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EMERGING AND CONVENTIONAL PHYSICAL PROCESSES IN THE PRESERVATION OF ARTISANAL NATURAL JUICES

PROCESSOS FÍSICOS EMERGENTES E CONVENCIONAIS NA CONSERVAÇÃO DE SUCOS NATURAIS ARTESANAIS

PROCESOS FÍSICOS EMERGENTES Y CONVENCIONALES EN LA CONSERVACIÓN DE JUGOS NATURALES ARTESANALES

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ABSTRACT
Physical preservation methods play a fundamental role in reducing microbial load and extending the shelf life of artisanal natural juices, balancing microbiological safety with the preservation of the product's sensory and nutritional characteristics. These methods operate through mechanisms of microbial inactivation or inhibition without the direct addition of chemical substances, which makes them particularly attractive in the context of artisanal production, where the perception of naturalness is highly valued by consumers. Among conventional physical processes, thermal pasteurization remains the reference technology due to its high effectiveness in inactivating pathogenic and spoilage microorganisms, although it may cause nutritional losses and sensory changes when improperly applied. Low-temperature preservation methods, such as refrigeration and freezing, act mainly in an inhibitory manner, reducing microbial metabolic activity and slowing chemical and enzymatic reactions, and are more effective when combined with other technological barriers. Emerging non-thermal technologies, such as UV-C radiation, membrane filtration, high hydrostatic pressure, pulsed electric fields, and high-pressure homogenization, have been widely studied for their ability to reduce microbial load with less impact on thermosensitive compounds and sensory attributes. However, the effectiveness of these methods is strongly dependent on juice characteristics, operational conditions, and the resistance of the microorganisms

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present. These approaches allow the optimization of microbiological efficiency, the minimization of adverse effects on product quality, and the technical feasibility of preserving artisanal natural juices.

Keywords: Artisanal Juices. Juice Preservation. Non-Thermal Technologies. Physical Methods. Microbial Load Reduction.

RESUMO

Os métodos físicos de conservação desempenham papel fundamental na redução da carga microbiana e na extensão da vida útil de sucos naturais artesanais, conciliando segurança microbiológica e preservação das características sensoriais e nutricionais do produto. Esses métodos atuam por mecanismos de inativação ou inibição microbiana, sem a adição direta de substâncias químicas, o que os torna atrativos no contexto da produção artesanal, onde a percepção de naturalidade é valorizada pelo consumidor. Entre os processos físicos convencionais, a pasteurização térmica permanece como a tecnologia de referência, devido à sua elevada eficácia na inativação de microrganismos patogênicos e deteriorantes, embora possa ocasionar perdas nutricionais e alterações sensoriais quando aplicada de forma inadequada. Métodos de conservação por baixa temperatura, como refrigeração e congelamento, atuam de forma inibitória, reduzindo a atividade metabólica microbiana e retardando reações químicas e enzimáticas, sendo mais eficazes quando associados a outras barreiras tecnológicas. Tecnologias não térmicas emergentes, como radiação UV-C, filtração por membranas, alta pressão hidrostática, campos elétricos pulsados e homogeneização sob alta pressão, têm sido amplamente estudadas por sua capacidade de reduzir a carga microbiana com menor impacto sobre compostos termossensíveis e atributos sensoriais. No entanto, a eficácia desses métodos é fortemente dependente das características do suco, das condições operacionais e da resistência dos microrganismos presentes. Essas abordagens permitem otimizar a eficiência microbiológica, minimizar efeitos adversos sobre a qualidade do produto e viabilizar tecnicamente a conservação de sucos naturais artesanais.

Palavras-chave: Sucos Artesanais. Conservação de Sucos. Tecnologias Não Térmicas. Métodos Físicos. Redução de Carga Microbiana.

RESUMEN

Los métodos físicos de conservación desempeñan un papel fundamental en la reducción de la carga microbiana y en la extensión de la vida útil de los jugos naturales artesanales, conciliando la seguridad microbiológica con la preservación de las características sensoriales y nutricionales del producto. Estos métodos actúan mediante mecanismos de inactivación o inhibición microbiana, sin la adición directa de sustancias químicas, lo que los hace atractivos en el contexto de la producción artesanal, donde la percepción de naturalidad es valorada por el consumidor. Entre los procesos físicos convencionales, la pasteurización térmica sigue siendo la tecnología de referencia debido a su alta eficacia en la inactivación de microorganismos patógenos y alterantes, aunque puede ocasionar pérdidas nutricionales y cambios sensoriales cuando se aplica de forma inadecuada. Los métodos de conservación por baja temperatura, como la refrigeración y la congelación, actúan de manera inhibitoria al reducir la actividad metabólica microbiana y retardar las reacciones químicas y enzimáticas, siendo más eficaces cuando se asocian con otras barreras tecnológicas. Las tecnologías no térmicas emergentes, como la radiación UV-C, la filtración por membranas, la alta presión hidrostática, los campos eléctricos pulsados y la homogeneización a alta presión, han sido ampliamente estudiadas por su capacidad para reducir la carga microbiana con menor impacto sobre los compuestos termosensibles y los atributos sensoriales. Sin embargo, la eficacia de estos métodos depende en gran medida de las características del jugo, de las condiciones operativas y de la resistencia de los microorganismos presentes. Estos enfoques permiten optimizar la eficiencia microbiológica, minimizar los efectos adversos sobre la calidad del producto y viabilizar técnicamente la conservación de jugos naturales artesanales.

Palabras clave: Jugos Artesanales. Conservación de Jugos. Tecnologías No Térmicas. Métodos Físicos. Reducción de la Carga Microbiana.

1 INTRODUCTION

The consumption of artisanal natural juices has grown consistently in recent decades, driven by the appreciation of minimally processed foods, associated with naturalness, freshness and high nutritional value. This movement reflects changes in consumer behavior, which starts to demand products perceived as healthier and with a lower degree of industrialization. However, this same characteristic gives artisanal juices greater microbiological vulnerability, since such products, in general, are not subjected to intensive conservation processes and have high water activity and nutrient availability, conditions that are highly favorable to microbial development (Franco; Landgraf, 2008).

From a microbiological point of view, natural juices are complex matrices that are susceptible to contamination by pathogenic and spoilage microorganisms, capable of compromising both food safety and the sensory quality and stability of the product. Contamination can occur at different stages of the production chain, including harvesting and handling of raw materials, processing, storage, and packaging. Bacteria, yeasts and molds, when present, can promote undesirable fermentations, physicochemical alterations and significant reduction of shelf life, reinforcing the need for effective technological strategies for the microbiological control of these products (Beuchat, 2002).

Historically, thermal pasteurization has been consolidated as the main physical method used in the preservation of juices, due to its high efficiency in the inactivation of pathogenic and spoilage microorganisms. This process has become a technological reference both in industrial systems and in scientific studies, due to its reliability and wide regulatory acceptance. However, the application of more severe heat treatments can lead to adverse effects on the quality of juices, such as degradation of thermosensitive vitamins, color modifications and loss of volatile compounds responsible for aroma, aspects that are particularly relevant for artisanal products, whose acceptance is strongly associated with the perception of freshness and sensory quality (Cheftel, 1995).

In view of these limitations, there is a growing interest in the development and application of alternative or complementary physical methods to conventional thermal pasteurization. These methods seek to ensure the reduction of the microbial load with less impact on the nutritional and sensory attributes of the juices, meeting the requirements of food safety and the expectations of the consumer market. In this context, low-temperature conservation technologies, such as refrigeration and freezing, have been widely used as strategies to inhibit microbial growth, acting to reduce the metabolic activity of microorganisms and to delay chemical and enzymatic reactions associated with spoilage.

In addition to temperature-based methods, several emerging non-thermal physical technologies have been the subject of intense scientific investigation. Processes such as membrane filtration, UV-C radiation, high hydrostatic pressure, pulsed electric fields, and homogenization under high pressure stand out for their potential to promote the reduction of the microbial load by specific physical mechanisms, such as structural damage to microbial cells, changes in membrane permeability, or physical removal of microorganisms. These technologies have the advantage of preserving, to a greater extent, thermosensitive compounds and sensory attributes of natural juices (San Martin *et al*., 2002).

However, the effectiveness of physical preservation methods is strongly dependent on several factors, including the intrinsic characteristics of the juice, such as pH, turbidity and composition, as well as the operating conditions of each process and the resistance of the microorganisms present. More resistant microorganisms, such as bacterial spores, may not be completely inactivated by certain physical methods when applied in isolation, which highlights the need for careful selection and optimization of the technologies employed. Thus, the understanding of the mechanisms of action, limitations and potential of each physical method becomes essential for its efficient application in artisanal production systems.

Thus, this chapter aims to discuss in depth the main physical methods used to reduce the microbiological load of artisanal natural juices, addressing their fundamentals, mechanisms of action, advantages, limitations and technological applicability. By focusing exclusively on the physical processes of conservation, it seeks to provide technical and scientific subsidies that contribute to the development of processing strategies capable of reconciling microbiological safety, preservation of sensory quality and technological feasibility, strengthening the production of safe artisanal juices in line with contemporary market demands.

2 PHYSICAL PROCESSES RELATED TO THE REDUCTION OF THE MICROBIAL LOAD IN JUICES

2.1 PASTEURIZATION

Thermal pasteurization is widely recognized as one of the main physical methods for reducing the microbiological load in natural juices, being used as a reference technology both in scientific studies and in commercial and artisanal production systems (Rezzadori, 2010). The process consists of the controlled application of heat, for a defined time and temperature, with the objective of inactivating pathogenic and spoilage microorganisms, ensuring the microbiological safety of the product without promoting its complete sterilization (Gomes, 2006).

Fruit juices are matrices that are highly susceptible to microbiological contamination due to their high water content, nutrient availability and, frequently, acidic pH. These characteristics favor microbial growth, but also increase the effectiveness of heat treatment, since microorganisms present in acidic media have less resistance to heat. Thus, pasteurization can be conducted with relatively short times and moderate temperatures, when compared to low-acid foods (Rezzadori, 2010).

The mechanism of microbial inactivation promoted by thermal pasteurization involves the denaturation of structural and enzymatic proteins, the alteration of the permeability of cell membranes and the interruption of metabolic processes essential to the survival of microorganisms. These effects make heat treatment particularly effective in reducing pathogenic and spoilage bacteria associated with juices, being widely used as a fundamental processing step (Gouvea, 2022).

Experimental studies show the efficiency of thermal pasteurization in reducing the microbiological load of vegetable beverages. In research conducted with sugarcane juice added to passion fruit juice, the application of heat treatments between 90 and 95 °C for short periods resulted in significant reductions in indicator microorganisms, ensuring the microbiological conformity of the product and greater stability during cold storage (Rezzadori, 2010). Similar results are reported in studies with orange juice, in which pasteurization was used as an essential step to ensure the microbiological quality of the product before complementary processes, such as ultrafiltration (Gomes, 2006).

In addition to microbiological safety, thermal pasteurization has a direct influence on the physicochemical stability of juices during storage. Evaluations carried out with previously pasteurized whole orange juice and kept refrigerated showed that parameters such as pH, total soluble solids, and titratable acidity remain relatively stable over time, indicating that heat treatment contributes to maintaining product quality after processing (Sousa, 2022). These results reinforce the importance of pasteurization as an initial step for the control of microbiological and physicochemical deterioration.

However, the application of heat is also associated with limitations related to the nutritional and sensory quality of juices. Thermosensitive compounds, such as vitamin C, can suffer degradation due to the intensity of the heat treatment, in addition to the possibility of changes in color, aroma, and flavor resulting from chemical reactions induced by heating (Gouvea, 2022). These aspects are particularly relevant in the context of artisanal natural juices, whose consumer acceptance is strongly associated with the perception of freshness.

In view of these limitations, it is essential to optimize pasteurization conditions, seeking a balance between microbiological efficacy and the preservation of product quality. Strategies such as the use of *high temperature short time* (HTST) processes have been widely employed with the aim of maximizing microbial inactivation while minimizing the deleterious effects of heat (Rezzadori, 2010; Gomes, 2006). In addition, thermal pasteurization can be associated with other technologies, such as refrigeration, filtration, and membrane processes, composing approaches based on the concept of barrier technology (Sousa, 2022).

Even with the advancement of non-thermal technologies, such as high hydrostatic pressure, thermal pasteurization continues to be widely used as a reference method in comparative studies of microbiological safety. Research evaluating emerging technologies often uses pasteurization as a base parameter, due to its proven efficacy, wide regulatory acceptance, and consolidated history of application in juices (Gouvea, 2022). Thus, especially in artisanal production systems, thermal pasteurization remains a technically robust, accessible and validated strategy for reducing the microbiological load in natural juices.

2.2 FILTRATION

Filtration is a physical method widely used in juice processing, being used both for clarification and for the reduction of the microbiological load, through the physical removal of particles, microorganisms and suspended components. Unlike thermal methods, filtration acts without the application of heat, which makes it an attractive alternative for the preservation of the sensory and nutritional characteristics of natural juices (Cheryan, 1998).

In the context of juice processing, filtration can be performed through different membrane technologies, such as microfiltration and ultrafiltration, whose efficiency is directly related to the pore size of the membrane, the pressure applied, and the characteristics of the food matrix (Borges, 2006). These technologies allow the retention of microorganisms, plant cells and colloidal particles, promoting the improvement of the microbiological and physicochemical stability of the product (Habert et al., 2006).

Microfiltration has been highlighted as an efficient technology for the removal of bacteria, yeasts and molds in juices, acting as a physical barrier that prevents the passage of these microorganisms to the final product (Nóbrega, 2006). Studies report that the application of microfiltration processes in citrus juices results in significant reductions in the microbial load, contributing to the increase of the shelf life of the product, especially when associated with other conservation stages (Cheryan, 1998).

Ultrafiltration, in turn, has an additional capacity to retain macromolecules, proteins and polysaccharides, and is widely used for the clarification of juices and to improve their physical stability. Although the main focus of ultrafiltration is not the complete elimination of microorganisms, this process indirectly contributes to the reduction of the microbiological load, by removing particles to which microorganisms may be attached (Gomes, 2006).

Despite its benefits, filtration has important limitations in terms of microbiological safety. As it is a non-lethal method, microorganisms of smaller size or capable of crossing the pores of the membrane can remain in the final product. In addition, operational failures, such as inadequate membrane integrity or biofilm formation, can compromise process efficiency (Habert et al., 2006).

From the point of view of sensory and nutritional quality, filtration has advantages over heat treatments, since it minimizes the degradation of thermosensitive compounds, such as vitamin C and volatile aromatic compounds. However, excessive removal of solids can result in undesirable changes in the color, body and turbidity of the juice, aspects that must be carefully evaluated, especially in artisanal natural juices, in which the presence of pulp is often associated with the naturalness of the product (Ordóñez et al., 2005).

Due to these limitations, filtration is often employed as part of combined conservation strategies, integrating the concept of barrier technology. The association of filtration with refrigeration, light thermal pasteurization or other conservation methods contributes to extending the shelf life and improving the microbiological safety of juices, without excessively compromising their sensory characteristics (Leistner, 2000).

In artisanal production systems, the application of filtration can represent a viable alternative for improving the microbiological quality and stability of juices, as long as strict criteria of hygiene, equipment maintenance and operational control are respected. Thus, filtration is a relevant complementary technology for the reduction of the microbiological load in natural juices, especially when integrated with other technological barriers along the production chain.

2.3 UV-C RADIATION

Ultraviolet radiation in the C range (UV-C), between 200 and 280 nm, has been widely studied as a non-thermal technology for reducing the microbiological load in liquid foods, including fruit juices. Its mechanism of action is mainly based on the absorption of radiation by the nucleic acids of microorganisms, resulting in the formation of thymine dimers in DNA, which compromises cell replication and leads to microbial inactivation (Koutchma et al., 2009).

Unlike conventional heat treatments, UV-C radiation does not promote significant heating of the product, and is considered a promising alternative for the preservation of the sensory and nutritional characteristics of natural juices (Barbosa-Cánovas, 2004). This characteristic is particularly relevant for artisanal juices, whose acceptance by the consumer is strongly associated with the perception of freshness and naturalness (Guerrero-Beltrán et al., 2004).

Experimental studies demonstrate that the application of UV-C can result in significant reductions of the microbial population in juices, especially of vegetative bacteria, yeasts and molds. In an evaluation of the effectiveness of UV-C radiation in passion fruit juice, it was observed that the increase in the radiation dose promoted progressive reductions in the microbial load, evidencing the direct relationship between radiation intensity and process efficiency (Gouveia, 2022). These results confirm the potential of the technology as a method of microbiological control in acidic beverages.

The efficiency of UV-C radiation, however, is strongly influenced by the optical characteristics of the juice, such as turbidity, color, and suspended solids content. Juices with high turbidity or high pulp content have greater absorption and dispersion of radiation, reducing the penetration of UV light and, consequently, the effectiveness of the microbial inactivation process (Koutchma et al., 2009). This technical limitation represents a major challenge for the application of the technology in unclarified natural juices.

From the microbiological point of view, although UV-C radiation is effective against vegetative microorganisms, its efficiency against more resistant forms, such as bacterial spores, is limited (Rodrigues, 2007). In addition, some microorganisms may exhibit DNA repair mechanisms after exposure to radiation, especially when the product is subsequently exposed to visible light, which reinforces the need for strict control of processing conditions.

Regarding product quality, several studies indicate that UV-C radiation promotes fewer changes in physicochemical and nutritional parameters when compared to heat treatments. Thermosensitive compounds, such as vitamin C, tend to be better preserved, as long as the doses applied are adequately controlled (Guerrero-Beltrán et al., 2004). However, excessive doses can induce undesirable photochemical reactions, resulting in color and aroma changes.

Due to these limitations, UV-C radiation is often proposed as part of combined conservation strategies, integrating the concept of barrier technology. The association of UV-C radiation with refrigeration, filtration or light heat treatments can increase microbiological efficacy and reduce the risks associated with microbial survival (Leistner, 2000). This approach is particularly interesting for artisanal production systems, in which the aim is to balance microbiological safety and preservation of sensory quality.

Thus, UV-C radiation is a promising non-thermal technology for reducing the microbiological load in artisanal natural juices. However, its isolated application has technical and microbiological limitations, and its integration with other conservation strategies is essential to ensure the safety and quality of the final product.

2.4 HIGH HYDROSTATIC PRESSURE (HPP)

High Pressure Processing (HPP) is an emerging non-thermal technology widely studied for the preservation of liquid foods, including fruit juices, with emphasis on its high efficacy in reducing the microbiological load associated with minimal alteration of the sensory and nutritional characteristics of the product (Swanson et al., 2002). The process consists of applying high pressures, usually between 100 and 600 MPa, in a uniform and isotropic manner, using a transmitting fluid, usually water (Hugo et al., 2001).

The main mechanism of microbial inactivation promoted by PPH is associated with structural and functional changes in microbial cells, including cell membrane disorganization, protein denaturation, enzyme inactivation, and impairment of essential metabolic processes. Unlike heat treatments, HPP does not break low molecular weight covalent bonds, which contributes to the preservation of heat-sensitive sensory and nutritional compounds (Cheftel, 1995).

Several studies have shown that HPP is effective in inactivating pathogenic and spoilage vegetative microorganisms in juices, including bacteria such as *Escherichia coli*, *Salmonella spp.* and *Listeria monocytogenes*, as well as yeasts and molds. Experimental evaluations indicate that pressures above 400 MPa, applied for a few minutes, are capable of promoting significant reductions in the microbial load in acidic juices, meeting the microbiological safety criteria (San Martin *et al*., 2002)

The effectiveness of HPP is directly related to factors such as pressure level, application time, process temperature, and intrinsic characteristics of the food, including pH, composition, and water activity. Juices with an acidic pH have a greater susceptibility to the action of pressure, allowing the use of less severe conditions to achieve adequate levels of microbial inactivation (Gouvea, 2022). These aspects make the technology particularly promising for natural and artisanal juices, which are generally characterized by high acidity.

From the point of view of nutritional quality, HPP has significant advantages over thermal pasteurization. Studies indicate greater retention of vitamin C, phenolic compounds and natural pigments in juices processed by high pressure, compared to conventional heat treatments (Torres et al., 2005). In addition, sensory changes are generally less pronounced, contributing to greater consumer acceptance of the product.

However, PPH has important limitations regarding the inactivation of bacterial spores, which demonstrate high resistance to pressure when applied alone. Thus, the technology may require association with other factors, such as slight heating, acidic pH, or cold storage, to ensure greater microbiological stability (Hoover; Mertens, 1998). This need reinforces the application of HPP within the concept of barrier technology.

In studies focused on the physical stability of juices submitted to high-pressure processes, it was observed that HPP can influence parameters such as turbidity, sedimentation and colloidal stability, due to structural changes in macromolecules and suspended particles. Evaluations conducted with cashew juice have indicated that high-pressure treatments can improve the physical stability of the product by reducing phase separation during storage (Velázquez, 2005).

Despite its technological advantages, the application of HPP in artisanal production systems is still limited by factors such as high investment cost, the need for specialized equipment, and greater operational complexity. However, studies on consumer risk perception indicate that high-pressure processed products tend to be associated with greater microbiological safety and better quality preservation, when compared to traditional thermal methods (Gouvea, 2022).

Thus, High Hydrostatic Pressure is a highly effective non-thermal technology for reducing the microbiological load in natural juices, presenting relevant advantages in terms of sensory and nutritional quality. However, its isolated use has technical and economic limitations, being more appropriate when integrated with combined conservation strategies, especially in the context of artisanal productions that seek innovation combined with food security.

2.5 PULSED ELECTRIC FIELDS (PEF)

Pulsed Electric Fields (PEF) are an emerging non-thermal technology widely researched for the preservation of liquid foods, including fruit juices, due to their ability to promote microbial inactivation with minimal impact on the sensory and nutritional properties of the product. The method is based on the application of high-intensity electrical pulses, usually between 10 and 80 kV/cm, for very short periods, on the order of microseconds, through the food positioned between two electrodes (Rivas *et al*., 2012).

The main mechanism of action of pulsed electric fields is associated with the phenomenon of electroporation of cell membranes. The application of the electric field induces the formation of hydrophilic pores in the plasma membrane of microorganisms, resulting in increased cell permeability, loss of osmotic equilibrium and, in more severe cases, irreversible cell death (Zimmermann, 1986). The intensity of cell damage depends on the magnitude of the electric field, the number of pulses applied, and the characteristics of the microorganism.

Several studies report that PEF is effective in inactivating vegetative bacteria, yeasts, and molds present in juices, especially when applied to acidic products. Pathogenic microorganisms such as *Escherichia coli* and *Salmonella spp.* demonstrate high sensitivity to PEF treatment, allowing significant reductions in the microbial load without the need for significant heating (Wouters *et al*., 2001). These results reinforce the potential of the method for application in natural artisanal juices.

The efficiency of PEF is influenced by intrinsic factors of the food, such as pH, electrical conductivity, composition, and the presence of suspended solids. Juices with higher electrical conductivity favor the homogeneous distribution of the electric field, increasing the efficiency of the process. On the other hand, the presence of solid particles can cause electrical shading, reducing the uniformity of the treatment (Alrunakar, 2005).

From the point of view of nutritional quality, PEF has relevant advantages over conventional heat treatments. Studies indicate greater retention of vitamins, phenolic compounds and natural pigments in juices treated with PEF, since the process does not involve high temperatures capable of promoting significant thermal degradation (Rivas *et al*., 2012). In addition, sensory changes, such as changes in flavor and aroma, tend to be less pronounced when compared to thermal pasteurization.

However, PEF has important limitations regarding the inactivation of bacterial spores and resistant enzymes. Spores demonstrate high resistance to pulsed electric fields when applied alone, requiring association with other factors, such as moderate heating, acidic pH, or refrigeration, to ensure greater microbiological stability of the product (Hoover; Mertens, 1998*).* This characteristic reinforces the framing of the PEF within the concept of barrier technology.

In the context of industrial and artisanal application, PEF has been proposed as an alternative or complement to thermal pasteurization for refrigerated juices, allowing the extension of shelf life with less sensory impact. However, its adoption in artisanal production systems is still limited by factors such as equipment cost, the need for strict control of operational parameters, and greater technological complexity (Gouvea, 2022). Despite this, the technology has high potential for future applications in niche markets that value minimally processed foods.

Thus, Pulsed Electric Fields are a promising non-thermal technology for reducing the microbiological load in artisanal natural juices, standing out for its effectiveness against vegetative microorganisms and for preserving the quality of the product. However, its isolated use does not ensure complete microbiological safety, and its integration with other conservation strategies along the production chain is recommended.

2.6 HOMOGENIZATION UNDER HIGH PRESSURE

High Pressure Homogenization (HPH) is a physical technology widely employed in liquid food processing, characterized by subjecting the product to high pressures, usually between 50 and 300 MPa, followed by its forced passage through valves or small diameter orifices. This process results in the simultaneous application of shear, cavitation, impact and intense turbulence forces, promoting structural modifications in the feed matrix (Hayes; Kelly, 2003).

In the context of reducing the microbiological load, HPH acts through physical damage to microbial cells, especially cell membranes, leading to loss of structural and functional integrity. The combination of high mechanical stresses and pressure gradients can cause partial or total cell lysis, resulting in a decrease in the viability of bacteria, yeasts and molds present in juices (Datta, 1999).

Studies indicate that the microbiological effectiveness of homogenization under high pressure depends directly on the operating conditions of the process, including pressure level, number of cycles, product inlet temperature, and intrinsic characteristics of the juice, such as pH and composition. Acidic juices tend to be more susceptible to the action of HPH, allowing for greater microbial reduction under less severe conditions (Patrignani *et al*., 2010).

Although HPH promotes significant reductions in vegetative microorganisms, its efficiency against more resistant microorganisms, such as bacterial spores, is limited. Thus, the technology should not be considered a sterilization method, but rather a complementary tool in the microbiological control of natural juices (Wouters *et al*., 2001). This aspect reinforces the importance of associating HPH with other technological barriers.

In addition to the microbiological effects, homogenization under high pressure exerts a significant influence on the physical and colloidal stability of the juices. The reduction in particle size and homogeneous redistribution of the pulp contribute to the reduction of sedimentation and phase separation during storage. In a study conducted with cashew juice, it was observed that the application of ultra-high pressure homogenization resulted in greater physical stability of the product, improving its appearance and sensory acceptability (Deeth, 1999).

From a nutritional point of view, HPH has advantages when compared to conventional heat treatments, since it does not involve the direct application of heat for long periods. This contributes to the preservation of thermosensitive compounds, such as vitamin C and phenolic compounds, as long as the temperature increase resulting from the process is adequately controlled (Ordóñez *et al*., 2005). However, excessive temperature rises during homogenization can compromise this advantage.

In artisanal production systems, homogenization under high pressure can be employed as a strategy to improve physicochemical stability and reduce the initial microbiological load of juices, as long as it is associated with good manufacturing practices and additional conservation methods, such as refrigeration or light pasteurization. This integrated approach is in line with the concept of barrier technology, which is widely used in the preservation of liquid foods (Leistner, 2000).

Thus, homogenization under high pressure is a promising technology in the processing of artisanal natural juices, contributing both to the improvement of physical stability and to the reduction of the microbiological load. However, its isolated application has limitations, and its integration with other technological strategies is recommended to ensure microbiological safety and quality of the final product.

2.7 FREEZING

Freezing is a physical method widely used in the preservation of liquid foods, including natural juices and fruit pulps, acting mainly to reduce microbial activity and slow down the chemical, biochemical and enzymatic reactions associated with product deterioration. This method is characterized by its predominantly inhibitory effect, since it does not promote the complete elimination of microorganisms, but drastically reduces their metabolic activity during the storage period (Jay, 2005).

The reduction of the temperature below the freezing point results in the formation of ice crystals in the food matrix, causing a decrease in the activity of water available to the microorganisms (Landgraf, 2008). Water activity is one of the main limiting factors of microbial growth, and its reduction compromises essential physiological processes, such as solute transport, nutrient diffusion, and intracellular enzymatic activity (Franco, 2008). In natural juices, which have a high content of water and nutrients, this mechanism plays a fundamental role in controlling microbiological deterioration.

In addition to limiting water activity, freezing can cause physical damage to microbial cells due to the formation and growth of ice crystals (Ordóñez *et al*., 2005). These crystals can cause disruption of cell membranes, protein denaturation, and changes in cell permeability, resulting in reduced viability of part of the microbiota present. Such effects are more pronounced when successive cycles of freezing and thawing occur (Evangelista, 2008).

Despite these effects, several microorganisms have high resistance to low temperatures. Pathogenic bacteria, yeasts, and molds can survive for long periods under freezing, resuming their metabolic activity after thawing the product (Jay, 2005). Psychrotrophic and psychrotolerant microorganisms, in particular, have a greater capacity to adapt to the heat stress imposed by freezing, which reinforces the non-lethal character of this method (Fellows, 2006).

From the point of view of physicochemical and nutritional quality, freezing has significant advantages when compared to refrigeration and storage at room temperature. Maintaining very low temperatures substantially reduces the speed of oxidative and enzymatic reactions, contributing to the preservation of thermosensitive compounds, such as vitamin C, carotenoids and phenolic compounds (Ordóñez *et al.*, 2005). However, changes in the physical stability of the juice can be observed after thawing, such as phase separation and solids sedimentation.

The freezing efficiency is directly related to the operating conditions of the process. Rapid freezes tend to form smaller and more homogeneous ice crystals, causing less structural damage to the food matrix and the sensory components of the juice. In contrast, slow freezes favor the formation of larger crystals, which can intensify cell damage and compromise the quality of the product after thawing (Evangelista, 2008).

In artisanal production systems, freezing is often used as a conservation strategy to extend the shelf life of juices and pulps, enabling seasonal storage and subsequent commercialization (Landgraf, 2008). However, due to microbial survival during freezing, it is recommended that this technology be associated with other control measures, such as strict cleaning of raw materials, the application of good manufacturing practices and, when possible, the use of prior heat treatments. This integrated approach is in line with the concept of barrier technology, widely adopted in food preservation (Leistner, 2000).

Thus, freezing is a relevant tool for the conservation of artisanal natural juices, contributing to the maintenance of nutritional quality and to the extension of the shelf life of the product. However, its isolated use does not guarantee microbiological safety, and its integration with other technological strategies along the production chain is indispensable.

2.8 REFRIGERATION

After the production and packaging of juices, refrigeration is widely used as a physical method of preserving natural juices, acting mainly in the inhibition of microbial growth and in reducing the speed of chemical, enzymatic and biochemical reactions responsible for the deterioration of the product. Unlike lethal processes, refrigeration does not promote the destruction of the microorganisms present, but directly interferes with their metabolism, extending the shelf life of the juices when applied properly (Jay, 2005).

Artisanal natural juices are highly perishable matrices, due to their high water content, nutrient availability and the absence of chemical preservatives or severe heat treatments. Under these conditions, the control of the storage temperature becomes a critical factor for the maintenance of microbiological quality. The reduction in temperature causes a decrease in microbial metabolic activity, affecting protein synthesis, the fluidity of cell membranes, and enzymatic activity, which results in the slowing of microbial growth (Fellows, 2006).

Studies indicate that cold storage contributes significantly to the maintenance of the microbiological quality of juices, especially when associated with good manufacturing practices and adequate pre-processing. Stability evaluations of refrigerated juices demonstrate that maintaining the cold chain reduces the speed of microbiological and physicochemical deterioration, slowing down the growth of bacteria, yeasts and molds (Evangelista, 2008).

Despite these benefits, the efficiency of refrigeration as a method of microbiological control has important limitations. Psychrotrophic and psychrotolerant microorganisms are able to survive and, in some cases, multiply at refrigeration temperatures, compromising product safety throughout storage. Among these microorganisms, *Listeria monocytogenes* stands out, whose ability to grow at low temperatures represents a relevant risk for refrigerated products, including natural juices (Franco; Landgraf, 2008).

From the point of view of physicochemical and nutritional quality, refrigeration has advantages over storage at room temperature, since it contributes to the preservation of sensitive compounds, such as vitamin C, and to the maintenance of parameters such as pH, titratable acidity and total soluble solids. However, even under refrigeration, oxidative and enzymatic processes continue to occur, albeit at a lower intensity, which may result in gradual losses of sensory quality over time (Ordóñez *et al*., 2005).

Due to its predominantly inhibitory character, refrigeration is more effective when integrated with combined conservation strategies, according to the concept of barrier technology. The association of refrigeration with light heat treatments, filtration, adequate hygiene of raw materials and strict control of processing conditions contributes to extending the shelf life and improving the microbiological safety of artisanal natural juices (Leistner, 2000).

Thus, although refrigeration alone is not enough to guarantee the microbiological safety of natural juices, its role as a complementary step in the conservation of these products is fundamental. When correctly applied and integrated with other technological barriers, refrigeration contributes significantly to the maintenance of the microbiological, physicochemical and sensory quality of artisanal juices, being an indispensable strategy in the production chain of these foods.

3 FINAL CONSIDERATIONS

The physical preservation processes have been shown to be effective in reducing the microbiological load and ensuring the safety of artisanal natural juices, constituting the technological basis for maintaining the quality and stability of these products. Thermal pasteurization remains a consolidated method with high microbiological reliability, as long as it is applied in an optimized way, while refrigeration and freezing play an essential complementary role in inhibiting microbial growth and delaying deterioration reactions. Emerging non-thermal physical technologies, such as membrane filtration, UV-C radiation, high hydrostatic pressure, pulsed electric fields, and high-pressure homogenization, significantly expand the possibilities of conservation by allowing significant reductions in microbial load with less impairment of sensory and nutritional attributes. However, the effectiveness of these processes is directly conditioned by the characteristics of the juice, the operating conditions and the resistance of the microorganisms, which makes the adoption of any technology alone inadequate.

Thus, the integrated and rational application of physical methods, based on the knowledge of their mechanisms and limitations, is the most efficient and technically feasible strategy to ensure the production of safe, stable artisanal natural juices in line with the current requirements of quality, food safety and appreciation of naturalness.

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