cell membrane thinning and production of free radicals, that all contribute to the inactivation of microorganisms (Piyasena et al., 2003; Rastogi, 2011). While heat- and/or pressure-assisted US treatments improve the processing efficacy against vegetative microorganisms, US processes are limited to the level thermal pasteurization type treatments, not allowing for food sterilization.

Effect on micro and micro components

Depending on the treatment intensity applied and the specific application the effect of stand-alone or assisted US treatments on macro- and micronutrients varies considerably. Hence, for product preservation the treatment intensity must be optimized to the food product to avoid potentially adverse effects regarding protein denaturation, generation of off-flavour compounds, and high loss in vitamins. Generation of off-flavour is a major challenge in US processing.

Main applications

Currently, Ultrasound (US) is applied industrially combined with other unit operations like moderate heat, pressure, or both, mainly for intensification purposes, and the effects include improved heat transfer in heating, freezing, and drying operations. The vibrations caused by US can furthermore enhance unit operations like filtration, emulsification, and homogenization. Use of US for extraction of valuable food ingredients, and to induce structural changes in food products to alter functional properties of food are also emerging increasingly.

3.2.2 Shockwaves

The most recent non-thermal technology introduced were shockwaves (SW) that are generated in water environment and then spread concentrically form its source to hit a food product submerged in this environment with a high-pressure wave. SWs is another acoustic processing technology that combines in its mode of action elements of other processes previously discussed such as US and HHP. However, compared to HHP, where the product treatment is applied over a specific time period, and US, which is based on continuous product exposure to sonic waves, SW is a single high intensity pressure wave technology. SW technology may also be referred to as electrohydraulic processing or hydrodynamic processing.

Principle

A supersonic shockwave is generated underwater from electric discharge and carries energy corresponding to a pressure in the wavefront of 30-100 MPa. The SW is formed in liquid/water tank as heat energy from the electric discharge or explosion is converted into mechanical energy, which is then released in the form of a wave within the liquid (Barba et al., 2018), where the food product is subjected to its impact.

Effect on microorganisms

When an underwater SW hits a food material, microbubbles formed in the wave will then collapse on the surface of the food material and create areas with high shear and temperatures. The cavitation of microbubbles on the surface of the food bas been proposed as the main mode of action to cause microbial inactivation, but the effect of SW on microorganisms for preservation purposes remains unclear to date and the treatment is therefore mainly applied for tenderization purposes. Combined with other processes and sanitary hurdles US has shown significant reductions in microbial load and the same may apply to SW (Fan et al., 2022). A 5-log reduction for pasteurizing juice as required by Food and Drug Administration (FDA 2017), which e.g., has been achieved by researchers in orange juice for the pathogenic *E. coli* O157:H7. SW has shown promising results for liquid foods, but there is still insufficient evidence on solid materials (Fan et al., 2022). However, it should be noted, that the application of SW to tenderized meat has been shown to reduce the storage time for ripening and ageing of meat by 3 to 5 days compared to conventional meat processing practice. In addition to a higher productivity resulting from shorter preservation times needed after SW treatment of meat, also significant energy savings were observed due to the shortened refrigerated storage duration.

Effect on food micro and macro components

The impact of the SW on a food material and how it travels through the food highly depends on the density of the food material. Cell wall damage, destruction of connective tissue, and spalling, depend on the intensity of the SW and the specific composition and structure of the food subjected to the treatment. Treating food with SW can lead to release of micro components such as aroma-and flavor compounds and antioxidants.

Meat tenderization is by far the most researched application of SW. The effect on the meat tissue is characterized by extreme high-pressure disturbance of the myofibrillar structure by breaking of the peptide bonds and, thereby, modifying the collagen structure. Improved tenderness was observed for fresh and frozen beef, pork, and lamb meat without inducing noticeable changes in the sensory quality.

Main applications

Using the technology for microbial inactivation and improving juice extraction from fruit and vegetables has recently been investigated, but the technology is still in the investigation stage prior to industrial application.

Increased tenderness of meat and fish products, enhanced juice/ oil yield, increased extraction of bioactive components, and reduction of microorganisms are potential opportunities for industrial adoption of USP (Fan et al., 2022), but the technology still faces several challenges that must be addressed before industrial implementation is possible. SW was initially studied for tenderization of meat in 1958, and since then the technology has been successfully applied for this purpose albeit commercial use of the technology is still at the development phase.

3.3. Gamma, X-ray and electric beam

Irradiation by gamma-rays, X-rays and electron beams are based on ionising radiation as described in section 2.2. Research regarding the application of irradiation in food processing has been studied since the 1950’s, first time used to preserve food for US military troops in the field in the time after the Second World War, however, poor consumer acceptance almost banned the use of the technology, until recent developments of e-beam technology. (Krishnamurthy, 2020).

Principle

Electron beams are high energy, accelerated electrons produced by a particle accelerator. The penetration depth of electron beams is just below four cm, and the technology is therefore mainly suitable for small products. Compared to electron beams, gamma rays and X-rays are photons with no mass and no charge and have considerable penetrating depth. X-rays have lower demands regarding the setup of a suitable processing facility because less radiation shielding is needed and based on this, they are qualifying as an effective sterilization method for large volumes of high-density products. However, the use of X-rays is limited as the energy consumption is very high and the efficiency low (only 8-12% of the electrons are converted into X-rays). While the energy efficiency is better for gamma rays than the other ionizing radiation technologies, their application is confronted with other challenges, for example, the need for the construction of heavy shielding and the generation and storage of radioactive waste material. Table 3 provides an overview of the advantages and disadvantages of the three types of ionizing radiation technologies.

Table 3. Advantages and disadvantages of gamma-ray, X-ray and electron beam for food applications.

Gamma-ray	**X-ray**	**Electron beam**
Low operation/ maintenance cost	Highest operation/ maintenance cost	High operation/ maintenance cost
High penetration	High penetration	Low penetration
Isotopes, disposal of radioactive material	No radioactive waste	No radioactive waste
Require heavy shielding	Require less shielding than gamma	Require less shielding than X-ray
Require regular replenishment of Radioisotopes	High energy costs	High energy costs
Good dose uniformity	Good dose uniformity	Poor dose uniformity

(Adapted from (Demirci et al., 2020)*).*

Effect on microorganisms

All types of microorganisms can be inactivated by ionizing radiation technologies, depending on the radiation dosage applied, the food product and type of microorganisms found in the product. Bacterial spores can be eliminated by gamma radiation in dry food, for example, spices, and the latter is challenging for most processing technologies without severely compromising the product quality. Reports about food products exposed to gamma radiation causing potentially adverse effects for the consumer's health, have limited a widespread commercialization in the food processing industry and led to bans of the technology for food processing in some countries. However, the radiation dosage currently used for irradiated food (up to 10 kGy) is deemed safe in many countries and, thus, it is a powerful technology that allows for effective preservation of food products (Krishnamurthy, 2020).

Effect on micro and macro components

Moderate irradiation dosages applied to ensure microbial safety have not shown to induce any negative changes regarding meat quality. However, at high doses irradiation can produce off-odours and colour changes, indicating that the process needs to be optimized regarding the dosage applied and the food system treated to obtain a safe and shelf stable product of good quality. Water-soluble vitamins are more sensitive to ionizing radiation than fat-soluble vitamins, but it should be borne in mind that in general, vitamins are very sensitive, and many factors can contribute to their degradation. Fresh fruit and vegetables are more prone to irradiation than meat as fruit and vegetables are living organisms, and ionizing radiation treatment can lead to softening or sogginess and loss of vitamin C (Demirci et al., 2020).

Main applications

Based on the concerns regarding the safety of food processed with e ionizing radiation as well as their environmental impact, gamma-rays, X-rays, or electron beams treatments have not succeeded to become established as common, all-purpose food preservation technologies. Although these technologies enable effective preservation for a wide range of products, the lack of customer acceptance remains a major challenge for wide commercial implementation. (Jermann et al., 2015). At present gamma radiation is still the most prevalent form of ionizing radiation used in the agriculture and food industry for sprouting and ripening control in fruit and vegetables, disinfestation in fresh fruit, cereals, nuts, spices, dried fruit and vegetables, dried fish, and meat, parasite inactivation in raw meat and fish, and surface disinfection of seafood, meat, and poultry.

3.4 Ultraviolet (UV) based processes

Ultraviolet light allows non-ionizing and low-energy irradiation of food products in the range from 100 nm to 400 nm in the electromagnetic spectrum, as previous shown in Figure 1.

Principle

Ultraviolet light (UV) treatment of food is applied either in continuous mode at lower power levels, or in pulses (PUV), where a higher power radiation is applied in intervals. The UV processing range can be further subdivided into UV-A (315–400 nm), UV-B (280–315 nm), UV-C (200–280 nm), and vacuum UV (100–200 nm), of which UV-C has been established as the most efficacious for food processing.

UV for continuous emittance is produced from mercury lamps that emit radiation with wavelengths ranging from 100 to 400 nm. Pulsed UV is a more recent technological development, which delivers short-duration pulses of high intensity while, similar to UV, it also remains non-thermal and non-chemical, based on photons in the wavelength of 100 to 1100 nm. Photons generation is induced by application of a high voltage to an inert gas, which makes the molecules enter an excited state and, thereby, release photons. The power of pulsed UV light is amplified by building and storing the energy in a capacitor and releasing it during short bursts (Demirci et al., 2020) and noteworthy advantages of the pulsed UV treatment over the continuous UV is a longer lifetime of the UV lamps and the shorter time duration of the treatment.

Effect on microorganisms

A major benefit of using UV for food preservation is that the light radiation is lethal to most microorganisms, with the germicidal effect of UV peaking in the UV-C region of the electromagnetic spectrum, between wavelengths of 250 and 270 nm. UV inactivation of bacterial, fungi, viral, and protozoan microorganisms is obtained by heat formation and by inducing changes to the DNA (deoxyribonucleic acid) in the cells (Barba et al., 2018b)but it is limited in penetration depth by the transparency of liquid food and allowing only surface treatments for solid food products.

Effect on micro and macro components

In general, due to the short time exposure times during pulsed UV treatment needed for microbial inactivation, the technology has a negligible effect on the food components and produces no undesired by-products that could affect the sensory or nutritional quality of the food. In some cases, the surface of UV treated food may be damaged, e.g., causing colour and flavour changes, due to oxidation reactions. UV processing of food sensitive to lipid or protein oxidation needs to be optimized carefully to prevent an adverse effect on the sensory attributes of a product.

Main applications

So far, the technology has mainly been used for surface disinfection and for preservation of clear liquids such as water. The penetration depth of the waves in the UV-C area (200-280 nm) is limited, which is another major challenge that needs to be addressed in equipment design to make the application of UV-C more attractive for commercial food preservation. While UV is widely established as a key part in drinking water decontamination and preservation, for other, more complex food systems new promising equipment solutions are merging that needs to be further investigated and optimized to enable for sufficient energy input that allow for larger product throughput.

3.5. Cold Plasma

Plasma is considered the fourth state of matter, with the three others being liquid, solid and gas. Plasma is formed naturally as the case for Northern Light, but it can also be generated artificially either by heating a gas to very high temperatures or by applying energy to the gas e.g., by microwaves or radio frequencies. The latter is referred to as cold plasma (CP) and is the type used in the food industry as the former is incompatible with heat-sensitive materials.

Principle

The ionization of gas forms so-called reactive species from oxygen and nitrogen, and these components are known to have an impact on biological cells. The effects and the inactivation mechanisms are not fully understood, but the lethal effect could be brought about from perforation of the cell membrane and as a result of a combination of several mechanisms. Three main mechanisms have been suggested (Knorr et al., 2011): a) intrinsic photo desorption (i.e. chemical bond-breaking in microorganisms by UV photons), b) etching (i.e. plasma species induced surface material removal), and c) irradiation of genetic material. Furthermore, oxidation of cellular components and electrostatic disruption of the cell membrane have been proposed as modes of action, contributing to the efficacy of CP treatments.

Effect on microorganisms

To date, the effect of CP on the food compounds is not fully understood. The secondary structure and fragmentation of proteins are two areas that have been found to be affected by plasma. It is not until recently, that is has become possible to operate plasma at ambient pressure and low temperatures and thus, the knowledge about the application of CP on heat-sensitive materials, including food products, is still limited.

Effect on micro and macro components

The effect of CP on the food components is not fully understood. The secondary structure and fragmentation of proteins are two effects that have been found to be affected by plasma. It is not until recently that is has become possible to operate plasma at ambient pressure and low temperatures and thus, the application on heat-sensitive materials such as food is still limited.

Main applications

Food-related application of CP is mainly related to inactivation of microorganisms as little is still known on the effect of CP in food quality. The technology is still at research state for food applications and potential fields of application include enzyme inactivation on some food surfaces, food and packaging surface decontamination, decontamination of food equipment contact-surfaces, and pre- and post-harvest inactivation and plant modification. Potential advantages of CP as a non-thermal technology for food preservation include that surface treatments have little effect on the internal structure of a product, the antimicrobial effect takes place at temperatures below 70°C, the process is residue-free, and can be tailored to specific applications. However, there are also drawbacks of CP such as concurrent modes of action with varying intensity that can impede uniform treatments, the lack of established equipment manufacturers and designs, relatively high operation costs and challenging scale up to commercial scale processing, and a difficult route to approval by legal authorities for specific fields of application.

4. Conclusions

Several technologies presented in this report have been developed and keep evolving to preserve foods, enabling food products to reach consumers far away from their production site. In table 4 presents a summary of the main applications, advantages and disadvantages of the technologies described in this report.

The rising importance of sustainability and waste reduction has created demand for redesigned processes and equipment and a growing interest to explore alternatives to thermal processing. A better understanding the effect of processing technologies and their impact on physical, chemical, and structural characteristics of foods provides a strong knowledge platform to develop gentle preservation processes to produce sustainable, healthy, and high-quality products. However, nowadays there is an increasing complexity in developed foods and processes for their manufacturing, and the success is determined by trade-offs and economic feasibility.

In the report are described single unit operations, however producing food require development of processing lines where processing equipment used within them are increasingly automated to keep high production standards. Furthermore, in the context of gentle processing technologies should be mentioned the hurdle concept, that exploits synergistic interactions between preservation technologies or approaches. For example, the implementation of effective HACCP (Hazard Analysis and Critical Control Point analysis) is necessary to identify and prevent food contamination hazards during processing and avoid over-processing. It should not either be forgotten that packaging plays a vital role in preserving food throughout the distribution chain, having a considerable impact, sometimes determinant, on the shelf life of food. In addition, the environmental impact of packaging needs to be considered and shelf-life and waste are strongly related. In general, many non-thermal processes require very high intensity treatments to achieve adequate microbial destruction, however, when thermal and non-thermal preservation techniques have been combined synergistic effects on microbial inactivation and preservation of sensorial and nutritional properties have been observed.

Table 4. Summary of applications, pros, and cons for the gentle preservation technologies

	PROCESSING PARAMETERS	APPLICATIONS	PRODUCT CATEGORIES	PROS	CONS
THERMAL TECHNOLGIES					
HTST	Time, temperature	Pasteurization	Dairy, fruit and vegetable, juices and beverages, chocolate drinks, cereal grains (rice, oats, wheat), and pasta	Cost-effective, well established inactivation kinetics on pathogenic microorganisms, spoilage organisms and enzymes	Heat-induced changes of fresh product quality, e.g. flavor and color changes, potential loss of heat sensitive vitamins
ESL	Time, temperature, possibly in combination with another process (hurdle technology)	Pasteurization	Dairy, fruit and vegetables, juice and beverages, meat, seafood	Inactivation of vegetative cells and psychotropic bacteria; prolonged shelf-life compared to HTST	Heat-induced changes to fresh product quality comparable to those of HTST
UHT	Time, temperature,	Sterilization using direct (steam injection/infusion) or indirect (heat exchanger based) systems	Shelf-stable, liquid dairy products (e.g., milk and nutrition shakes), juices, and other beverages, pastes, sauces, and purees	Complete elimination of pathogenic and spoilage microorganism; long-term storage and distribution at ambient temperature enabled	Both indirect and direct systems only applicable for low-viscosity products; risk of severe heat-induced changes to fresh product quality, e.g., cooked milk flavor and color changes, loss of heat sensitive vitamins
CANNING / RETORT PROCESSING	Temperature, treatment time	Sterilization (static, forced convection or continuous type equipment)	Dairy beverage products, juices, fruits, vegetables, soups, and RTE meals for ambient temperature distribution	Long-term storage and distribution; no risk of post-production contamination provided that the container seal integrity is kept	Long cooling time required, which results in loss of heat sensitive nutrients and sensory properties
MW	Wavelength, frequency, time	Drying, thawing, tempering, pasteurization, sterilization	Pre-cooked meat, poultry, and fish, cooked vegetables, peanuts, sauces, purees, soups, paste, slurries, smoothies and drinks	Rapid heating; causes less structural changes compared to other thermal processes	Limited penetration depth, only suitable for small products; tendency to hot- and cold spots and inhomogeneous heating without optimized processing setup; relatively high energy consumption

RF	Wavelength frequency, time	Pasteurization, microbial inactivation	Dairy, meat, grains, pasta products, salmon caviar	Rapid heating; causes less structural changes compared to other thermal processes; better penetration depth than MW	Comparable to those of MW; more difficult to control and set up; less energy-consuming than MW
IR	Wavelength, exposure time	Surface pasteurization, drying, baking, blanching and sterilization	Part-baked bread and similar bakery products, meat, potatoes, grains, and vegetables	Short treatment time; successfully combined with convective air heating	Limited penetration depth, lack of processing uniformity
OHMIC HEATING	Frequency, electric voltage applied, temperature, time	Pasteurization, sterilization, blanching, extraction, baking	High-viscosity products like jam and fruit puree, particulate foods, solid food like fruit and ham	Very rapid heating; no penetration depth limit; causes less structural changes compared to other slower thermal processes, very suitable for viscous, multi-phase food matrices (including particles)	Increased energy consumption for low viscosity food, longer optimization process for uniform heating, elevated product fouling potential
NON-THERMAL TECHNOLOGIES					
HHP	Pressure, time, temperature	Pasteurization, sterilization only with added heat	Dairy, fruit and vegetable juices, meat, seafood, jams, dips, hummus	Food safety at pasteurization level with minimal effect on the fresh product quality made possible	High equipment costs, suitable for batch-and semi-continuous processing only, need refrigerated distribution and storage
HPH	Pressure, time, temperature	Homogenization, sterilization only with added heat	Low viscosity products including dairy products, juices and beverages	Continuous liquid food decontamination, structuring (homogenization or microfluidization), and extraction up to cell disintegration	High energy consumption and equipment costs; higher heat portion, resulting in more heat impact than with other nonthermal technologies
MEMBRANE FILTRATION	Trans membrane pressure, temperature, membrane pore size. membrane material	Reduction of somatic and microbial cell count, fractionation, concentration, demineralization	Beverages including juices, milk, wine, water, and beer	Low energy consumption, no chemical or structural effect on food components	Limited membrane material lifetime, substantial investment and operating costs
PEF	Electric field strength, treatment time,	Microbial- and in part enzymatic inactivation at	Microbial- and enzymatic inactivation at	High application versatility for preservation and	Must be optimized with regard to the treatment

	pulse frequency, pulse shape	pasteurization level; pre-treatment for dehydration; used for or to intensify extraction; structural modification	pasteurization level; pre-treatment for dehydration and extraction	pre-treatment purposes; gentlest of all non-thermal technologies	conditions to the product specific characteristics; loss of dissipated energy
US	Power (W), amplitude and frequency, treatment time	Pasteurization; cleaning; extraction; drying; structural modification; ultrasonication assisted by heat, pressure or both for intensification of the treatment effect	Beverages such as milk, juices, wine, and beer, sauces, meat tenderization, enzymatic inactivation in plant food, emulsification	High application versatility, relatively easy (to learn) operation; smaller investment cost and floor space requirements than for other non-thermal technologies	Must be adjusted according to product type; potential generation of off-flavors and other undesirable by-products
GAMMA	Ionizing radiation dosage (intensity of the emitting source and processing time) based on radioactive isotopes	Pasteurization, sterilization, including spore elimination up to 1.33 MeV; ripening control	Spices and other dry food, shelf-life extension of fruit and vegetables, disinfection of frozen food (e.g. meat, seafood, liquid egg, and cheese)	Considerable penetration depth suited for treatment of packaged food; allows effective preservation without compromising product quality	Needs heavy shielding; produces radioactive waste material
X-RAY	Ionizing radiation dosage (intensity of the emitting source and processing time) from electron accelarator source	Pasteurization, sterilization with energy up to 5MeV, including spore elimination; ripening control	Spices and other dry food, shelf-life extension of fruit and vegetables, disinfection of frozen food (e.g. meat, seafood, liquid egg, and cheese)	In-package treatment of food avoiding recontamination; less shielding requirements than for gamma radiation and no radioactive waste	Limited dosage delivery over greater penetration depths; high energy consumption and low efficiency; lack of consumer acceptance due to safety concerns; not established as food processing technology
E-BEAM	Ionizing radiation dosage (intensity of the emitting source and processing time) from electron accelerator soudrce	Processing hurdle as part of a hurdle technology or stand-alone up to pasteurization or sterilization level using an energy up to 10 MeV; ripening control	Spices and other dry food, shelf-life extension of fruit and vegetables, disinfection of frozen food (e.g. meat, seafood, liquid egg, and cheese)	In-package treatment of food avoiding recontamination; less shielding requirements than for gamma radiation and no radioactive waste	Limited dosage delivery over greater penetration depths, high operation costs; faces several challenges similar to those of X-ray
UV	Wavelength, voltage, gas type, steady or pulsed	Surface disinfection, decontamination of drinking water and transparent liquid food	Beverages, ideally, with a high transparency (e.g. drinking water, juices, white wine, tea),	Negligible effect on food components; no effect on sensory properties	Risk of surface damage (oxidation, colour, and flavor changes) to some food types, challenges related to equipment

			surface treatment of fruit and vegetables, dairy products, and bakery products		design and other factors need to be addressed prior to commercial application in food preservation
COLD PLASMA	Reactive species (generation of free radicals, free electrons, UV photons, electric field formation, thermal radiation, acoustic and pressure waves)	Mainly inactivation of microorganisms and enzymes on surfaces, food packaging decontamination	Lettuce and other vegetables, fruit, meat and poultry	High effect at sub-pasteurization temperatures; plasma type customizable to specific applications, surface treatment without little impact on the food matrix below the surface	Implementation of the technology still faces several challenges, e.g., regarding modes of action and their control, equipment establishment and design, possible formation of undesired by-products

(adapted from The Institute of Food Technologists (IFT) Organization).

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