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Review

Effects of High-Pressure Processing (HPP) on Antioxidant Vitamins (A, C, and E) and Antioxidant Activity in Fruit and Vegetable Preparations: A Review

Concepción Pérez-Lamela [1,2,*] and Ana María Torrado-Agrasar [1,2]

[1] TEZE Research Group, Nutrition and Bromatology Area, Analytical Chemistry and Food Department, Faculty of Sciences, Campus of Ourense, University of Vigo, 32004 Ourense, Spain; agrasar@uvigo.gal
[2] Instituto de Agroecoloxía e Alimentación (IAA), Campus Auga, University of Vigo, 32004 Ourense, Spain
* Correspondence: conchipl@uvigo.gal; Tel.: +34-988387091

Abstract

This work has reviewed the recently published literature (last 8 years) about the effects caused by HPP on the antioxidant properties (A, C, and E vitamins and antioxidant activity) of F&V (fruits and vegetables) preparations in comparison to thermal treatments (TP). The methodology of this revision was performed mainly by using keywords related to HPP, F&V, and antioxidant compounds in the Scopus database. High-pressure technology was briefly described, considering its principles and historical milestones, and justifying that it can be applied as a green and sustainable preservation method (with pros and cons). It is also relevant for the present food market due to their growing tendency in F&V derivatives (especially juices). The main effects on vitamins and antioxidant compounds point to it as an emerging preservation method to maintain and avoid vitamin and bioactive substances loss in comparison with pasteurization by heat. Maximum efficiency, cost-effectiveness, and quality improvement are aspects to be improved in the future by HPP technologies.

Keywords: high-pressure processing (HPP); antioxidant vitamins; ascorbic acid; carotenoids; tocopherol; antioxidant capacity; polyphenols; fruits and vegetables preparations

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1. A Brief History of Pressurization Technology

It can be said that the generation of high pressure for industrial purposes was almost exclusively linked to the military industry in the 18th century, until the first studies on the compressibility of water were carried out by Perkins in the early 19th century. At the end of the 19th century, the first research on the design of high-pressure equipment was carried out, and methods for measuring high-pressure values were developed by Cailletet and Amagat [1].

The first use of this technology in food was performed by Hite at the end of the 19th century, who designed his own pressurization equipment and applied high pressure (up to 670 MPa) to milk, demonstrating its preservation by the inactivation of microorganisms [2].

Engineering aspects of HPP were investigated in the early 20th century (1909–1959) [3]. In this period, Bridgman, awarded the Nobel prize, contributed with his work towards the development of equipment able to produce high pressures. But the implementation of this technique at the industrial food level was performed in the 90s by two Japanese companies. They applied HPP to fruits: one of them, Meidi-ya Corp. (founded in 1990), used it to obtain jams from strawberry, apple, and kiwi; the other, Pokka Corp. (1991), used it to produce grapefruit juice.

HPP technology has also been quoted as being one of the best innovations in food processing since 1990 [4]. In the last 3 decades, commercial products obtained by HPP are being increased year by year, especially the ones made with vegetable and/or fruits: beverages, nectars, juices [5], smoothies [6], plant-based milks [7], jellies, jams, fruit desserts, purées, sauces, creams, soups, etc. that had a quarter of the market share for pressurized foods 7 years ago [8] and still being high nowadays. This sector has experienced great growth due to the variety of fruit and vegetable preparations developed in recent times, and considering that this sector is still very relevant in the food market [9], these products have been the ones to be revised since 2018.

2. High-Pressure Processing (HPP) as a Food Preservation Technology

High-pressure processing (HPP) is an advanced preservation method employed in the food industry to extend the shelf life of food products while retaining their nutritional and sensory attributes as well as ensuring microbiological safety.

Historically, various preservation techniques have been utilized to prolong the edibility of food. Fruits and vegetables (F&V), in particular, are highly perishable due to their rich nutrient composition and elevated moisture levels. Consequently, they must be consumed shortly after harvest or undergo processing to enable longer-term storage [10]. Sometimes overproduction occurs, and to avoid losses for producers and food retailers, it is necessary to conserve the excess crop or to transform it into derivatives that maintain its properties for a long time. The application of high temperatures is one of the conventional procedures used in order to extend F&V preparations' shelf life. Moreover, fresh food units that do not comply with the minimum requirement quality criteria can be processed by HPP and contribute to the circular economy.

Excessive heat can negatively affect the components of food, often resulting in poor quality and reduced nutritional content [11]. There are several methods to apply high temperatures, with pasteurization being one of the most widely used. However, food manufacturers are increasingly interested in innovative pasteurization techniques that can meet growing consumer demand for high-quality, ready-to-eat products while still ensuring food safety. As a result, new technologies are being introduced alongside traditional heat treatments, leading to a broader interpretation of the term "pasteurization" [12]. Recently, the United States updated its definition of pasteurization to include "any process, treatment, or combination of treatments applied to food to reduce the most heat-resistant microorganisms of public health concern to levels that are unlikely to pose a risk during normal distribution and storage conditions" [13].

Moreover, minimal processing has become one of the fastest-growing segments of the food industry as a result of the emergence of a new consumer profile defined as "rich in cash, poor in time" [14]. In addition, no high temperatures and chemical additives are employed; so, HPP-treated foods possess very good and fresh-like nutritional and sensory attributes [15].

2.1. Methodology Used to Select HPP Bibliography

The importance of HPP can be illustrated by the growing tendency in the number of scientific articles published in the last 25 years. In the Scopus database, searching by keywords related to pressurization, "High Pressure Processing" OR "High Hydrostatic Pressure" OR "High Pressure Treatment" OR "Pressure assisted thermal processing" OR "High Pressure High Temperature" and articles also including "Novel technologies" OR "Non thermal technologies" OR "Emerging technologies," found almost 15,200. The number of publications has increased by 4 (results are shown in Figure 1).

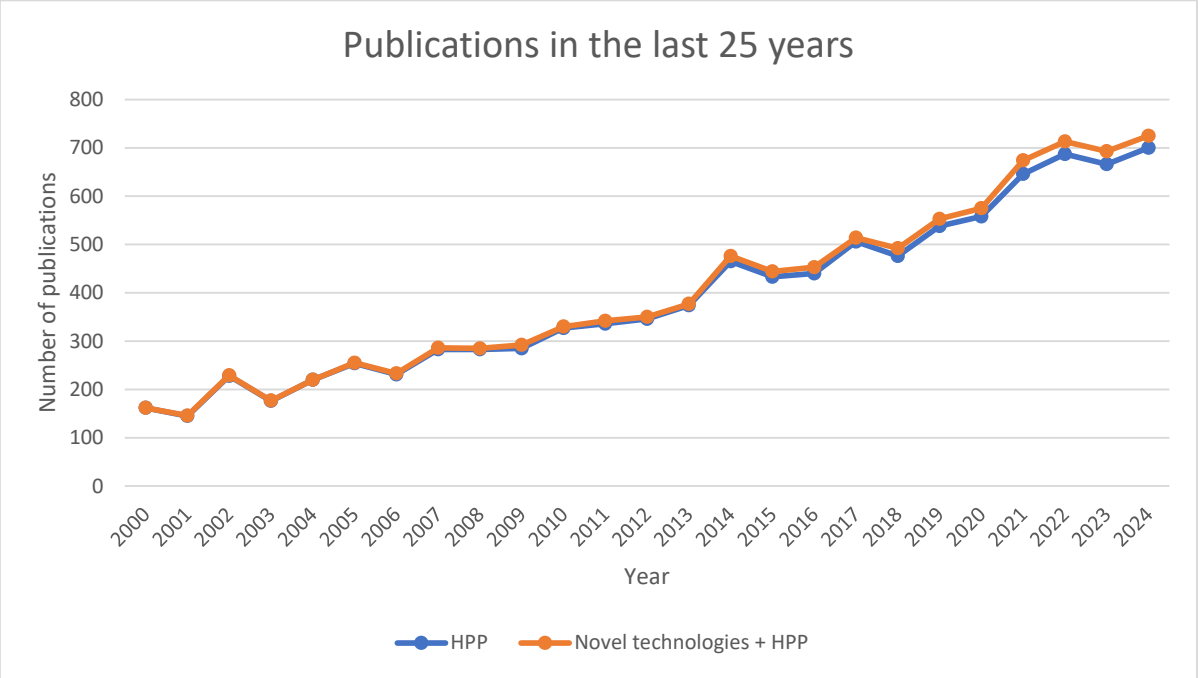


Figure 1. Number of publications searched in the Scopus database since 2000.

Moreover, other keywords introduced in the search sequence related to food products, including "Fruit derivatives," "Fruit preparations," "Vegetable preparations," "Plant based foods," puree, juices, smoothies, beverages and to the bioactive components with antioxidant activity: "vitamin A, carotene, carotenoids, "vitamin C," "ascorbic acid," "vitamin E," tocopherol, "antioxidant activity," "antioxidant capacity" and polyphenols, resulted in 389 documents (from 2018 to 2025). Studies excluded from this manuscript were the ones that apply other modalities of high pressure, such as high-pressure homogenization, high-pressure extraction, high-pressure microfluidization, and high-pressure for hyperbaric storage. We also have excluded works with preparations/beverages including milk or other ingredients of animal origin in their formulation (animal proteins) as well as studies that exclusively examined enzymes, microbiology, viruses, and the kinetics of vitamins/bioactive compounds degradation.

2.2. Principles of High-Pressure Technology Applied in Foods

In HPP technologies, packaged foods are subjected to high-pressure values (100–600 MPa) at varying temperatures: from refrigeration (4–8 °C), mild (9–49 °C) or high (50–100 °C), using a liquid (normally water) that circulates inside the vessel where the food is placed as a medium for pressure transfer. It is known as high-pressure processing if the temperature applied is between 4–49 °C, although other names could be used (high hydrostatic pressure, high-pressure treatment, or ultra-high pressure). If the temperature is higher than 49 °C, it is called PATP (pressure-assisted thermal processing) or high pressure high temperature (HPHT).

Principles to govern high-pressure effects on foods are managed by four main physical-chemical laws:

- The isostatic principle states that pressure is rapidly and evenly distributed throughout the entire food product, regardless of its shape, size, or structure. The pressure spreads equally in all directions, ensuring uniform impact across the sample. As a result of this balanced distribution, the molecular bonds and structure of the food remain unaffected [16].

- According to Le Chatelier's principle, when a system at dynamic equilibrium experiences a change in conditions, it will adjust to oppose that change and restore equilibrium. Therefore, if pressure is applied to a system in equilibrium, the system will respond in a way that reduces the effect of the pressure, typically by shifting toward a state with lower volume. Processes such as phase transitions, chemical reactions, and molecular rearrangements that result in a volume decrease are generally promoted by increased pressure, while those that cause volume expansion are inhibited [17]. The rate at which a reaction proceeds can either increase or decrease depending on the "activation volume"—the difference between the volume of the activated complex and that of the reactants. If this value is negative, pressure increases the reaction rate, and if it's positive, pressure slows it down [18]. Because biochemical reactions often involve volume changes, pressure can significantly influence their behavior [19].
- In physical chemistry, the Arrhenius equation describes how reaction rates are affected by temperature. It is widely used to explain the influence of temperature on the speed of chemical reactions [20].

$$k(T) = k(T_{ref})\ Exp\left[\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

where $k(T)$ is the reaction rate at temperature T, $k(T_{ref})$ is the reaction rate at a reference temperature T_{ref}, E_a is the activation energy, and R is the universal gas constant.

- The microscopic ordering principle states that at a constant temperature, increasing pressure leads to a greater degree of molecular organization within a substance. Therefore, pressure and temperature have opposing effects on molecular structure [21]. In microorganisms, low-pressure exposure may cause reversible alterations in cell shape, but at higher pressures, these changes become irreversible. Cell membrane disruption occurs, leading to leakage of large amounts of internal cellular material and ultimately resulting in cell death. Subsequently, the application of high pressure may lead to cellular deformation and structural damage, resulting in tissue softening and the release of intracellular fluids (cell serum).

Additionally, compression can induce changes in the pH of food matrices, depending on the magnitude of the applied pressure. This pH shift can be quantitatively estimated using the following empirical equation [22]. Usually, high pressure at ambient temperatures decreases pH.

$$(pKa)_p = (pKa)_0 + \frac{p\Delta V_0}{\ln(RT(1+bp))}$$

where $(pKa)_p$ and $(pKa)_0$ represent the acid dissociation constants under pressure p and at atmospheric pressure, respectively;

T denotes the absolute temperature;

b is an empirical constant;

ΔV_0 is the partial molar volume change (which may be positive or negative) associated with the dissociation of the acid at atmospheric pressure;

R is the universal gas constant.

Thus, high-pressure processing (HPP) can influence chemical equilibrium processes, including the dissociation of weak acids, acid-base equilibria, ionization phenomena, and related reactions [23].

HPP is a hydrostatic method that uses water compression to apply pressure uniformly. For optimal microbial inactivation, it is generally recommended that foods have a water activity (aw) higher than 0.96 [24]. As a result, low-moisture foods—such as powdered

products, dried fruits, and items containing air like bread, cupcakes, and marshmallows, as well as certain fresh vegetables (e.g., strawberries and eggplants)—are typically not suitable for HPP. This is due to the reduced effectiveness of microbial inactivation in foods with moisture content below 40% [25], and because the process relies on water to transmit the pressure. Foods with unequal water distribution (i.e., breaded and battered) are not adequate to be pressurized.

The usual values of pressure, time, and temperature in food industries that apply HPP range between 200 MPa and 600 MPa, 0.5 min and 6 min, and 4 °C and 49 °C. The water temperature, due to the adiabatic effect, rises to about 3 °C per 100 MPa of pressure, and it can be higher for more compressible foods like fats. Thus, the temperature increase is higher during HPP for foods with a higher fat content [17]. In these cases, such as butter or cream, the temperature rise is greater (8–9 °C/100 MPa) [19]. So, adiabatic heating can increase food temperature between 18 °C and 54 °C, considering the application of 600 MPa in a certain product. It clearly showed that compression heating values were significantly dependent on the composition of liquid-phase food products [26].

Regarding equipment design, over 90% of the industrial machines in production have a horizontal configuration [27], which is easier to connect with other facilities in the food production chain.

Industrial equipment of HPP can operate in three modes: batch, semicontinuous, and continuous (the latter implemented recently, and called "in-bulk" HPP technology (Hiperbaric.com)). Batch and semicontinuous modalities require flexible packaging, usually made of plastic, to contain the food before being pressurized. Among available packaging options, plastic materials are currently considered the most suitable for high-pressure processing (HPP) applications. This is due to the requirement that packaging must withstand a compression of approximately 15% without compromising integrity [28]. In addition, certain plastics can serve as effective barriers against oxygen and light transmission, thereby contributing to product stability. Common examples include polyester, polypropylene, polyethylene, and ethylene vinyl alcohol.

However, the widespread use of polymer-based flexible packaging poses significant environmental concerns due to its non-biodegradable nature. A more sustainable alternative may lie in the adoption of biodegradable polymers, which offer comparable functionality while reducing ecological impact [29]. In recent years, biodegradable materials based on polylactic acid have been successfully tested for pressurized foods [30,31]. In the case of "in-bulk" HPP products, packaging is always performed after pressurization treatment, so different types of more sustainable materials (such as glass) could be used.

2.3. HPP as a Green and Sustainable Technology

The global food system is currently facing unprecedented challenges, including rapid population growth, climate change, ongoing resource depletion, and significant effects on biodiversity and traditional agricultural and production systems [32]. These systems rely on various environmental inputs—such as land, water, and energy—and generate outputs like greenhouse gas emissions, wastewater, packaging waste, and food waste [33].

In the food industry, food loss and waste are among the main inefficiencies [34]. Depending on the measurement methods used, between 30% and 80% of food—by mass and nutritional value—is lost or discarded globally [35,36].

The prevention of food loss and waste has recently gained significant global attention as part of efforts to fight hunger and enhance food security. Reducing food waste not only increases food availability but also supports environmental sustainability [37]. Research has shown that food loss and waste can occur at five main stages of the food supply chain: agricultural production, postharvest handling and storage, processing, dis-

tribution, and consumption. These five stages are integral to the life cycle assessment (LCA) approach used in the food industry [38]. According to the Food and Agriculture Organization of the United Nations (FAO), food waste largely arises from inefficiencies at the consumption stage, such as overproduction, expiration of products, and changing consumer preferences [39].

In North America, for example, losses of fresh fruits and vegetables—foods vital to public health—reach 50–60%, a rate higher than that of most other food categories [40]. In Germany, more than 25% of certain vegetables are lost, while losses at the farm level vary for fruits, from 15–20% for highly perishable strawberries to just 6–16% for more durable apples, based on farmers' estimates [41]. A portion of these losses results from overproduction or the rejection of produce that is imperfect or fails to meet minimum quality standards for fresh sale, such as with kiwi and other crops [42].

Looking ahead, many researchers emphasize the importance of adopting a whole value chain approach within the agri-food system to seize market-driven opportunities, reduce food waste, and increase the availability of fruit- and vegetable-based products for consumers [36]. There is limited research on the types and degrees of defects that influence consumer purchasing decisions, or how factors like price affect the willingness to buy imperfect produce [43]. Extending the shelf life of these products also plays a key role in minimizing food waste, supporting sustainability objectives, and offering economic advantages to producers [44].

In this context, such discarded raw materials can be "rescued" and processed using innovative technologies like HPP to create nutritious, safe food products with extended shelf life—thereby reducing organic waste and its environmental impact.

HPP can be used as a processing strategy to prepare sustainable foods [35,45,46], contributing to the circular economy and aligning with two of the UN's sustainable development goals (SDGs): SDG 11 (sustainable cities and communities) and SDG 12 (responsible production and consumption) proposed in the 2030 UN Agenda.

Moreover, this method is regarded as a green technology, as it does not involve the use or generation of substances harmful to human health or the environment [38].

2.4. HPP Relevance in the Food Market

HPP technology is currently employed by over 200 companies worldwide, spanning countries such as the United States, Spain, Italy, Germany, Switzerland, the United Kingdom, Mexico, Canada, India, South Korea, Japan, New Zealand, Brazil, Argentina, Chile, Peru, Colombia, and Australia [47]. Notably, China has emerged as a rapidly expanding market for HPP.

The adoption and industrial-scale implementation of HPP have experienced significant growth. In 2000, there were approximately 20 commercial HPP units in operation globally. This number increased to 160 by 2010, and by the end of 2019, more than 520 HPP machines were in use, with a combined vessel capacity of around 130,000 L dedicated to the processing of commercial food and beverage products. In addition to these commercial installations, approximately 25 research-scale systems—with capacities ranging from 35 to 135 L—had been installed in academic institutions, research centers, and pilot facilities to support research and development initiatives [27].

Food processing using nonthermal technologies can be up to 20 times more energy-efficient than traditional thermal preservation methods [48,49]. In terms of cost, these nonthermal methods save approximately 15% energy compared to conventional thermal treatments [50]. However, when comparing the cost of HPP to traditional pasteurization for orange juice preservation, thermal processing remains more economical. Processing 1 kg of juice with HPP costs about 1.40 to 1.78 times more than thermal methods [51]. Depending

on the pressure, temperature, and scale of operation, HPP processing typically costs around $0.10 more per unit than thermal processing [17]. While HPP tends to be more expensive, it generally has a lower environmental impact across nearly all categories [52]. To make HPP products more cost-competitive with traditional thermal options, reducing energy consumption—which represents a large portion of operating costs—is crucial [53]. The cost of a high-pressure vessel, at a commercial scale, ranges from $500,000 to $2.5 million, contingent upon the equipment's capacity and level of automation [54], and on the operation mode (batch, semicontinuous, or continuous). Continuous mode or "in-bulk" technology [27] is the most expensive.

The global market for high-pressure processing is projected to reach USD 766.6 million by 2026, reflecting a compound annual growth rate (CAGR) of 11.2% from 2021 to 2026 [55]. Furthermore, it is expected to expand to approximately USD 1529.5 million by 2032, with a projected CAGR of 11.6% over the forecast period from 2024 to 2032 [56]. HPP has firmly established itself as the leading non-thermal food processing technology, commanding a substantial 35.6% market share among emerging technologies such as pulsed electric fields, pulsed light, irradiation, ultrasound, oscillating magnetic fields, and cold atmospheric plasma. Alongside microwave heating, HPP is recognized as one of the two most commercially promising food processing innovations currently attracting significant consumer and industry interest [11].

One of the fastest-growing sectors in the global food and beverage industry is the market for mixed fruit and vegetable (F&V) beverages, including juices, smoothies, nectars, and related drinks [57]. Among the various F&V-based products, juices represent the highest volume category processed by many HPP tolling service providers (which offer pay-as-you-go HPP services). A particularly dynamic segment within this market is the cold-pressed juice category. Promoted with claims such as "Never Heated," "Fresh," "Unpasteurized," and "Cold Pressurized," these products have gained considerable traction in premium juice markets worldwide. This segment has become a key adopter of HPP technology, leveraging its benefits for extended shelf life and enhanced food safety [9]. Nevertheless, "Pressurized" does not often appear on the labels of these products, where it is common to use "cold pressed" and sometimes the abbreviation HPP, which is not understandable by consumers.

In Figure 2, eleven pressurized juices were collected from the Spanish market and from web pages, and the terms related to "pressed" or "pressurized" are marked in blue circles.

Seven mentions were related to applied pressure procedure in this Figure 5: "Cold pressed" (products 1, 2, 3, 4, 5), "High pressed" (product 6), "Pure pressed" (product 7), "Under pressure" (product 8), "Pressurized cold" (product 9), HPP (products 1, 10) and "*Smoothie tratado en altas presiones*" (product 11).

The confusion between "cold-pressed" and "cold-pressurized" is clear to consumers. Their main differences are related to the production procedure illustrated by several researchers [58]. So, "pressurized" products are high-pressure processed, contained in plastic bottles or pouches and their extended shelf life is longer lasting (0–45 days) while "cold pressed" are usually contained in glass or plastic bottles and their shelf life is up to 3–4 days, but these latter juices are really cheaper and fresher, although pressurized beverages can be considered "raw" or minimally processed. Manufacturers are not required by the FDA or European laws to utilize understandable words related to HPP in their labels.



Figure 2. Labels examples of HPP juices and smoothies with several mentions ("pressed," "cold pressed", "pressurized") highlighted in a blue circle.

2.5. Advantages and Limitations of High-Pressure Processing

HPP offers a range of advantages that contribute to the improvement of food quality across nutritional, safety, sensory, and commercial dimensions:

- Nutritional Quality: HPP is known for its ability to preserve the nutritional integrity of food products. It enables high retention of heat-sensitive vitamins, particularly those found in fresh produce, and helps maintain the bioactivity of functional compounds. Moreover, it supports the production of clean-label foods by reducing or eliminating the need for chemical preservatives, additives, or salt [29]. Additional health-related nutritional benefits associated with HPP include increased levels of γ-aminobutyric acid (GABA) and polyphenols, reduction in the glycemic index, and enhanced antioxidant activity [59].
- Food Safety: One of the key advantages of HPP is its effectiveness in microbial inactivation, thereby significantly enhancing food safety. The process can activate or

deactivate specific enzymes depending on the pressure and duration applied, and it enables substantial shelf-life extension—from as little as 2–3 days up to 180 days in some cases. HPP has also been shown to facilitate the removal of certain toxins and prevent their formation in food matrices [60]. However, further research is needed to assess its effects on other harmful substances, such as food contaminants [61]. Additionally, extended shelf life contributes to a reduction in the number of expired products and, consequently, lowers waste and disposal costs.

- Sensory Attributes: HPP-treated foods typically exhibit excellent retention of sensory qualities such as taste [62], flavor, and color, closely resembling those of fresh, untreated products [6]. Nevertheless, the technology may affect certain textural elements [63] and alter the aroma profile [64,65], which requires careful formulation and process optimization.
- Commercial Advantages: High-pressure processing (HPP) is particularly advantageous for application to packaged foods, as it significantly reduces the risk of secondary contamination. The technology is adaptable to both batch and semi-continuous operation modes, making it versatile for industrial use. HPP is also considered an environmentally friendly technology that supports the production of "clean-label" foods—products formulated with a minimal number of safe, hazard-free ingredients that are generally accepted by consumers [66]. It is important to note that the term "clean label" encompasses a broad range of often ambiguous descriptors such as "all-natural," "locally grown," "GM-free," and "minimally processed," which are frequently associated with claims of wholesomeness and health benefits despite lacking robust scientific validation [67]. From an environmental perspective, HPP demonstrates a lower carbon footprint compared to traditional thermal processes [49]. The energy requirements for HPP are notably lower than those for conventional thermal pasteurization, and the process generates minimal waste. While the overall production costs per unit for HPP-treated products tend to be higher than those of thermally processed equivalents—partly due to energy consumption—HPP utilizes relatively low amounts of electricity and allows for the recycling of the pressurization fluid (typically water), resulting in virtually zero emissions. Once the target pressure is reached during processing, maintaining this pressure requires minimal additional energy input. Moreover, unlike heat-based technologies, HPP does not necessitate additional energy for cooling the product after the treatment duration has elapsed [28]. Advantages related to being a greener technology compared to traditional ones using heat are another issue to be considered before installing this technology in the food industry. Life cycle analysis has shown that HPP technology may reduce environmental impacts when compared to traditional thermal processing methods [4].

An additional functional advantage of (HPP) is its ability to reduce the rate of non-enzymatic browning reactions, particularly the Maillard reaction. This complex reaction involves two main stages: the initial condensation of amino compounds with carbonyl compounds, followed by subsequent browning reactions that include melanoidin formation and various polymerization processes. The initial condensation step is not accelerated under high pressure (5–50 MPa at 50 °C), as pressurization inhibits the generation of stable free radicals derived from melanoidins—key contributors to browning [68].

Another significant benefit is the enhanced bioavailability of certain bioactive compounds following HPP treatment [69].

At the molecular level, chemical changes in foods subjected to high hydrostatic pressure are minimal, as covalent bonds remain intact during processing. Instead, weaker interactions—such as Van der Waals forces, electrostatic interactions, and hydrogen bonds—are more susceptible to disruption by the applied pressure [70]. This means that small molecules

such as vitamins and polyphenols are not affected, but macromolecules (proteins, lipids, polysaccharides) modify their structure, affecting the texture of food products.

HPP can affect the activities of enzymes such as pectinmethylesterase and polygalacturonase on pectin, which causes the texture degradation of fruit and vegetables [71].

To overcome consumers' concerns, food industries that produce pressurized foods do not need to mention this technology on the label. Therefore, comprehensive labeling and education are essential to inform consumers about HPP's benefits [54].

HPP's drawbacks affecting food quality are related to the following:

- Nutritional quality: possible modification of lipids and the structure of other macromolecules. Several researchers have reported that enzymatic browning and flavor changes during storage remain challenges [72]. Other effects are possible damage from free radicals.
- Food safety: high-pressure treatments do not inactivate microbial spores; more research is needed on reactions producing contaminants that can be affected by HPP [59]. Enzyme inactivation can't be completely performed by HPP treatments.
- Sensory attributes: HPP can induce modifications in the structure and texture of food products, including phenomena such as cloud loss and alterations in key physical properties—such as melting point, solubility, density, and viscosity—which can, in turn, impact textural quality [38]. Additionally, HPP may lead to undesirable changes in the overall flavor profile of plant-based foods, particularly during storage, if enzymatic inactivation is incomplete [71].
- Commercial: higher equipment cost, which means huge amounts of capital; difficulties for continuous processing; although "in-bulk" HPP technology was implemented in 2021 for juices, but it is more expensive than HPP units working in batch mode; limited technical knowledge among food manufacturers regarding its implementation and validation protocols [72] as well as concerns related to process scalability and varying levels of consumer acceptance [49]; although, the emergent technology most accepted by consumers was HPP [73] despite the fact that pressurized food is more expensive.

Other disadvantages include its limited applicability to fluids and solid foods with high moisture content (above 40%) [74]. Whole fruits, products in rigid packaging (such as glass or Tetra Pak), and foods with very low moisture content (e.g., spices and dry goods) are unsuitable for this type of processing [75]. Additionally, solid foods that contain entrapped air—such as bread, cakes, and peanut butter—are incompatible with high-pressure processing (HPP) treatments [13].

Regarding packaging, plastic is currently the only suitable material for use in batch or semi-continuous HPP systems. However, "in-bulk" HPP technology allows greater flexibility, as packaging occurs after processing and can utilize a wider range of materials. Another limitation is that HPP-treated foods must be stored under refrigerated conditions. Furthermore, operating HPP systems requires adequate technical knowledge and sufficient space to ensure efficiency and safety [28].

Looking ahead, future research should focus on optimizing operational parameters and processing conditions to enhance both efficiency and cost-effectiveness. Efforts should also aim to overcome technical, economic, and regulatory hurdles by developing industry-specific guidelines and best practices [76].

3. Antioxidant Vitamins (A, C, E) and Antioxidant Compounds in Fruits and Vegetables Preparations

Fruits and vegetables are rich sources of micronutrients, phytochemicals, and bioactive compounds. According to the European Food Safety Authority (EFSA), a bioactive compound is a chemical found in small quantities in plants and certain foods—such as fruits,

vegetables, nuts, oils, and whole grains—that exerts biological effects which may support health. In this context, the term phytochemical refers to both nutritive and non-nutritive biologically active compounds naturally present in edible plant-based foods, including fruits, vegetables, grains, nuts, seeds, and tea. These compounds are recognized for their role in preventing or delaying the onset of chronic diseases in both humans and animals [77].

Fruits and vegetables (F&V) are particularly rich in a variety of bioactive compounds, including polyphenols—both flavonoids (such as anthocyanins, flavanols, and flavonols) and non-flavonoids (such as phenolic acids, stilbenes, and lignans)—as well as carotenoids, vitamins, dietary fiber, and essential minerals. These compounds contribute to human health primarily through antioxidant and anti-inflammatory mechanisms [78]. Flavonoids, a major subclass of polyphenols, share a common basic structure consisting of two aromatic rings connected by a three-carbon bridge that forms an oxygen-containing heterocyclic ring. Structural variations in this central C-ring give rise to various flavonoid subclasses [79] (see Figure 3).

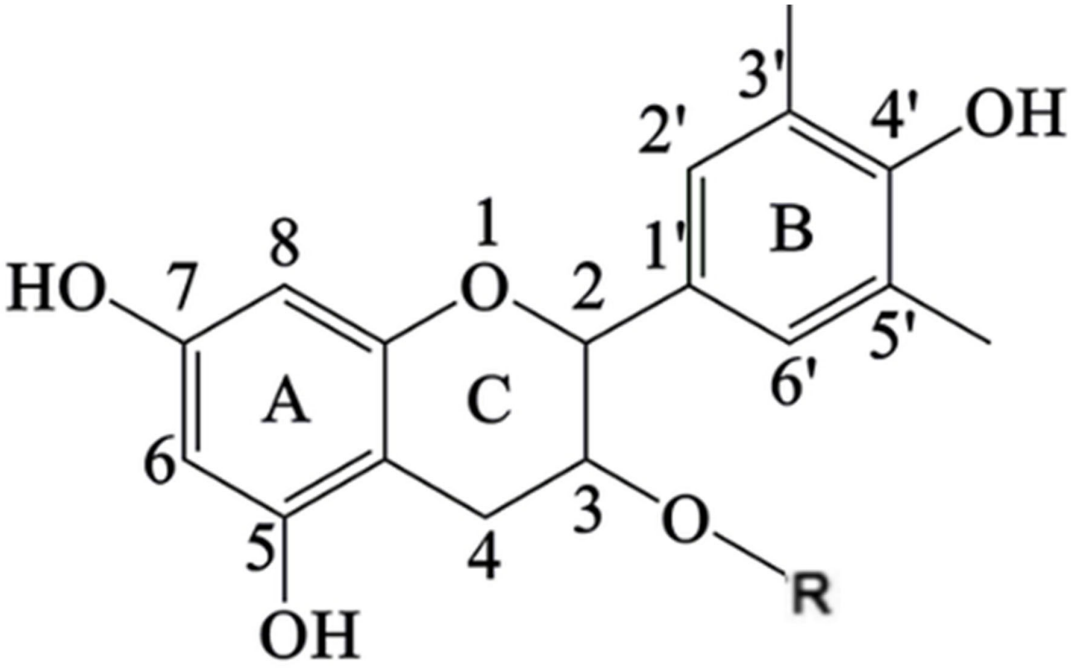


Figure 3. Basic chemical structure for flavonoids, if R = OH (flavonols); R = H (flavones).

The body's defense against oxidative damage can be strengthened by consuming fruits and vegetables [59], which may play a key role in supporting a healthy diet and promoting overall well-being [50].

Antioxidant compounds are substances that, even at low concentrations, can delay or prevent the oxidation of a substrate. They exert their effects through various chemical mechanisms, including hydrogen atom transfer (HAT), single electron transfer (SET), and transition metal chelation [80]. The antioxidant potential of a food is commonly described in terms of its antioxidant activity or antioxidant capacity. Antioxidant activity refers to the reaction rate between an antioxidant and an oxidant—essentially a kinetic measurement. In contrast, antioxidant capacity is a thermodynamic concept, reflecting the total amount of free radicals that an antioxidant can neutralize. It relates to the stoichiometry and equilibrium of the redox reaction between the antioxidant and the oxidizing agent [81,82].

In vitro methods for assessing antioxidant potential are generally classified into two main categories:

1. Radical/ROS scavenging assays, such as ORAC (oxygen radical absorbance capacity), DPPH (2,2-diphenyl-1-picrylhydrazyl), and TEAC (Trolox equivalent antioxidant capacity).

2. Non-radical redox potential assays, including FRAP (ferric reducing antioxidant power) and CUPRAC (cupric ion reducing antioxidant capacity), among others [83].

Thus, all molecules present in foods, capable of reducing or eliminating free radicals, can be considered antioxidants. In addition to vitamins A, C, and E, fruits and vegetables contain other compounds with this capacity, such as organic acids (citric, malic, acetic, etc.), polyphenols (phenolic acids; flavonoids: anthocyanins, flavanols, flavonols; stilbenes, etc.), minerals (Se, Zn, Cu, Mn, and Fe), volatile compounds, and others. The high reactivity of phenolics against active free radicals is considered the main mechanism for acting as an antioxidant compound [84]. Some authors have published antioxidant activity values obtained by different in vitro methods for various phenolic compounds [85]. Other authors have proposed that the observed increase in plasma antioxidant capacity following the consumption of certain foods may suggest that specific phenolic compounds exert antioxidant effects in vivo, beyond merely interacting with existing plasma antioxidants. These three vitamins: A, C, and E (Figure 4 only shows three vitamers) act as antioxidants, promoting free radical scavenging and reducing themselves to other compounds [86].

Vitamin C (ascorbic acid) plays a critical role in maintaining intracellular redox homeostasis throughout all stages of plant growth, development, fruit ripening, and in response to abiotic stress [87]. It neutralizes both reactive oxygen species (ROS) and reactive nitrogen species (RNS) by donating a hydrogen atom, forming the ascorbyl radical (or dehydroascorbic acid), which can subsequently be regenerated into active vitamin C. A key advantage of vitamin C is its water solubility, allowing it to function both intracellularly and extracellularly [88]. In humans, vitamin C is not only essential for preventing scurvy but is also implicated in reducing the risk of various diseases, including cancer [89,90].

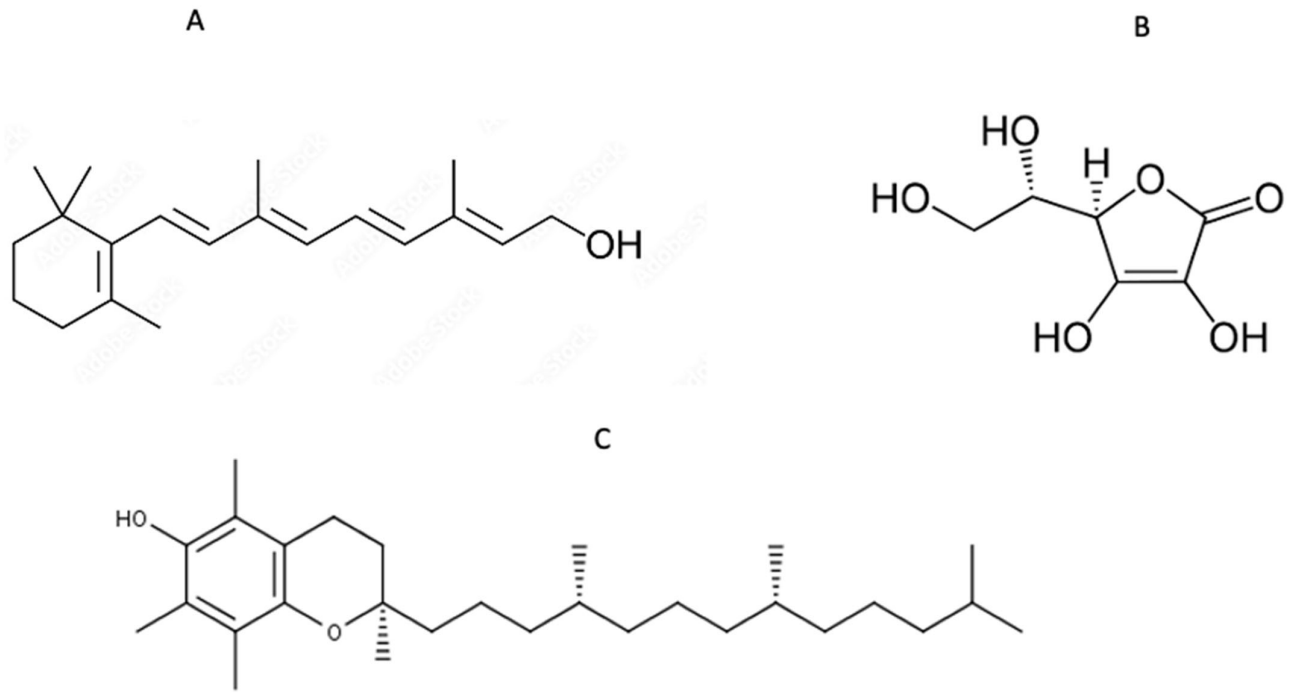


Figure 4. Antioxidants vitamers for vitamins A, C, and E; structure (**A**): retinol, structure (**B**): ascorbic acid, and structure (**C**): α-tocopherol.

Vitamin A (including retinol, retinal, and retinoic acid) and its precursors, such as carotenoids, exert their antioxidant effects primarily by reducing oxidative stress—a key factor in the progression of many chronic diseases [88]. Vitamin A and carotenoids contribute to the prevention of cardiovascular diseases, offer hepatoprotective and neuroprotective

benefits, and have shown positive effects in combating several cancers and metabolic disorders, including diabetes and obesity. Additionally, they promote skin health [91] and prevent xerophthalmia. Vitamin A deficiency remains a significant global health issue, affecting approximately 30% of young children and 15% of pregnant women in low- to middle-income countries [92].

Vitamin E includes a group of compounds with similar chemical structures, primarily tocopherols and tocotrienols. The health effects of vitamin E include anticancer properties [93], support for cardiovascular health, strengthening of the immune system [94], and improved skin health. Vitamin E is also involved in the formation of red blood cells and aids in the proper utilization of vitamin K. Moreover, blood concentrations of antioxidants—such as vitamin C, carotenoids, and vitamin E—have shown stronger and more linear inverse associations with cardiovascular disease, cancer, and all-cause mortality compared to dietary intake levels [95]. Vitamin E, a fat-soluble antioxidant, is predominantly found in fruits and vegetables such as leafy greens, as well as in nuts, seeds, and vegetable oils [96].

Other antioxidant compounds are found in F&V, but the methods for measuring antioxidant capacity are general and do not normally refer to a single compound when the measurement is performed on raw food. Therefore, the task of finding individual compounds performing this activity is not easy. Potential compounds, apart from antioxidant vitamins, present in F&V preparations with antioxidant activity are discussed in numerous reviews and publications (Figure 5). All of these compounds are capable of acting as antioxidants.

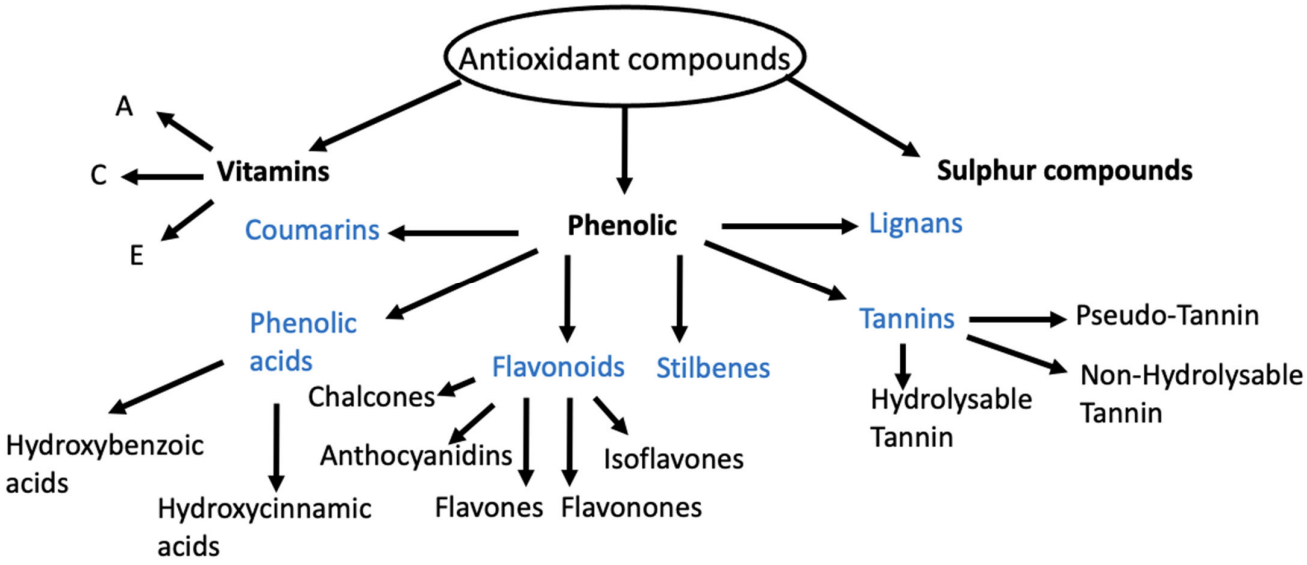


Figure 5. Chemical groups of several antioxidant compounds.

Usually, the contents of vitamins A, C, and E and other bioactive compounds in fresh fruits and vegetables decrease during storage at room temperature, after harvesting, especially ascorbic acid and tocopherols, due to contact with oxygen or light, as they are highly susceptible to degradation and oxidation.

Another alternative is to apply preservation techniques to obtain high-quality preparations in order to maintain their retention in F&V foods during the consumption period and to prolong shelf life. Some of these procedures are based on preparing bottled derivatives (beverages, juices, nectars, smoothies) or canned foods (jams, sauces, pickled vegetables) using discarded and/or surplus production of F&V, which can be packaged in glass, can, brick, or plastic materials (e.g., PET, PE. . .) to extend their shelf life.

Markets in the USA and EU offered various derivatives (juices/smoothies), containing amounts of vitamins that differed from those declared/claimed on the label [97,98]. Japanese consumers ingest more than 50% of the recommended vitamin C in their diet due to the consumption of vitamin-enriched juices [99].

Fruit juices, along with other fruit and vegetable preparations such as beverages, nectars, smoothies, salads, soups, sauces, creams, and jams, are convenient and easy-to-consume foods. They are known for their high pulp content, rich vitamin C, carotenoids, and polyphenols, offering excellent nutritional, functional, and therapeutic benefits. As a result, fruit juices have become a popular addition to the daily diet for people of all ages, backgrounds, and locations [58]. Globally, the juice market is expected to grow by 4.9% over 5 years, from 2022 to 2027. This growth is driven by consumers' growing preference for healthier beverage options and the rising awareness of the nutritional benefits of fruit juices. The market is changing, with a growing demand for organic and functional juices and an increase in the popularity of cold-pressed juices [100].

3.1. Modifications on Antioxidant Vitamins After HPP

Traditional heat preservation methods, such as UHT (ultra-high temperature) and HTST (high temperature short time), cause the degradation of bioactive ingredients. For this reason, innovative and emerging techniques have been applied in order to maintain nutritional characteristics as well as safety and sensory properties. One of these techniques is based on HPP.

The first studies demonstrating the minimal losses on water-soluble vitamins after pressurization were conducted in 1999 [101,102], using apple and model systems, respectively. Carotenoids were investigated earlier, in 1975 [103]. In general, HPP and PATP treatments significantly improved the retention/extractability of lycopene compared to heat treatment and control [104]; and vitamin E, much later (2012) [105], demonstrating that HPP did not alter or even increase its content. In a work involving lettuce juice, vitamin E decreased by up to 20% with thermal processing and only 4% with pressurization [106]; and in kale, the decrease with pressurization could reach up to 50%, while during storage, HP-treated kale resulted in greater loss of vitamin E and total carotenoid content compared to heat-treated samples [107]. However, in another study, tocopherols and vitamin E activity were not affected by pressurization in açai juice [108].

The changes in HPP treatments on antioxidant vitamins (A and C) are compiled in Table 1 since 2018. For vitamin C, thermal treatments (TP) resulted in lower retention than HPP, but one exception was found in blueberry–grape–pineapple–cantaloupe juice, where HPP caused a 23% loss and TP only an 11% loss, after storage. HPP treatments tend to preserve vitamin C much better than TP in several F&V products, with frequent reports of no significant changes or minor losses (e.g., 2.8–35% loss). Best examples are kiwifruit pulp (35.8% more retention than TP), mandarin juice (8.2%), and orange juice (no change vs. untreated in several studies). Regarding combined treatments, HPP-PATP slightly increased vitamin C (e.g., up to 37% increase in orange juice with xylooligosaccharides), and contrary effects were found in sugarcane juice (3–25% loss). TP frequently causes significant vitamin C degradation, with reductions of 14–70% depending on temperature and product (strawberry nectar (25% loss), bok choy (70.4% loss), prickly pear (2% loss), many >20% loss).

If we consider now the studies that compare the levels of vitamin C during storage (Table 1), HPP shows the best retention values, although the levels decrease over time.

Table 1. Pressurization and thermal treatment effects on vitamin C, carotenoids, and antioxidant activity from F&V foods since 2018.

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Açai juice	HPP	400–600 MPa, 20 °C, 5 min	NP	NP	No changes at 400 MPa, ↑ 22.4% at 500 MPa (ORAC)	[108]
	TP	85 °C, 1 min			↓ 8.2% (ORAC)	
Apple juice	HPP	600 MPa, RT, 3 min	NP	NP	No differences in DPPH TPC ↑ in HPP samples	[109]
	HPP	300 MPa (3 pulses)-600 MPa (1 pulse), 5–15 min, 22 °C 84 days storage, 4 °C	↓ 5–31% compared to untreated ↓ >99% after storage	NP	NP	[110]
	HPP	400 MPa, RT, 3 min 21 days storage, 4 °C	↓ 14% ↓ 79% after storage	NP	NP	[111]
	HPP	600 MPa, 25 °C, 5 min	No significant differences between HPP and control	NP	NP	[112]
Apple pieces	HPP	400, 500, 600 MPa, 35 °C, 5 min	NP	NP	↑ 26.2% (DPPH), ↑ 16.1% (ABTS), and ↑ 11.8% (FRAP)	[113]
Apple puree	HPP	200–500 MPa, 17 °C, 1 min			↑ 66.7% (DPPH), ↑ 58.8% (ABTS)	[114]
	TP	72 °C, 15 s			↓ 4.2% (DPPH) and ↓ 3.7% (ABTS)	
Apple, orange, and banana smoothies	HPP	450 MPa, 3 min, 11 °C 28 days storage, 4 °C	NP	↑ 40–48% No changes in Zeaxanthin; ↑ provitamin A		[115]
Aronia berry juice	HPP	600 MPa, RT, 5 min 12 months storage, 4 °C	NP	NP	No changes TPC, DPPH, FRAP TPC ↓ 17–24% and ↓ 6–12% in AA	[116]

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Bamboo shoots	HPP	378 MPa, RT, 3 min	↓ 7.0%	NP	NP	[117]
Barley-based non-dairy milk	HPP	100, 300 MPa; 40 °C; 2 min	NP	↓ 0–34%	↓ 38–45% (FRAP)	[118]
		3 pulses			↓ 10–21% (DPPH)	
		600 MPa; 40 °C; 2 min		↓ 10%	↓ 45% (FRAP), ↓ 20%(DPPH)	
		100, 300 MPa; 80 °C; 2 min		↓ 23–70%	↓ 47–58% (FRAP)	
		3 pulses			↓ 30–34% (DPPH)	
	PATP	600 MPa; 80 °C; 2 min		↓ 40%	↓ 54% (FRAP), ↓ 19%(DPPH)	
Bell peppers (fresh cut)	HPP	400, 500 MPa, 25 °C, 1–7.5 min 25 days storage, 4 °C	↓ 21–19% ↓ 30–36% during storage	NP	↑ 7–9% TPC and ↑ 14% AA ↓ 30.3–57.4% (DPPH) and ↓ 10.6–58.6% (FRAP) after storage	[119]
Blackcurrant juice	HPP	400 MPa, 18 °C, 1 min	↑ 3.3%	NP	↓ 6% in TPC,	[120]
	TP	74 °C, 3 s	No modifications		↑ 7% in TPC	
		42 days storage, 4 °C	↓ similarly (HPP, TP)		↓ 20% (HPP) and no losses (TP)	
Blackcurrant purée	HPP	200–600 MPa, RT, 5 min	Bioaccessibility ↑ using HPP	NP	Slightly ↑ AA (ABTS) and maintained (DPPH)	[121]
	TP	85 °C, 10 min				
Black/Red raspberry juice	HPP	400–600 MPa, 27–31 °C, 2–10 min	↑ 11–67% in comparison with the untreated	NP	NP	[122]
Blueberry–grape–pineapple–cantaloupe juice blend	HPP	550 MPa, 25 °C, 5 min	↓ 12% (day 48)	NP	NP	[123]
	TP	90 °C, 3 min	↓ 9% (day 48)			
		72 days of storage	↓ 23% (HPP) and ↓ 11% (TP)			
Bok choy	HPP	600 MPa; 5 °C; 2.5–20 min	No changes	↓ 22.2–32.1%	No changes (TPC)	[124]
	TP	95 °C; 0.5 min	↓ 2.5%	↓ 70.4%		

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Broccoli	HPP	200–600 MPa, 3–15 min	No changes	NP	↑ 54% (TPC)	[125]
Carambola puree	HPP	200–800 MPa, 25 °C, 15 min	NP	NP	↑ 2–3.3%(DPPH) 1.5% up to 3.2% ↑ (Hydroxyl radical)	[126]
Baby carrots	HPP	550 MPa, 5 min, 15 °C	NP	↑ 300%	NP	[127]
Carrot juice	HPP	300 MPa (3 cycles); 450, 600 MPa, RT, 5 min	NP	↓ 26–41%		[128]
	HPP	450, 600 MPa; 5 min, RT 300 MPa, 5 min (3 pulses) 84 days storage, 4 °C	NP	NP	↑ up to 48.8% (DPPH) ↑ up to 10.9% (ABTS) ↑ during storage	[129]
	HPP	600 MPa, 3 min, 20 °C	NP	↑ 19%	↓ 53% TPC; No changes (DPPH)	[130]
	TP	85 °C, 60 s		↓ 31%	↑ 45% TPC; ↑ 65% DPPH	
		15 days storage, 4 °C		↑ 18% HPP and ↑ 13% TP	↓ 53% HPP and ↑ 45% TP (TPC)	
					↓ 36% HPP and ↑ 22% TP (TPC)	
Carrot-orange juice blends	HPP	200, 300, and 400 MPa, 20 °C, 1–5 min	No changes between untreated and HPP	NP	NP	[131]
Cauliflower	HPP	400 and 600 MPa, RT, 2 and 5 min 28 days storage, 4 °C	↓ 3% ↓ between 11% (14 days)-18% (28 days)	NP	NP	[132]
Cherry juice	HPP	400, 600 MPa, RT, 5 min	NP	NP	↓ 6.9–13.9% (TPC); 3.7–5.1% (DPPH)	[133]
	TP	95 °C, 30 s			↓ 5.7% (TPC), ↓ 48.3% (DPPH)	
		60 days storage, 4 °C			↓ up to 23% (TPC), ↓ 70.1% (DPPH)	

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Chestnut	HPP	400–600 MPa, 20 °C, 5 min	↓ 0.5–2.2%	NP	NP	[134]
	TP	50 °C for 45 min	↓ 5.2%			
Citrus Maqui beverage	HPP	450 and 600 MPa, 20 °C, 3 min	↓ 45% and ↓ 31%	NP	NP	[135]
	TP	85 °C, 15 s	↓ 28%			
Clementine-mandarin juice	HPP	400 MPa, 40 °C, 1 min	↓ 15%	↓ 30%	↑ 25% TPC; ↑ 2% DPPH; ↓ 9.7% ABTS; ↓ 10% FRAP	[136]
Coconut water	HPP	350–550 MPa, RT, 3–7 min	↓ up to 7.8%	NP	↓ after HPP	[137]
Cranberry bush purée	HPP	200–600 MPa, 20 °C, 5 or 15 min	↓ 10–23%	NP	No differences (DPPH) Very slight ↓ (CUPRAC)	[138]
Gooseberry juice	HPP-PATP	200–500 MPa, 30–60 °C, 5–20 min	↓ 0.3–15%	NP	↓ 12% (60 °C) ↓ 28% (50 °C)	[139]
	TP	60 °C, 5–20 min	↓ <34%			
Grape juice	HPP	600 MPa, 5 °C, 3 min 5 months storage, 4 °C	NP	NP	No differences in TPC, DPPH, ABTS ↓ TPC, no changes in AA during storage	[140]
Green beans	HPP	600 MPa, 25 °C, 10 min	↓ 70%	NP	NP	[141]
	MW-TP	72 °C, 3 min	↓ 35%			
Date palm juice	HPP	400, 600 MPa, 25 °C, 10 min	NP	NP	↓ ~18% in TPC (TP) compared to raw and HPP	[142]
	TP	100 °C, 1 min			↓ 2.6%, 21.5%, 8.5%, and 31.3% for DPPH, FRAP, ABTS, and ORAC compared to control and lower in HPP	

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Dragon fruit puree	HPP	350 MPa, 25 °C, 5 min	NP	NP	↓ 6% in TPC, ↓ 7% (DPPH), and 4%(FRAP)	[143]
	TP	65 °C, 20 min			↓ 17%(DPPH) and 9%(FRAP)	
		60 days storage, 4 °C			↑ 29% TP than in HPP after storage	
Kale juice	HPP	600 MPa; RT; 5, 10, 20, 40 min	NP	↑ up to 22%	↑ up to 166% (ABTS)	[107]
	TP	80 °C; 5, 10, 20, 40 min		↓ 38% (TP)	↑ up to 150% (L-ORAC)	
		60 days storage, 5 °C		↓ 31% (TP ↓ 67% (HPP)	↓ ~50% (ABTS) and ↑ ~20% (L-ORAC) ↓ ~22% (ABTS) and ↑ ~20% (L-ORAC)	
	HPP	500 MPa, RT, 3 min	NP	↑ lutein		[144]
	TP	90 °C, 30 s		↓ β-carotene ↓ 12% carotenoids		
Kiwifruit pulp beverage	HPP	400–600 MPa, RT, 5–15 min	↑ 35.8% (400 MPa, 15 min)	NP	NP	[145]
	TP	85 °C, 10 min	compared to TP			
		40 days storage, 4 °C	Significant ↓ after storage in TP, better retention with HPP			
Lemongrass-lime mixed beverage	HPP	200–400 MPa, 25 °C, 1–2 min	No changes	NP	HPP and untreated have ↑ AA than TT	[146]
	TP	71.1 °C, 3 s	↓ 21%			
Mandarin juice	HPP	600 MPa, 4 °C, 30 s	↓ 8.2%	↓ 10.7%	↓ 29% TPC;	[147]
	TP	90 °C, 30 s	↓ 11.7%	↓ 41%	↓ 49.6% TPC	
Mango pulp	PATP	600 MPa, 52 °C, 10 min	↓ 5.0%	NP	NP	[148]
	HPP	592 MPa, 25 °C, 3 min	No significant difference compared with the control	NP	NP	[149]

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Mango juice	HPP	400 MPa, RT, 10 min	↓ 2.8%	NP	↓ 4.2%	[150]
Mixed fruit juices (2 formulations)	HPP	550 MPa, RT, 5 min 90 days storage, 4 °C	↑ 21–35% ↓ 23–58%	No changes	NP	[151]
Orange juices from Navel and Cara Cara varieties	HPP	200 and 400 MPa, 25° and 40 °C, 1 min	Navel: ↓ 2–30% Cara Cara: ↓ 0.1–9%	Navel: ↓ up to 34.1% Cara Cara: ↓ up to 20.1%	Navel: ↓ AA (11–26%) Cara Cara: ↑ AA (7–13%) at 200 MPa and ↓ AA (11–14%) at 400 MPa	[152]
Orange juice	HPP	600 MPa, 30 °C, 3 min	No significant difference between HPP and control	NP	NP	[153]
	HPP	550 MPa, 18 °C, 70 s	NP	↓ 12%	↓ 13%	[154]
	TP	70 °C, 30 s		↓ 20%	↓ 26%	
		36 days storage, 4 °C		HPP maintained ↑ than TP	Maintained ↑ than TP after storage	
	HPP	600 MPa, RT, 11 min	No significant difference	NP	↑ TPC, AA (DPPH and FRAP) ↑ in HPP	[155]
	TP	110 °C, 8.6 s	↓ content			
	HPP	550 MPa, 15 °C, 1.5 min	↑ 7%	NP	↓ 2.7%	[156]
	TP	72 °C, 20 s	↓ 7%		↓ 13%	
	HPP	400, 600 MPa, RT, 3.6 min	No changes	↑ up to 74%	No changes (TPC)	[157]
	TP	85 °C, 45 s	↓ 4%	↓ 12%	No changes (TPC)	
		60 days storage, 4 °C	↓ 18% HPP and 16% TP	↑ up to 74% HPP	↓ 13% HPP	
				↓ 22% TP	↓ 30% TP	
	HPP	600 MPa, 24 °C, 3 min	↓ 5.3%	No differences		[158]
	TP1	74 °C, 30 s	↓ 3.8%	No differences		
	TP2	92 °C, 31 s	↓ 2.6%	↓ 13.6%		
Orange juice enriched with XOS	HPP-PATP	100–600 MPa, 30–100 °C, 3 min (experimental design)	↑ 8% increase up to ↓ 37%	NP	NP	[159]

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Papaya cubes	HPP	50–400 MPa, 20 °C, 3–60 min	↑ 4–28%	NP	NP	[160]
Persimmon	HPP	200 MPa; 25 °C; 3, 6 min	NP	↑ 23–28% and	↓ 25–30% (DPPH)	[161]
		28 days storage, 4 °C		↓ 30–38% after storage	↓ ~80% after storage	
Pineapple pieces	HPP	100–300 MPa, RT, 5–20 min	↑ 10–40%	NP	↓ 0.4–↑ 13% in TPC	[162]
		16 days storage, 4 °C	↑ 17% raw and 10% (HPP)		↓ ~5% in TPC after storage	
Pomegranate juice	HPP	350, 450, 550 MPa; 23 °C; 1, 3, 5 min	Not significant ↓	NP	No significant effect (DPPH and ABTS)	[163]
	TP1	85 °C, 30 s	↓ 48%		↓ 24% (ABTS/DPPH)	
	TP2	110 °C, 30 s	↓ 60%		↓ 61% (ABTS/DPPH)	
	HPP	Not provided	↓ 35%	NP	↓ 28% TPC; ↓ 36% DPPH; ↓ 44% ABTS; ↓ 36% CUPRAC; ↓ 36% FRAP; ↓ 61% Chelating EDTA	[164]
Prickly pear puree	HPP	600 MPa, 5 °C, 180 s	↓ 2%	NP	↑ 21% (HPP) and no change (TP)	[165]
	TP	80 °C, 30 s	↓ 23%		↓ 35% AA (TP)	
		42 days storage, 4 °C	No changes (HPP)		Maintain TPC, AA during storage (HPP)	
Pumpkin cubes	HPP	200–600 MPa, 20 °C, 1–5 min	NP	↑ 40–56.9%	↑ AA (DPPH)	[166]
Chinese cabbage Sauce	HPP	200–600 MPa, 25 °C, 8 min	NP	No changes	↑ ~3% or no changes in TPC (HPP) and	[167]
	TP1	75 °C, 30 min		↓ ~6%	↑ 2.2% (DPPH) and FRAP (16.1%) (HPP)	
					Slightly ↑ AA (TP1)	
	TP2	110 °C, 15 min		↓ ~12%	↑ ~2% TPC and no changes (TP2)	

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Smoothies	HPP	350–450 MPa, 20 °C, 5–15 min (experimental design)	HPP provided a better retention compared to TP	No differences compared to TP		[168]
	TP	85 °C, 7 min	↓ 66% TP after storage	↓ 30.7% TP after storage	TPC ↓ in TP	
		21 days storage, 4 °C	↓ 18% HPP after storage		TPC ↓ 9.8% after storage	
Fresh purple smoothie	HPP	300–450 MPa, 20 °C, 11–4 min	↓ 21–26%	NP	NP	[169]
Functional smoothie	HPP	550 MPa, 15 °C, 3 min	NP	NP	No modifications or ↑ AA (TBARS)	[170]
	TP	90 °C, 30 s			Phenolics and AA ↓ with storage	
		50 days storage, 4 °C				
Green smoothie	HPP	300–600 MPa, RT, 2–10 min	NP	NP	No changes in TPC and AA	[171]
Strawberry smoothie	HPP	600 MPa, 4 °C, 3 min	↑ 15%	NP	↑ 12% (DPPH, ABTS)	[172]
Vegetable smoothie with apple	HPP	300 MPa, 10 °C, 5 min	↓ 28%	NP	NP	[173]
		28 days storage, 4 °C	Total ↓ after storage			
	HPP	350 MPa, 10 °C, 5 min	NP	NP	↑ TP (FRAP)	[174]
	TP	85 °C, 7 min				
Fruit salad	HPP	550 MPa, 15 °C, 3 min	NP	NP	No significant differences (ABTS)	[175]
		35 days storage, 4 °C			↓ AA after storage	
Sea buckthorn juice	HPP	500 MPa, RT, 6 min	No significant differences between HPP and untreated			[176]
	TP	100 °C, 15 s	↓ 14.3%	↓ 20.5%	↓ between 3.8–3.4% (DPPH and FRAP)	
Sea buckthorn syrups	HPP	600 MPa; 4, 8 min	No significant differences between HPP and heated samples during storage			[177]
	TP	88 °C; 15 s (hot filling)				
		56 days storage, 4 °C				

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Red pepper paste	HPP	100–600 MPa; RT; 0.5–10 min (experimental design)	NP	↑ 2.5%	↑ 2.9% (ABTS)	[178]
Spinach and rosehip puree	HPP	200, 400, 600 MPa; RT; 5 and 10 min	NP	↑ 22.9%	Not significant effect: Slightly ↑ (ABTS) Slightly ↓ (ORAC)	[179]
Strawberry nectar	HPP	600 MPa; 5 min	↓ 25%	NP	NP	[180]
	TP	72 °C; 117 s	↑ 72%			
		30 days storage, 4 °C	↓ 100% HPP and ↓ 50% TP			
Strawberry puree and juice	HPP	400 MPa, 20 °C, 3 min	↑ 2.9%	NP	NP	[181]
		49 days storage, 6 °C	Total ↓ after storage			
Sugarcane-based mixed beverage	HPP-PATP	400 MPa, 33 °C, 15 min	↑ 17%	NP	More retention	[182]
		400 MPa, 67 °C, 15 min	↓ 29%		↓ ~13.2%	
		(experimental design)				
Sugarcane juice	HPP-PATP	600 MPa, 30–60 °C, 25 min	↓ 3.0–25%	NP	NP	[183]
	HPP	523 MPa, 50 °C, 11 min	↓ 11%	NP	↓ 12–15%	[184]
	TP	90 °C, 5 min	↓ 25%		↓ 24–28%	
Sweet potato flour	HPP	200–600 MPa, 25 °C, 15 min (experimental design)	NP	↑ 0–52%	↑ 4.2–30.9% (DPPH) ↑ 1.1–22.5% (FRAP)	[185]
Tomato	HPP	400, 500 MPa, 50 °C; 8, 10 min	NP	NP	HPP ↑ AA (DPPH and Hydroxyl radical)	[186]
Tomato juice	HPP	400 MPa, 25 °C, 30 min		NP	NP	[187]
	TP	100 °C, 5 min				
		30 days storage at 4 °C	↓ 96% after storage (TP)			
			↓ 24% after storage (HPP)			
	HPP	400, 600 MPa, 2–10 min	↓ between 50–73%	NP	NP	[188]
	TP	65–115 °C, 2–10 min	↓ between 35–96%			

Table 1. *Cont.*

F&V Product	Method	Processing Conditions	Vitamin C	Carotenoids	Antioxidant Activity (AA)	References
Tropical beverage	HPP	500 MPa, RT, 4.2 min	The ↑ concentration appears in the HPP sample	NP	The ↑ values appear in HPP samples (DPPH and FRAP)	[189]
	TP1	65 °C, 10 min				
	TP2	75 °C, 2 min				
	TP3	95 °C, 1 min				
Wheatgrass juice	HPP	400–600 MPa, RT, 1–3 min	↓ 2% (not significant)	NP	↓ 36% TPC; ↓ 6.6% DPPH; ↓ 11.3% ORAC	[190]
	TP	75 °C, 15 s	↓ 27%		↓ 7.5% TPC; ↓ 13.2%; ↓ 35.8% ORAC	
Xiaomila (*Capsicum frutescens* L.)	HPP	600 MPa, RT, 5 min	NP	NP	↓ 68% TPC	[191]
	TP	80 °C, 20 min			↓ 36% TPC and ↓ 5–6.7% (DPPH-ABTS)	
		30 days storage, (25–42 °C)			↓ 47.3–70.5% in TPC after storage	

F&V: fruit and vegetable. AA: antioxidant activity. HPP: high-pressure processing, MW: microwave, NP: not performed, PATP: pressure-assisted thermal processing, RT: room temperature, TPC: total phenolic content, TP: thermal processing. XOS: xylooligosaccharides. ↑: Increase and ↓: Decrease

With respect to carotenoids, the data compiled for vitamin A came from 25 articles that were reviewed, and the main effects were that HPP generally maintains or slightly increases carotenoid content. Some increases have been reported (e.g., provitamin A in smoothies). So, in apple/orange/banana smoothies, a 40–48% increase and no zeaxanthin loss were found, in baby carrots, up to a 300% increase, and in orange juice, up to a 34% for the navel variety. PATP effects were variable; some modest retention or increase was detected, depending on matrix and temperature. For example, barley milk had up to a 70% loss, and a sugarcane mixed beverage had a 29% loss. In thermal processing, often lower retention, degradation, or minimal increase compared to HPP was reported (especially at higher temps). Some cases are bok choy (70% loss in TP), mandarin juice (41% loss vs. 10.7% loss in HPP), and carrot juice (31% loss in TP vs. 19% increase in HPP). According to the research (5 articles), HPP generally maintains or enhances carotenoids better than TP. TP often causes greater carotenoid losses, especially at higher temperatures or long durations.

There are not a lot of studies on the proportion of bioactive compounds that reach the bloodstream to interact with their site of action (bioavailability) or are available from the gastrointestinal tract to be absorbed (bioaccessibility). In F&V foods treated by HPP, one study found that bioaccessibility was significantly reduced for carotenoids in the small intestine, but the proportion of cis-lycopene was increased in pressurized tomato juice [192]. Another study investigated the plasma concentration of carotenoids after the intake of freshly squeezed and processed orange juice under high pressure. There was a higher increase in β-cryptoxanthin, and no significant differences were observed for the other carotenoid compounds [69].

The studies that investigate the effects of HPP on vitamin E in F&V derivatives are very few and controversial. One of them did not find differences in tocopherols present in buckthorn syrups, even after 8 weeks of storage at 4 °C [177]. Nevertheless, one of the vitamin E vitamers decreased up to 31% in pressurized kale, compared to the untreated sample [107], while the bioaccessibility of this vitamin was slightly favored by HPP treatment [193]. In other work, the application of 450 MPa and 600 MPa did not alter α-tocopherol levels compared to the untreated sample [115]. Finally, in a pressurized puree containing spinach and rosehip, vitamin E content was higher after treatment, probably due to an increased extractability [179]. Briefly, for vitamin E, only a few studies were found, and their results do not confirm a general tendency.

3.2. Effects of HPP on Antioxidant Activity (AA)

The first study on the effects of high-pressure processing (HPP) on antioxidant activity was published in 2000 [194], showing that the antioxidant potential of pressurized apple juice was comparable to that of fresh apple juice stored for one month at 4 °C. The impact of various processing methods on the antioxidant activity of fruit and vegetable (F&V) derivatives has been well-documented over the years. Processing can lead to different outcomes: no effect, a loss of naturally occurring antioxidants, an enhancement of the antioxidant properties of existing compounds, the formation of new antioxidant compounds (e.g., Maillard reaction products), or even the creation of pro-oxidant compounds (e.g., Maillard reaction products). Additionally, interactions among compounds, such as lipids with natural antioxidants or Maillard reaction products, can also occur [195]. Throughout storage, the antioxidant capacity of many fruits and vegetables tends to remain stable, and they generally show visible signs of spoilage before any significant loss in antioxidant activity [196]. HPP has emerged as a viable alternative to heat treatments for preserving the antioxidant properties of F&V preparations.

Looking at the effects in antioxidant activity shown in Table 1, HPP maintains or improves AA in many products (e.g., 54% TPC in broccoli and 48.8% DPPH in carrot

juice). In general, effects vary by matrix; also, PATP modifications on AA can vary with a pressure-temperature combo. Several examples are gooseberry juice (12–28% increase) and a sugarcane beverage (13.2% gain). Generally, thermal processing leads to AA loss and often lower TPC or DPPH compared to HPP. So, the TPC in carrot juice increases 45% with TP and 53% with HPP; the AA in prickly pear increases 35% with TP and 21% with HPP.

The main results obtained from researchers who investigate these treatments after storage are that HPP-treated samples generally retain more antioxidant activity, especially when measured as total phenolics (TPC), DPPH, or ABTS assays. TP may outperform HPP in rare cases (e.g., cherry juice), but usually under specific conditions. Long storage tends to reduce AA in both treatments, but HPP degradation is generally slower.

In comparison to other studies examining the effects of HPP on antioxidant preparations from fruits and vegetables [79], a positive correlation was found between bioactive compounds—such as anthocyanins, flavonoids, vitamin C, and carotenoids—and antioxidant activity. These researchers also concluded that HPP more effectively preserves both the antioxidant compounds and their overall antioxidant capacity compared to thermal treatments. Additionally, other researchers have highlighted the importance of selecting the appropriate temperature and processing time to optimize the retention of antioxidant activity [197].

In summary, all the studies reviewed (included in Table 1) were heterogeneous and varied in several aspects: fruit derivatives (juice, smoothie, puree…), plant species and varieties (strawberry, orange, apple…), HPP treatment conditions (200–600 MPa; 0.5–15 min; 15–60 °C), methods to determining all quality parameters, e.g., DPPH, ABTS, FRAP, TPC (for antioxidant activity), volumetric, spectrophotometric or chromatographic assays (for vitamin C); and compounds measured in each method (ascorbic acid and/or dehydroascorbic acid for vitamin C; carotene and/or carotenoids for vitamin A).

On the other hand, the reviewed studies often lack an analysis of the correlation between parameters such as vitamin content and antioxidant activity, and several of them do not evaluate all these components simultaneously. As a result, it is difficult to draw general conclusions applicable to different fruits and vegetables (F&V) and their associated compounds.

Nevertheless, based on the results presented in Table 1, it can be observed that, overall, studies assessing the effects of pressurization on both vitamin levels (particularly ascorbic acid) and antioxidant activity tend to report better retention of these compounds compared to conventional heat pasteurization (see Table 2).

Table 2. Main conclusions from the results in Table 1.

Treatment	HPP	PATP	TP
Vitamin C	Best retention	Good potential, less consistent	Frequently degraded
Vitamin A	Often enhanced/retained	Promising, limited data	Lower retention
Antioxidant activity	Often enhanced or stable	Moderate to strong retention	Often reduced

HPP: High-Pressure Processing. PATP: Pressure Assisted Thermal processing. TP: Thermal Processing.

Therefore, it seems that HPP is the best of the three technologies, considering the higher retention values caused by ascorbic acid, carotenoids, and the antioxidant activity.

4. Conclusions

HPP is a relatively emergent technology used to preserve food and is environmentally friendly, as it only requires electricity and water, making it a green and sustainable technology with a lower carbon footprint.

It is clear that HPP consistently offers the best preservation of vitamin C. HPP-PATP can also be beneficial, but is less consistently reported. TP shows the greatest degradation for ascorbic acid. As for carotenoids, HPP tends to maintain or improve vitamin A compounds better than TP. TP tends to cause greater carotenoid losses, especially at higher temperatures or over longer periods. HPP-PATP shows promising results, but with less data to confirm them.

Studies on vitamin E are very few and show contradictory results. So, no clear conclusion can be reached regarding tocopherols in pressurized F&V preparations.

The studies that investigate the levels of antioxidant compounds/activity after storage yield similar results to those mentioned for vitamins.

Recommendations for the future: Researchers would find a labile compound suitable for comparing the effectiveness of HPP treatment with other novel and conventional treatments (pasteurization by heat, by pulsed electric fields, ultrasound, etc.). In this way, the industry could choose the most suitable preservation method for its products, similar to the use of "F" values for heat treatments. Another recommendation is the use of food simulants enriched with labile compounds (e.g., ascorbic acid) to check and compare treatments, avoiding differences in food matrices. Moreover, legal concerns could be a barrier to exporting and selling pressurized products to other countries, and consumer acceptance with labels advertising the use of these emerging technologies is also a challenge.

Lower operational temperatures in HPP ensure the retention of heat-labile nutrients like vitamins and several polyphenols with antioxidant capacity, making F&V preparations nutritionally superior to thermally processed products. Maximum efficiency, cost-effectiveness, and quality improvement (especially in packaging) are aspects to be addressed in the future by HPP technologies.

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