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*Review*

# Processing Fresh-Cut Potatoes Using Non-Thermal Technologies and Edible Coatings

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**Abstract:** The increasing consumer demand for minimally processed and ready-to-cook food products has elevated the significance of fresh-cut potatoes, which offer health benefits, high sensory properties, and convenience. However, extending the shelf life of fresh-cut potatoes while preserving their organoleptic qualities remains a significant challenge. This review examines the effectiveness of emerging non-thermal technologies, such as osmotic dehydration (OD), high-pressure processing (HPP), pulsed electric field (PEF), and ohmic heating (OH), in processing fresh-cut potatoes. Among these, HPP and PEF have shown particular promise in extending shelf life and preserving sensory attributes, while OD and OH present advantages in maintaining nutritional quality. However, challenges such as high energy consumption, equipment costs, and industrial scalability limit their broader application. The use of natural preservatives and edible coatings is also explored as a means to enhance product quality and address the demand for clean-label foods. Further research is needed to optimize these technologies for large-scale production, reduce energy usage, and explore combined approaches for improved shelf life extension. This comprehensive review provides a critical analysis of the operational parameters of these technologies and their impact on the quality and shelf life of fresh-cut potatoes, identifying current research gaps and proposing directions for future studies.

**Keywords:** anti-browning agents; edible coatings; fresh-cut potato; high-pressure; non-thermal processing; ohmic heating; osmotic dehydration; pulsed electric field; thermal processing



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## 1. Introduction

Ready-to-cook and ready-to-use food products are currently gaining popularity due to the busy lifestyle of consumers and the demand of catering enterprises for less perishable food [1]. Within this trend, minimally processed foods—foods that are lightly altered to maintain freshness without undergoing extensive processing—have emerged as a focal point, with fresh-cut fruits and vegetables gaining significant prominence. Potatoes are among the most widely consumed vegetables globally, with the total harvested area worldwide being 17,788,408 hectares and production reaching 375 million tons (Mt) in 2022 according to the FAO. Major producers include China (95.5 Mt), India (56 Mt), and the USA (17.8 Mt), with the highest production volumes being achieved in Asia (203.3 Mt) and Europe (98.1 Mt). Potatoes (*Solanum tuberosum* L.) have been a fundamental source of human nutrition for centuries and stand as the most crucial food crop [2]. Fully mature potatoes contain around 80% water, 12% starch, and 2% proteins [3]. Therefore, the dry matter mainly consists of starch, with a smaller amount of vitamins. The year-round availability of potatoes makes them an attractive crop for both fresh market sales and processing. Their versatility allows for consumption in various forms and diverse processing methods, including dehydration, freezing, and minimal processing, yielding an array of final products [4]. Fresh-cut potatoes, a form of minimally processed potatoes, have gained popularity as convenient products, significantly reducing the time needed for meal preparation in both households and restaurants. The heightened demand for fresh-cut potatoes is a response to the accelerated lifestyle prevalent in today's world. However, like other fresh-cut fruits and vegetables, fresh-cut potatoes face the challenge of being convenient yet highly perishable products [5].

The production process of fresh-cut potatoes is a complex interplay of various factors that significantly influence both processing and shelf life, with cultivar selection playing a crucial role. Different potato varieties, like Spunta in Greece [6,7], Alpha, Chica, and Gallo in Mexico, Marabel and Primura in Italy, Caesar in France, Karlena and Saturna in Germany [8], Netherlands 15 in China [9], Agria in Iran [10], Russet Burbank in USA, Birgit in Croatia [11], and Maris Piper and Rooster in Ireland [12], bring unique characteristics to fresh-cut processing. Predominantly, potato varieties encompass a wide range of characteristics, including color, flesh type, and maturation times (mid-early, mid-late, and late). Different potato varieties exhibit unique morphological and chemical characteristics, which impact their suitability for various processing methods and their resistance to spoilage. For example, high-starch cultivars, such as Russet Burbank, are typically used for frying due to their texture but are more susceptible to enzymatic browning after cutting, linked to higher levels of starch and sugars, which can shorten shelf life [13]. Additionally, smooth-skinned varieties are generally easier to peel, which can reduce surface damage, while peel and cell structure differences influence resistance to microbial growth during storage. Cultivar selection, therefore, plays a key role in optimizing the quality, appearance, and durability of fresh-cut potato products. Additionally, the systematic variation in cutting shapes, ranging from slices of 1.5 to 5 mm thickness [14], tubes of 1.2 cm side length, disks [15], and cylinders with a diameter of 1 cm and a length of 1.5 cm [16] to slabs with dimensions like $4 \times 4 \times 0.7$ cm [17], allows for a comprehensive understanding of how different potato varieties respond to distinct processing techniques. This aids in identifying optimal choices for specific end products and contributes to the ongoing refinement of fresh-cut potato processing methods to preserve quality and extend shelf life effectively.

In the conventional fresh-cut processing of potatoes, which includes washing, peeling, slicing or cutting, and treatment with food additives, the resulting products are packed in sterilized packaging material and stored at refrigeration temperatures [18]. A significant quality issue for peeled and sliced potatoes is their susceptibility to rapid browning and microbial growth due to the loss of natural protective skin. This physical stress initiates chemical and biochemical spoilage processes, exacerbated by temperature fluctuations during distribution and storage [19]. As a result, peeled and packaged potatoes are afforded a limited shelf life, usually lasting 5–7 days at 4–5 °C, due to browning and microbiological, sensory, and nutritional deterioration [20].

Traditionally, various chemical additives, such as calcium chloride, calcium lactate, calcium phosphate, ascorbic acid, citric acid, L-cysteine, and sulfur dioxide, have been used to stabilize the shelf life of fresh-cut potatoes by minimizing quality degradation and browning [21]. These additives function as acidulants with multiple roles, including anti-browning, textural firming, antioxidation, and antimicrobial effects, which collectively delay tissue breakdown in fresh-cut fruits and vegetables [18,22]. However, health-conscious consumers are increasingly concerned about the safety and potential toxicity of synthetic preservatives, prompting a shift towards cleaner alternatives.

To address these concerns, researchers have turned to natural preservatives, such as plant extracts and essential oils, either used independently or combined with advanced packaging and edible coatings. These natural agents are intended to preserve the sensory qualities of fresh-cut products, such as color and texture, without resorting to synthetic additives [23,24]. Additionally, thermal treatments like sterilization or pasteurization, though effective for microbial control, are often less desirable for fresh-cut products due to their adverse effects on freshness and sensory appeal [25].

In recent years, non-thermal technologies, including high-pressure processing (HPP), ultrasound, pulsed electric field (PEF), etc., have gained prominence as alternatives to chemical and physical preservation methods [26]. Their application, either individually or in combination with other non-thermal treatments and natural additives, has demonstrated efficacy in extending the shelf life of fresh-cut fruits and vegetables [27,28]. This trend has been observed across various products, including apples, strawberries, avocados, juices (various fruits), grapes, tomatoes, berries (e.g., blueberries), lettuce, oranges, carrots, and mangoes [29–35]. Achieving high-quality fresh-cut potatoes with satisfactory sensorial and nutritional qualities, along with an extended shelf life, necessitates the exploration of advanced chemical, clean-label, and non-thermal technologies and their combinations.

The processing of fresh-cut potatoes via conventional and non-thermal methods is mentioned in previous review papers dealing generally with fruit and vegetable preservation [36–39] or specifically with potato products [18,38,40,41]. Another review summarized emerging technologies towards the recovery of valuable bioactive compounds from potato peel [42]. Numerous studies have been published in the recent years dealing with the challenging topic of the prediction of the shelf life of minimally processed fresh-cut potatoes [43].

This work is based on a comprehensive review of the literature, which set relevant keywords in Google Scholar and Science Direct. The middle part of this review deals with the non-thermal technologies of osmotic dehydration (OD), HPP, PEF, ohmic heating (OH), ultrasound, irradiation, and plasma treatment. At the end of the present paper, traditional and novel anti-browning agents, as well as edible coatings and films, are presented. Finally, there is an increasing trend of combining these agents with the non-thermal technologies described in the previous subsections. It should be noted that this review does not focus on works that applied thermal or non-thermal methods as postharvest handling to inhibit the sprouting of raw potato tubers [44–47] or reduce the losses during their storage [48–53]. The primary focus of this review is on non-thermal technologies employed in the processing of fresh-cut potatoes. Notably, while the majority of studies adhere to this focus, a limited number of investigations have explored the impact of non-thermal treatments on the oil uptake content during the frying of potatoes [54].

The aim of this comprehensive review is to meticulously compare the operational parameters of the various technologies applied in the processing of fresh-cut potatoes. Through a systematic evaluation, the aim is to demonstrate the influence of these technologies on the shelf life of potatoes, shedding light on their efficacy in preserving the overall quality of the end product. In pursuit of this goal, this review critically examines the existing literature, highlighting both the strengths and limitations of each technology.

## 2. Signs and Mechanisms of Deterioration in Fresh-Cut Potatoes

The appearance, flavor, taste, and texture of processed food are key factors in their acceptance by consumers. Various physicochemical and organoleptic parameters of fresh-cut potatoes are examined to determine alterations during storage, especially after processing. The alterations are indicated by (i) visual attributes related to color (browning), (ii) sensory attributes such as taste (sweetness, mealiness, adhesiveness) and odor (typical or cardboard-like off-odor) [55], (iii) physical properties (weight loss), (iv) mechanical-textural properties (firmness or hardness, shear force, break force, crispness) [3], (v) chemical properties (respiration rate, ethylene generation, ascorbic acid, malondialdehyde and amino acid content, $H_2O_2$, superoxide anions, nutrient loss), and (vi) microbiological parameters (number of bacteria colonies), primarily involving spoilage microorganisms such as *Pseudomonas* spp., *Lactic acid bacteria*, *Clostridium botulinum*, *Enterobacteriaceae*, and yeasts (*Penicillium* and *Aspergillus*) and molds (*Candida*), which contribute to off-odors, sliminess, and textural degradation [56,57]. All these parameters affect the commercialization of fresh-cut potato products and the consumer's willingness to purchase them.

The color of fresh-cut potatoes is the first significant commercial and consumption-related property. The color scale most commonly utilized for referencing color is the CIE $L^*a^*b^*$ scale, which relies on parameters such as $L^*$, $a^*$, and $b^*$, along with derivative measurements like hue and chroma [58]. The $L^*$ parameter indicates brightness, ranging from 0 (black) to 100 (white). An increase in $L^*$ indicates lighter color, while a decrease suggests a darker hue. The $a^*$ parameter measures the green-to-red axis (positive for red, negative for green), and $b^*$ measures the blue-to-yellow axis (positive for yellow, negative for blue) [56]. Studies have demonstrated the importance of these parameters in monitoring color changes in fresh-cut potatoes during storage. For instance, Song et al. (2013) investigated browning inhibition in fresh-cut potatoes using heat and ascorbic acid treatments. The study found that ascorbic acid treatments effectively reduced browning by inhibiting polyphenol oxidase (PPO) activity, with the treated samples showing better color retention over time [59]. Furthermore, studies by Wang et al. (2015) on postharvest curing highlight that treating fresh-cut potatoes can effectively stabilize color by inhibiting PPO activity and modifying phenolic metabolism, thereby minimizing browning and maintaining L* values [60]. Similarly, Tang et al. (2023) demonstrated that ascorbic acid content in fresh-cut potatoes can prevent browning by inhibiting PPO and maintaining high ascorbic acid levels, linking ascorbic acid with reduced browning susceptibility [61]. Additionally, Tsouvaltzis et al. (2011) examined hot water treatment as a method to reduce browning in fresh-cut potato slices. Short hot water treatments were found to lower browning severity by decreasing PPO activity and controlling phenolic synthesis [62]. The difference between the initial and final values of these parameters indicates changes in the processed food product during storage at low (4–5 °C) or ambient temperatures [56]. Thereafter, the total color difference ($\Delta E^*$) and the browning index ($BI$) can be determined by the three coordinates ($L^*$, $a^*$, and $b^*$) [63]. Generally, the $L^*$ value declines with browning and increasing storage time, whereas $BI$ increases. A higher $\Delta E^*$ value indicates a notable color alteration compared to the initial color values. Values greater than one ($\Delta E^* > 1$) means visible (detectable by naked eyes) color changes [63].

The amount of weight loss, expressed on a percentage (%) or wet weight basis (g/kg), has been determined in packed [57] and unpacked fresh-cut potato products, with samples weighed on a daily basis or on the final day. Weight loss gradually increases with increased storage time and temperature due to water loss. Particularly, Tsakiri-Mantzorou et al. (2024) showed that the rate of weight loss presented an increasing trend over time for edible-coated fresh-cut potato samples during their storage at 4 °C [64]. Potato slices treated by pressurized gasses (Ar, $N_2$, and mixed Ar + $N_2$) were observed to lose significantly less water than the control (untreated) sample [56]. The firmness (hardness) of a potato sample, expressed in Newton (N) units, reflects the maximum force required to puncture a potato slice or cube to the depth of 3 mm at a rate of 3–5 mm/s. A cylindrical probe is used to push the potato sample. Generally, the hardness of fresh-cut potatoes decreases during storage [64].

Microbiological spoilage is a critical concern in maintaining the quality and safety of fresh-cut potatoes. Studies have demonstrated that specific bacterial communities and antimicrobial treatments can significantly impact the rate and nature of spoilage. Recent research by Li et al. (2022) highlighted the dynamic shifts in bacterial populations in vacuum-packaged, peeled potatoes during storage, showing that bacteria like *Clostridium* and *Lactococcus* correlate with sensory deterioration and spoilage odors [65]. Meanwhile, Sarengaowa et al. (2022) explored the use of natural antimicrobials, such as cinnamon oil in chitosan-based coatings, which effectively inhibit spoilage microorganisms and preserve quality attributes, thus extending the shelf life of fresh-cut potatoes [66]. Additionally, Inoue and Izumi (2020) demonstrated that inoculation with *Pseudomonas* fluorescens accelerated browning in fresh-cut potatoes by increasing PPO activity, highlighting the role of specific spoilage bacteria in quality degradation [67]. These studies provide valuable insights into microbial activity and potential treatments to control spoilage in fresh-cut potatoes, highlighting the importance of microbial management in food processing and storage.

Chemical parameters serve as indicators of changes occurring at the cellular and tissue levels in processed potatoes. Specifically, the oxidation of cell membrane is indicated by the concentration of malondialdehyde (MDA), reflecting the degree of membrane damage [56].

For instance, a study on fresh-cut potatoes conducted by Hu et al. (2021) demonstrated a direct correlation between elevated MDA levels and the degree of membrane damage, thereby illustrating the utility of this chemical parameter in assessing the oxidative status and overall quality of processed potatoes [68]. The respiration rate, typically expressed in mg $CO_2$ $kg^{-1}$ $h^{-1}$, is a key indicator of the metabolic activity and degradation processes occurring in fresh-cut potatoes. This measurement involves quantifying the emission of carbon dioxide ($CO_2$) as a by-product of physiological and biochemical reactions within the potato tissues. A higher respiration rate often corresponds to increased metabolic activity and degradation of chemical constituents, reflecting changes in the organoleptic and nutritional qualities of fresh-cut potatoes [69]. Ethylene generation, expressed in ng/kg/s, is another critical parameter used to assess the chemical properties and degradation of fresh-cut potatoes. Ethylene is a plant hormone that plays a crucial role in various physiological processes, including the ripening and senescence of fruits and vegetables. In the context of fresh-cut potatoes, monitoring ethylene generation provides insights into the progression of ripening and associated biochemical changes. Increased ethylene production is often associated with the degradation of certain chemical constituents, affecting the overall quality and shelf life of fresh-cut potatoes [57]. Aldehydes are found to be the main cause of an off-flavor in fresh-cut potatoes during storage. These compounds are considered the primary contributors to the distinctive odor associated with the deterioration of fresh-cut potatoes over time. The presence of aldehydes serves as a key indicator of oxidative processes and the degradation of lipids, leading to the formation of undesirable sensory attributes in fresh-cut potatoes [70]. Furthermore, the retention of ascorbic acid, total polyphenol content, and antioxidant activity indicate an effective processing. Finally, more advanced analytical techniques have been used such as nuclear magnetic resonance imaging (NMRI) to estimate the water distribution within a potato slice [56].

## 3. Packaging and Storage Conditions of Fresh-Cut Potatoes

Packaging is of great importance for the proper handling and distribution of fresh-cut potatoes. These products are generally packaged in (i) flexible polymeric bags, (ii) rigid plastic trays, sealed with cover polymeric films, or (iii) overwrapped trays [71]. Generally, packaging methods can extend the shelf life of fresh-cut potatoes without using chemical agents. The selection of appropriate packaging materials and techniques is essential for maintaining the quality and safety of the product during storage and transportation.

One of the simplest and most minimal treatments of potatoes aiming at storage and preservation is vacuum and modified-atmosphere packaging [57]. Vacuum packaging is a preservation technique that involves removing air from the packaging to create a vacuum-sealed environment, which helps reduce oxidative reactions and microbial growth. Unlike other modified-atmosphere packaging (MAP) methods that involve altering the gas composition (such as introducing $CO_2$ or $N_2$), vacuum packaging simply removes air to create a low-oxygen environment [72]. Vacuum packaging is considered a low-cost technique and is widely employed for extending the shelf life of various food products. In vacuum packaging, the absence of oxygen helps preserve sensory qualities such as texture and moisture by preventing oxidation, which is particularly beneficial for fresh-cut potatoes. Additionally, vacuum packaging is relatively low-cost and simple to implement, making it a widely used technique in the food industry for extending shelf life without the need for complex gas management systems [70]. The combination of vacuum packaging with anti-browning agents can extend the shelf life of fresh-cut potatoes to about 2 weeks [73]. However, a primary limitation of vacuum packaging is the potential for anaerobic bacterial growth, especially pathogens like *Clostridium botulinum*, if the product is stored at improper temperatures [73]. Li et al. (2022) explored the bacterial community shifts in vacuum-packaged peeled potatoes during storage. They observed changes in dominant bacteria species over a 12-day period, correlating these shifts with sensory and chemical deterioration, particularly with the accumulation of volatile organic compounds responsible for spoilage odors. Their study highlights vacuum packaging's ability to extend shelf life while noting the importance of monitoring microbial dynamics [65]. Korzan and Lovkis (2022) evaluated the preservation of peeled potatoes using various types of vacuum packaging materials. Their findings indicated that vacuum-sealed potatoes stored at 4 °C maintained quality, with reduced moisture loss and minimized microbial growth, particularly in packaging using biodegradable films. Their study confirms the utility of vacuum packaging in extending the shelf life of minimally processed potatoes [74].

Sous vide, often considered a specialized variation of vacuum packaging, involves vacuum-sealing food in airtight bags followed by slow and controlled cooking at low temperatures [75]. The vacuum-sealing process removes air from the packaging, creating a modified atmosphere that helps prevent oxidation and microbial growth [76]. The sous vide method has several advantages, particularly in retaining the flavor, texture, and moisture of the product through gentle, low-temperature cooking, which also helps preserve nutrients. However, one significant disadvantage of sous vide is the food safety risk associated with its anaerobic environment; if temperatures are not precisely controlled, pathogens like *Clostridium botulinum* may grow. Additionally, sous vide requires specific equipment, such as vacuum sealers and immersion circulators, which adds to operational complexity and costs [77,78]. Rizzo et al. (2018) evaluated the use of sous vide packaging method in association with rosemary essential oil (REO) as a strategy for quality preservation of sliced potatoes. The results demonstrated that the synergic use of REO and sous vide packaging positively influenced the texture of the potatoes and effectively inhibited the growth of mesophilic bacteria and Enterobacteriaceae throughout the storage period [75]. Onyeaka et al. (2022) reviewed the safety and quality aspects of sous vide processing. They highlighted its effectiveness in retaining nutrients and limiting microbial growth when combined with natural antimicrobials, which makes it suitable for delicate products like fresh-cut potatoes. However, they noted that precise temperature control is essential to prevent food safety risks [78].

Modified-atmosphere packaging (MAP) is a preservation technique that involves altering the composition of the gasses surrounding a food product within its packaging. MAP is designed to create an environment with controlled levels of oxygen ($O_2$), carbon dioxide ($CO_2$), and nitrogen ($N_2$), which helps slow down various deterioration processes such as oxidative reactions and microbial growth [79]. MAP at a ratio of 30% $CO_2$/70% $N_2$ has been observed to reduce some anaerobic bacteria compared to vacuum packaging. However, effective MAP should consider the lowest, critical $O_2$ concentration that does not provoke anaerobic metabolism to ensure optimal conditions for product preservation [80]. This approach helps maintain the quality and freshness of fresh-cut potatoes for an extended shelf life. One of the key advantages of MAP is its ability to preserve sensory qualities, such as color, texture, and moisture, by limiting oxidation and reducing undesirable off-flavors. Additionally, it offers flexibility and is applicable to a variety of food types. However, MAP also has some drawbacks; for instance, if gas levels are not properly managed, anaerobic conditions may develop, potentially promoting harmful bacteria like *Clostridium botulinum*. Furthermore, MAP requires specialized equipment and can be cost-intensive, especially when combined with refrigeration to maximize effectiveness [81,82]. Compared with vacuum packaging, modified-atmosphere packaging inhibits the generation and development of undesirable flavors and maintains the sensory profile of fresh-cut potatoes in a better manner during storage [70]. Siracusa et al. (2012) conducted a study on the gas permeability and thermal behavior of polypropylene films in MAP for fresh-cut potatoes. They found that MAP with an optimized gas composition (low $O_2$, high $CO_2$) slowed down browning and microbial growth, extending the shelf life for catering applications. The study emphasized the benefits of MAP in maintaining quality during storage [83]. Montouto-Graña et al. (2012) evaluated consumer acceptance and quality of fresh-cut potatoes under MAP compared to vacuum packaging. MAP maintained sensory qualities, including texture and flavor, effectively extending shelf life and increasing consumer purchase intent. The study highlighted MAP's role in sensory quality preservation [84]. In summary, packaging materials and methods used for the storage of fresh-cut potatoes are presented in Table 1.

**Table 1.** Packaging materials and methods used for the storage of fresh-cut potatoes *.

| Packaging Method | Packaging Conditions | Storage Conditions | Reference |
|---|---|---|---|
| Air storage | 100 g potato strips per replicate, continuous air flow: 10 mL/min | 6 d, 4 °C | [85] |
| Vacuum packaging | PE bags | 5 d, 0–10 °C | [43] |
| Vacuum packaging | vacuum time: 30 s; sealing time: 2 s; cooling time: 3 s; PE bags | 5 d, 4 °C | [57] |
| Vacuum packaging | vacuum time: 20 s; VOH packaging bags | 18 d, 4 °C | [70] |
| Vacuum packaging | PE and PA/PE bags | 10 d, 3 and 10 °C | [86] |
| Modified-atmosphere packaging | 30% $CO_2$/70% $N_2$ | 18 d, 4 °C | [70] |
| Modified-atmosphere packaging (MAP) | 100 g potato strips per replicate, sealed in LDPE bags | 6 d, 4 °C | [85] |
| *Sous-vide* packaging | - | - | [76] |
| *Sous-vide* packaging | - | 11 d, 4 °C | [75] |

* PE: polyethylene; VOH: vinyl alcohol; PA/PE: polyamide/polyethylene; LDPE: low-density polyethylene.

The importance of temperature for food shelf life is mentioned in several studies. Storage temperature and duration play a vital role in the shelf life and physicochemical properties of fresh-cut potatoes. PPO activity, weight loss, and the total number of colonies in fresh-cut potatoes processed with chemical solutions were observed to increase with temperature increase from 0 to 10 °C and time [43]. Low-temperature storage following chemical preservation is a simple and effective way to keep potatoes fresh, reducing the reproduction rate of microorganisms and delaying the senescence of tissues [43]. However, few studies have investigated the multifactorial aspects of shelf life growth of microorganisms considering variables such as storage temperature, duration, and processing methods.

In summary, effective packaging and storage methods are essential to maintaining the quality and extending the shelf life of fresh-cut potatoes. Vacuum packaging offers a simple and cost-effective way to slow oxidation and preserve texture, though it requires careful temperature control to prevent anaerobic bacterial growth. Sous vide adds value through its low-temperature cooking, enhancing texture and flavor retention but with specific equipment and safety requirements. MAP provides controlled gas environments that help retain sensory qualities, reduce browning, and inhibit microbial growth. However, it requires careful gas management and can be more costly. Each method provides distinct benefits and challenges, underscoring the importance of selecting the most suitable packaging strategy based on storage conditions, product quality goals, and cost considerations.

## 4. Conventional Processing Technologies and Chemical Treatments

Conventional processing of fresh-cut potatoes includes two main categories: (i) thermal treatment and (ii) the application of anti-browning or firming agents (chemicals). The scientific interest in thermal methods is still lively, and researchers are trying to optimize their application or to combine them with novel techniques. The most common thermal technologies are boiling [55], blanching with hot water or steam [87], freeze-drying (lyophilization)[15], freeze–thawing [88], and thermal shock cycling, which consists of blanching at 90 °C followed by soaking in ice water [89]. Freeze–thaw dehydration is considered a conventional processing method to produce dehydrated potatoes. This treatment was applied on fresh-cut potato tubes, and studies have examined different freezing rates (0.02–0.40 °C/min), dehydration efficiency, reduction in immobilized water ($T_{22}$), protein and mineral retention, and metabolomic changes (lipids, organic acids, and amino acids) [88]. Blanching is widely used to inactivate the enzymes that cause browning and spoilage, which helps in preserving the color and texture of fresh-cut potatoes. However, it can also lead to a reduction in water-soluble nutrients, such as vitamin C and some polyphenols, due to high temperatures and water exposure. This loss of nutrients, particularly antioxidants, can reduce the nutritional value of the product despite the sensory benefits achieved in color and texture preservation [90,91]. Different blanching methods, such as low-temperature blanching and stepwise blanching, can minimize nutrient loss while still achieving the desired sensory effects by carefully controlling temperature and time [92].

Freeze-drying (lyophilization), on the other hand, offers a significant advantage in retaining both the freshness and nutritional quality of potatoes. This process removes water by sublimation at low temperatures, which helps preserve heat-sensitive compounds such as vitamins, polyphenols, and other bioactive components that are prone to degradation in high-heat methods [93]. Freeze-drying also maintains the structural integrity of the potato tissues, resulting in a product with better rehydration properties, a brighter color, and a fresher appearance compared to traditional drying techniques [94]. However, freeze-drying is energy-intensive and has high operational costs, which limits its practicality for large-scale production, despite its advantages in preserving sensory and nutritional quality. Conventional thermal treatments have drawbacks such as damage in heat-sensitive food compounds like vitamins and polyphenols, high energy consumption, low environmental sustainability, and waste production [95]. Conventional oven-drying usually results in food tissues of a darker color [96]. Conversely, freeze-drying (lyophilization) offers an advantage in terms of retaining the freshness of the product. Chemical treatments and conventional thermal technologies applied to fresh-cut potatoes are summarized in Table 2.

**Table 2.** Chemical treatments and conventional thermal technologies applied to fresh-cut potatoes *.

| Treatment | Processing Conditions | Storage Conditions | Treatment Purpose | Reference |
|---|---|---|---|---|
| Boiling after immersion in lactic acid (LA) + $CaCl_2$ | 0.5% $v/v$ LA + 0.5% $w/v$ $CaCl_2$, 10 h immersion, packed in aluminum foil vacuum pouches (−70 kPa), boiling for 10 min | - | To improve hardness using lactic acid and $CaCl_2$ | [97] |
| Boiling | 15 min, 95–100 °C, 200 g slices/1.5 L water, storage at 4 °C | 5–24 h * | To evaluate thermal processing impact on sensory profile and off-odors | [55] |
| Blanching (hot water) | 3.5 min at 85 °C, vacuum-packaged | 12 d, 3 ± 1 °C | To evaluate coatings, blanching, and ultrasound effects on vacuum-packed potatoes | [98] |
| Blanching (hot water) | 95 °C, 3 min | | To assess radiofrequency blanching effects on enzyme activity and structure | [99] |
| Blanching (hot water) | 5 min at 65 °C, potato/water = 1:60 ($w/v$) | - | To examine browning and fat absorption | [54] |
| Blanching (hot water) | Pre-cutting treatment at 55 °C for 10 min | 6 d, 5 °C | To reduce browning in potato slices | [62] |
| Blanching (low temperature) | 30 min at 60 °C, frying at 185 °C for 4.5 min | - | To improve cell wall calcium and firmness in fries | [100] |

**Table 2.** *Cont.*

| Treatment | Processing Conditions | Storage Conditions | Treatment Purpose | Reference |
|---|---|---|---|---|
| Blanching (high temperature) | 4 min at 85 °C, frying at 185 °C for 4.5 min | - | To improve cell wall calcium and firmness in fries | [100] |
| Blanching (steam) | 80 and 90 °C, 0.5–10 min, steam injection | - | To investigate effects on PPO activity | [87] |
| Curing (postharvest) | Curing treatment: 10 d at 16 °C, slices dipped in 50 mg/L NaOCl for 5 min, packed in PE bags | 12 d, 2–3 °C | To study effects on color and phenolic metabolism | [60] |
| Deep freezing | 100 g potato strips per replicate, freezing in liquid $N_2$ | 6 d, −22 °C | To measure vitamin C retention | [85] |
| $CaCl_2$ (3% *w*/*w*) | Firming agent, different cut shapes: slices, wedges, cubes, dice | 12–60 d, 4 °C | To evaluate effects of cut type on quality and shelf life | [34] |
| $CaCl_2$ (3% *w*/*w*) | 3 min dipping, potato slices packed in PE bags | 14 d, 4 °C | To prevent enzymatic browning | [101] |
| Freeze–thaw treatment and dehydration | Freezing rate: 0.11 °C/min, freezing at −5 °C and thawing at 4 °C | - | To analyze changes in potato properties during freeze–thaw dehydration processing | [88] |
| Superheated steam (SHS) + hot water microdroplet (WMD) spray | SHS at 115 °C and 2.46 kg/h flow rate, WMD at 0.54 kg/h flow rate, 2.5–16 min heating time | - | To compare steam and water spray blanching for potato processing | [102] |

* PE: polyethylene.

In recent years, innovative thermal technologies such as OH, microwave heating, radiofrequency heating, infrared heating, and inductive heating have emerged. These methods aim to generate heat directly within the food material, enhancing energy efficiency in processing [103]. These innovative techniques are discussed in Section 5, with a focus on OH, because they have been recently used under various processing conditions or in conjunction with natural active compounds including plant extracts and essential oils, edible coatings, and non-thermal technologies.

Conventional chemical agents employed for fresh-cut potatoes include citric acid, potassium sorbate, chlorine dioxide ($ClO_2$), sulfites, ascorbic acid, ethylenediaminetetraacetic acid (EDTA), citric acid ($C_6H_8O_7$), and kojic acid ($C_6H_6O_4$). These substances serve as anti-browning or firming agents, contributing to the preservation and quality of the potato products. Ascorbic acid, for instance, acts by reducing quinones to phenolic compounds, preventing further reactions that lead to pigment formation [104]. On the other hand, citric acid operates by lowering pH and chelating the copper at the active site of the enzyme [105]. Traditional agents like sulfites are highly effective in preventing both enzymatic and non-enzymatic browning, as they inhibit PPO and other oxidation processes. However, sulfites present health risks, particularly for individuals with sulfite sensitivity or asthma, as they can cause respiratory reactions and allergic responses [106]. Due to these health concerns, regulatory restrictions have been placed on sulfite use in fresh-cut produce, leading to a search for safer alternatives [107].

To mitigate these risks, alternative anti-browning agents, such as plant extracts and essential oils, are being explored for their natural antioxidant properties and lower risk of adverse health effects [108]. The application of traditional anti-browning agents (e.g., ascorbic acid) [56], synthetic preservatives (e.g., citric acid, benzoates, nitrates) [63], and novel anti-browning agents (e.g., plant extracts, essential oils) are discussed in Section 6. These alternatives offer promising results, providing effective browning prevention while reducing the potential health risks associated with traditional chemical additives.

In summary, conventional processing methods, including thermal treatments and chemical agents, remain central to extending the shelf life and maintaining the quality of fresh-cut potatoes. While methods like blanching and freeze-drying are effective in preserving sensory attributes, they also come with limitations such as nutrient loss and high energy costs. Innovative thermal technologies offer potential improvements in energy efficiency, although they are still being optimized for large-scale application. Conventional chemical agents like ascorbic acid and citric acid effectively prevent browning, yet consumer demand for safer, natural alternatives is driving interest in plant extracts and essential oils. Overall, these traditional and emerging techniques highlight the balance between efficacy, safety, and sustainability in fresh-cut potato preservation.

## 5. Emerging Processing Technologies: Operating Principles and Examined Parameters

Several novel methods of fresh-cut potato processing have been investigated on a lab-scale level. The most studied methods are OD, HPP, PEF, and OH. Other technologies include ultrasound [6], irradiation [109], and plasma [110] treatment, application of low direct current (DC) electrical field [96], intermittent microwave drying [10], and microwave vacuum drying [111]. The common aim of these technologies is to displace conventional treatments and prevent the enzymatic browning of the products. It should be noted that certain studies did not investigate the effect of the processing on the shelf-time of fresh-cut potato but focused on modeling mass transfer or evaluating quality indexes such as shrinkage, bulk density, rehydration capacity, phenolic content, or energy consumption. The advantages of non-thermal technologies are lower temperatures, shorter treatment times, lower energy consumption, and higher environmental sustainability than thermal methods [95].

Each emerging technology offers unique advantages for fresh-cut potato processing, yet certain methods show more potential for widespread application. HPP and PEF are particularly effective in inhibiting enzymatic browning and preserving texture, phenolic content, and nutrient levels, making them promising alternatives to conventional thermal methods [112,113]. OH, though a thermal method, provides rapid and uniform heating, reducing the degradation of heat-sensitive compounds compared to traditional heating [114]. Ultrasound and plasma treatments demonstrate additional potential by enhancing microbial safety with lower energy consumption, contributing to a more environmentally sustainable approach [115,116]. Among these, HPP and PEF stand out as the most promising technologies due to their strong balance of quality preservation, efficiency, and energy sustainability, positioning them as viable options for large-scale fresh-cut potato processing.

As mentioned in the introduction, this review mainly focuses on OD, PEF, HPP, OH, ultrasound, irradiation, and plasma treatment, as well as edible coatings, in the context of fresh-cut potatoes. Additionally, this review explores studies on combined processes, where multiple technologies are applied together to achieve synergies. In this context, synergies refer to the enhanced effectiveness and improved outcomes that result from integrating different methods, which may amplify the benefits of each individual approach. For instance, combining HPP with ultrasound may lead to more effective microbial inactivation and browning prevention than either method alone, as each technique targets different aspects of quality preservation [117]. Such combined treatments can outperform single-method approaches by utilizing the strengths of multiple technologies, resulting in improved texture, reduced enzymatic browning, extended shelf life, and potentially lower energy consumption compared to conventional or single-method treatments. This synergistic approach offers promising potential for large-scale application in the fresh-cut potato industry.

In summary, emerging technologies such as HPP, PEF, OH, and ultrasound provide promising alternatives to conventional thermal methods for fresh-cut potato preservation, offering improved quality retention, energy efficiency, and environmental sustainability. Among these methods, HPP and PEF are particularly notable for their potential in large-scale applications due to their effectiveness in preserving texture, nutrient content, and phenolic levels while inhibiting enzymatic browning. Additionally, combining these technologies, as seen with treatments like HPP and ultrasound, may further enhance preservation outcomes by leveraging the strengths of each method. Overall, the application of novel non-thermal technologies and their synergies presents a viable path toward more sustainable and effective processing solutions for the fresh-cut potato industry.

### *5.1. Osmotic Dehydration (OD)*

This process is based on the immersion (dipping) of a solid food in a hypertonic (highly concentrated) solution [6]. As a result, the food loses water, and the osmo-active solute is transferred into the food [36,118]. Hence, OD is a counter-current mass transfer process, the optimization of which depends on the cellular foodstuff and the operating conditions [119]. The diffusion of the solute compound into the product depends on the food tissue (structure), immersion time, solution temperature, concentration, and agitation (or stirring) [120]. However, the critical concentration of the osmotic agent should be taken into account, since below this concentration, the fresh-cut food can uptake water instead of dewatering [6].

The optimal result of OD treatment is to maximize water loss (g/100 g fresh sample) and minimize solid gain (g/100 g fresh sample) [17,119]. The first parameter reflects the dehydration extent, whereas the second one indicates the dry solids (salt or sugar) diffused from the osmotic solution into the potato. In addition, the lower the solid gain, the healthier the processed potato [14]. Generally, water loss and solid gain increase with increasing immersion time. The initial rate of salt uptake by potato cubes was found to increase with increasing NaCl concentration (10–18% *w*/*w*) in the osmotic solution, whereas the water loss increased with temperature (20–55 °C) and NaCl concentration (10–18% *w*/*w*) [121].

OD offers significant energy and quality advantages since it operates at lower temperatures (30–50 °C) than conventional, vacuum, or hot air drying methods, reducing the risk of heat-induced quality degradation [36]. Unlike high-energy processes like freeze-drying (lyophilization), OD requires less energy, making it a more economical and environmentally sustainable choice [10,121]. Low temperatures in OD also help prevent structural damage to cell membranes and reduce the loss of volatile flavor compounds, preserving the sensory quality of the fresh-cut food [36]. In an industrial setting, OD can be used to pretreat fresh-cut potatoes to lower the water content, which helps reduce microbial growth and extend shelf life, making it particularly valuable for potatoes destined for drying or frying applications. However, a key disadvantage of OD is the management of spent osmotic solution, which needs proper disposal or valorization; a common approach is its reuse in beverage production [36].

According to the reviewed papers presented in Table 3, the most commonly employed osmotic agents used in fresh-cut potato processing are sodium chloride and sucrose. In a few studies, these agents were used simultaneously [119,122] or in combination with maltodextrin [6,7] and grape seed extract [118]. Other studies used only maltodextrin [123] or ethanol [124]. Higher water loss and shorter drying times were observed at higher ethanol concentrations [124]. It should be noted that ethanol used at a relatively high concentration (30% *w*/*v*) in the aforementioned study is considered a higher-cost liquid compared to other osmotic agents in Table 3. Generally, the concentration of sucrose (up to 50–70%) used in osmotic solution was higher than that of NaCl (up to 30%) (Table 3). The immersion time in NaCl or sucrose solutions usually varied from 1 to 3 h (Table 3). On the other hand, different potato-to-osmotic-solution ratios were used in the studies listed in Table 3. Some works suggested ratios >1:10 in order to avoid dilution during treatment and operational cost [122].

**Table 3.** OD treatments applied to fresh-cut potatoes.

| Osmotic Agent and Concentration (*w*/*v*) | Immersion Conditions | Potato-to-Solution Ratio | Storage Conditions and Time | Practical Application | Reference |
|---|---|---|---|---|---|
| Ethanol (30%) | 20 min at 25 °C | 1:8 | Not Studied | Nutrient retention and dehydration efficiency | [124] |
| Maltodextrin (25%) | 30 min at 24 °C | 1:10 (*w*/*v*) | 4 °C | De-oiling method for potato chips | [123] |
| NaCl (5%) | Pre-cut immersion: 3 h at 20 °C | - | 5 d, 5 °C | Browning prevention in fresh-cut potato | [9] |
| NaCl (30%) | 60 min, with and without stirring | 1:40 (20 g/L) | Not studied | Improvement in drying rates and water removal | [6] |
| NaCl (10, 14, 18%) | 3 h at 20, 40, or 55 °C, magnetic stirring at 300 rpm | 1:20 | Not Studied | | [121] |
| NaCl (10%) | 1.5 min at 20–22 °C | 1:30 | Not Studied | Water content control in potato slices with minimal solid gain | [14] |
| NaCl + maltodextrin (total 30%) | 60 min at 45 °C, OD assisted by ultrasound at electrical power of 130 W, and frequency of 20 kHz, treatment with and without agitation | 1:40 (20 g/L) | Not Studied | Improvement in drying rates and water removal | [6] |
| NaCl + maltodextrin (total 30%) | 30–300 min at 32.5 °C, 6% NaCl, 22.5% total NaCl + maltodextrin, OD assisted by US at 130 W and 20 kHz | 1:15 | Not Studied | Impregnation of functional ingredients into foods | [7] |
| NaCl (10%) + grape seed extract (0.63%) | 8 h at 25 °C with solution stirring | 1:20 (50 g/L) | - | Texture and sensory quality retention in fresh produce | [118] |
| NaCl (1.5%) | 30 min at 24 °C | 1:10 (*w*/*v*) | 4 °C | De-oiling method for potato chips | [123] |
| NaCl (15%) | 90 min, OD assisted by US | 1:25 | Not Studied | Color, texture, and taste maintenance in dehydrated fruits and vegetables | [17] |
| NaCl (15%) + sugar (50%) | 90 min | 1:25 | Not Studied | Color, texture, and taste maintenance in dehydrated fruits and vegetables | [17] |
| Sucrose (50%) | 1.5 min at 20–22 °C | 1:30 | Not Studied | Water content control in potato slices with minimal solid gain | [14] |
| Sucrose (54.5%) + NaCl (14%) | 329 min at 22 °C, agitation at 200 rpm | 1:5 | Not Studied | Energy-efficient drying of fruits | [119] |
| Sucrose (36.35%) + NaCl (12.5%) | 68 min, 4 min microwave exposure, microwave power density: 0.38 W/g, vacuum pressure: 0.16 kPa | 1:10 | Not Studied | Rapid moisture reduction in fresh produce | [122] |
| Sucrose (10, 30, 50, 70%) | 2 h at 25 °C, without stirring | 1:5 | Not Studied | Water removal optimization with minimal nutrient loss | [10] |

The immersion of fresh potatoes in NaCl solutions was also tested in pre-cut (unpeeled) potato tubers in order to investigate its influence on browning, PPO activity, and amino acid content [9]. In another study, a novel variant of OD in NaCl or sucrose solutions, called post-dipping dehydration, was used, with a short immersion time of 1.5 min [14]. As a result of short immersion, the dipped potato slices gained a lower amount of sugar or salt.

Repeated, multistage dipping for short periods of time was proposed instead of a longer OD to achieve lower solid gain (solute uptake) and the same levels of water loss [14].

The experimental results of various studies on the impact of NaCl on enzymatic browning are contradictory. Some researchers found that pre-cut treatment of tubers inhibited the browning of fresh-cut potato slices by reducing the activity of PPO [9]. In other cases, post-cut treatment with NaCl did not inhibit PPO activity and enzymatic browning [9].

The optimization of OD has also been studied in combination with other methods (see Tabel 6) such as OH, ultrasound [7,17], and a pulsed microwave vacuum environment [122]. Ultrasound-assisted OD of potato cubes for 60 min, with and without agitation, increased the effective diffusivity of water due to the breaking of the cell structure [6]. In addition, the agitation of the osmotic solution during the dipping of potatoes promoted mass transfer from the solution to the potatoes [6]. In another case, ultrasound-assisted OD, as well as OD only, reduced oil uptake by fried potato slabs, with no significant difference between the two treatments [17]. Additionally, Mari et al. (2024) investigated the use of OH and OD to extend the shelf life of fresh-cut potatoes and inhibit enzymatic browning. The study optimized OD by varying solution concentrations and immersion times, while also adjusting the electric field strength and heating duration for OH. The results showed that OD effectively minimized weight loss, reduced enzymatic activity by 50%, and provided microbial control, whereas OH significantly enhanced sensory quality. However, combining both methods did not further improve quality attributes, highlighting the efficacy of OD alone as a preservation strategy for fresh-cut potatoes [125]. More information about binary treatments by OD and other technologies is given in Section 5.5.

### *5.2. High-Pressure Processing (HPP)*

High pressure (HP) is characterized as a "third dimension" in food processing, along with temperature and time [126]. The application of high hydrostatic pressure (100–1000 MPa) to the food at low–middle temperatures for a controlled time (1–20 min) and temperature deactivates or prevents the enzymatic browning of fruits and vegetables, inhibits or delays microbial growth, and enhances mass transfer phenomena. HPP can be performed in a horizontal or vertical mode, with the food sample placed in a hyperbaric vessel [12]. Non-toxic pressure-transmitting media, such as mixtures of ethanol and water with the desired thermophysical and chemical properties, are employed in HPP, facilitating the effective transmission of pressure to the samples.

This method has garnered attention for its various advantages. One notable benefit is its ability to extend the shelf life of perishable foods without the need for chemical preservatives. HPP effectively inactivates spoilage microorganisms and pathogens, such as bacteria, yeasts, and molds, thereby maintaining the nutritional quality and sensory attributes of the treated products [127]. Additionally, HPP is known for preserving the natural color, flavor, and texture of foods, offering a more appealing alternative to traditional thermal processing methods [128]. In an industrial setting, HPP can be applied to fresh-cut potatoes to extend shelf life by reducing microbial load and enzyme activity. This is particularly beneficial for ready-to-eat or minimally processed potato products, where maintaining texture, color, and freshness is essential. However, HPP comes with its set of disadvantages. One major drawback is its capital-intensive nature, as the equipment required for HPP can be costly to install and maintain. The technology is also energy-intensive, requiring substantial power to generate and sustain the high pressures involved [129]. Furthermore, not all food products are suitable for HPP, as certain items may experience changes in texture or quality after treatment [130]. Packaging considerations are also crucial, as materials must be capable of withstanding the intense pressures without compromising the integrity of the package [131]. Despite these challenges, ongoing research and advancements in technology continue to address some of these limitations, making HPP an increasingly viable and sustainable option for food preservation.

While HPP offers distinct advantages in terms of microbial inactivation and preservation of sensory qualities, it is also notably energy-intensive compared to other non-thermal technologies. Studies comparing the energy efficiency of HPP with methods such as PEF and cold plasma highlight that HPP requires substantially more energy due to the high pressures sustained over processing times. This high energy demand increases operational costs and has environmental implications, especially when applied on an industrial scale. By contrast, technologies like PEF and cold plasma generally consume less energy while still achieving effective microbial control, although they may differ in their impact on food quality attributes. Therefore, energy efficiency remains a critical consideration in choosing an appropriate non-thermal processing method, with ongoing research aimed at optimizing HPP systems to reduce power consumption while maintaining efficacy [132]. Parameters of HPP applied to fresh-cut potatoes are shown in Table 4.

**Table 4.** Parameters of HPP applied to fresh-cut potatoes *.

| Treatment | Processing Conditions | Pressurization Fluid | Storage Conditions | Reference |
|---|---|---|---|---|
| HPP | (i) Potatoes vacuum-packed in PE/PA pouches, (ii) HPP at 600 MPa for 3 min, maximum temperature: 10.6 °C | - | - | [133] |
| HPP | (i) Peeled potato tubers vacuum-packed in PE/PA pouches, (ii) HPP at 600 MPa for 3 min, maximum temperature: 10.6 °C | | 14 d, 4 °C | [12] |
| HPP | (i) Vacuum-packed in PE/PA bags, (ii) HPP at 600 MPa for 3 min, final temperature: 10.6 °C | - | - | [134] |
| HPP | (i) Immersion of slices in sodium ascorbate (2% $m/v/$) for 3 min, (ii) vacuum-packed in PA/PE bags, (iii) HPP at 400 MPa for 3 min | Propylene glycol/water (1:1) | 15 d, 6 °C | [11] |
| HPP | (i) HPP at 200–800 MPa for 5 min, (ii) potato slices fried at 185 °C for 4 min | 1,2-propanediol | - | [54] |
| HPP | (i) Homogenized potato extract: sealed in PE bags, (ii) HPP at 800 MPa for 10 min, | - | 1 h, 22 °C | [135] |
| HPP + ultrasound | (i) Peeled potato tubers vacuum-packed in PE/PA pouches, (ii) HPP at 600 MPa for 3 min, final temperature after HPP: 10.6 °C, (iii) potato cubes subjected to US after HPP: at 20 kHz and 200 W for 10 min, final temperature after US: 28 °C | - | 14 d, 4 °C | [12] |
| HPP + ultrasound | (i) Potato sticks vacuum-packed in PP bags with distilled water, (ii) HPP at 200 MPa for 2, 6 or 10 min and at 400 MPa for 1, 2 or 6 min, (iii) US at 53 kHz and 500 W for 15 min (20 °C), potato/water ratio = 1:4 | Distilled water | 12 d, 4 °C | [136] |

**Table 4.** *Cont.*

| Treatment | Processing Conditions | Pressurization Fluid | Storage Conditions | Reference |
|---|---|---|---|---|
| HPP + UV-C irradiation | (i) Immersion of slices in sodium ascorbate (2% $m/v/$) for 3 min, (ii) vacuum-packed in PA/PE bags, (iii) UV-C irradiation: 2.70 kJ/m$^2$ for 5 min, (iv) HPP at 400 MPa for 3 min, fluid temperature: 25 °C | Propylene glycol/water (1:1) | 15 d, 6 °C | [11] |
| HP, high temperature | (i) Potato cylinders packed in LDPE bags, (ii) HPP at 600 MPa for 1 min, final temperature: 117 °C | Propylene glycol | −40 °C | [137] |
| HP, low temperature | (i) Raw tubers were vacuum-packed in PE films, (ii) pressure-shift freezing at 280 MPa and −28 °C, (iii) storage at −22 °C for 7 d, (iv) pressure-induced thawing at 290 MPa and −28 °C | Water/ethanol (1:1) | 7 d, −22 °C | [126] |
| HP, low temperature | (i) Raw tubers were vacuum-packed in PE films, (ii) pressure shift freezing at 240 MPa and −22 °C, (iii) storage at −22 °C for 3 d, (iv) pressure-induced thawing at 290 MPa and −22 °C | Water/ethanol (1:1) | 3 d, −22 °C | [138] |
| HPP + citric acid 1% | (i) Immersion of potato cubes in 1% citric acid, (ii) vacuum packaging in plastic bags, (iii) HPP: 400 MPa for 15 min, | Distilled water | - | [139] |
| HP shift freezing + HP-assisted thawing | (i) Freezing and thawing at 200 MPa, thawing process started at −22 °C | Water + ethanol (1:1) | - | [140] |

* PE: polyethylene; PA/PE: polyamide/polyethylene; LDPE: low density polyethylene; US: Ultrasound.

The effect of HPP on PPO activity was studied in peeled and non-peeled potatoes. It was verified that HPP at 600 MPa was more effective against PPO activity than that at 400 MPa [12]. Elsewhere, HPP at 600 MPa for 6 min showed no statistically significant change in the antioxidant activity (AOA) of the treated potato samples [133]. HPP treatment at 400 MPa for 6 min was observed to inhibit microbial activity but not enzymatic browning in fresh-cut potato sticks, which exhibited the lowest values of the lightness parameter ($L^*$) on a scale from black to white [136].

The combined treatment of UV-C irradiation followed by HPP was the most effective in reducing the total aerobic mesophilic bacteria count during the storage of potato slices, compared to the individual treatments by UV-C or HPP [11]. On the other hand, HPP decreased the content of chlorogenic acid more than the combined treatment. Both HPP and UV-C/HPP treatments significantly increased the content of reducing sugars (fructose, glucose), resulting in an increased acrylamide content in fried potato slices [11]. The European Regulation 2017/2158 limits the content (750 µg/kg) of acrylamide, a probably carcinogenic substance, in fried potatoes [11]. Therefore, the effect of processing technologies on acrylamide content should be further investigated.

A variation of HPP, called high-pressure low-temperature (HPLT) processing, involves pressure shift freezing (PSF), storage at −20 °C for 3 days, and pressure-induced thawing (PIT); it has been applied to both potato cylinders [126] and entire, unpeeled tubers after vacuum-packaging in PE plastic films [138]. The pressurization fluid was a mixture of water and ethanol at a ratio of 50/50 $w/w$. The mechanism of this process is based on the impact of pressure on ice water transitions, where HP improves the kinetics of freezing and thawing, as well as crystal characteristics [126]. Precisely, ice nucleation during freezing and crystal growth during storing and thawing can result in undesired cell damage and extraction of enzymes from the potato cells, enhancing PPO activity [126].

### *5.3. Pulsed Electric Field (PEF)*

The operating principle of PEF is the application of high voltage (0.1–80 kV/cm) and very short repetitive monopolar (unipolar) or bipolar pulses on vegetable and fruit tissues. The pulse duration (or width) varies from micro- (µs) to milliseconds (ms). The shape of pulses can be square-wave [141], rectangular [142], or exponential [143]. The food sample is placed between two stainless-steel parallel electrodes within a treatment chamber, where high-voltage pulses are repeatedly applied [3]. Generally, a PEF system consists of three main parts: (i) high-voltage pulse generator, (ii) treatment chamber, and (iii) control–monitoring system [144]. Key process parameters are electric field strength, flow rate, pulse waveform (exponential, rectangular, square-wave), pulse repetition rate, exposure time (pulse duration), specific energy density, and temperature variation in the treated sample [144].

The treatment chamber can be filled with deionized or tap water, potato juice, or salt solution in order to improve the electrical conductivity between the immersed potato sample and the electrodes [145]. The size of the chamber and the adjustable distance between the electrodes depend on the sample size [142]. For example, lab-scale electrodes are reported to have a surface area in the order of 100–400 cm$^2$, dimensions of 20 mm × 20 mm, and a thickness of 1 mm, respectively, whereas the distance between them (electrode gap) can vary from 1 to 80 cm [3]. According to the literature, the potato sample (slice, cube, cylinder, etc.) is placed parallel to the electrodes and is in contact with either the left or right electrode. Hence, the sample can exhibit a lengthwise orientation. In case of a cylindrical chamber (tube), electrodes are located at the bottom and top of the chamber [15].

As a low-cost alternative to high-intensity pulsed electric fields, low-density direct current (DC) electrical fields (40 V/cm for 1 min) were successfully used to reduce the browning of rehydrated, freeze-dried (lyophilized), non-blanched potato cylinders [96].

The input of electrical energy density ($Q$, J/m$^3$) supplied to the sample is calculated as follows:

$$Q\ (\mathrm{J/m^3}) = V_0 \times I \times t/\nu, \tag{1}$$

where $V_0$ is the peak voltage (V), $I$ is the current intensity (A), $t$ is the treatment time (s), and $\nu$ is the volume of the treatment chamber (m$^3$). The total treatment time ($t_{\mathrm{PEF}}$) is calculated as follows [146]:

$$t_{\mathrm{PEF}} = N \times n \times \tau, \tag{2}$$

$$T = n \times \tau, \tag{3}$$

where $N$ is the number of trains, $n$ is the number of the pulses, and $\tau$ is the duration of each pulse (µs); T represents the total processing time. On the other hand, the specific energy input is calculated using the following equation [147]:

$$W_{\mathrm{specific}}\ (\mathrm{kJ/kg}) = (V^2 \times n \times m)/(R \times W), \tag{4}$$

where $V$ is the pulse voltage (kV), $n$ is the pulse number (dimensionless), $m$ is the pulse width (µs), $R$ is the pulse resistance (ohm), and $W$ is the total weight of the sample and processing liquid in the treatment chamber (g).

The advantages and disadvantages of PEF are described in a recent publication [144]. One of the significant advantages of PEF lies in its ability to enhance microbial inactivation. The application of short, intense electric pulses to food products disrupts the cell membranes of microorganisms, leading to their deactivation [148]. This results in extended shelf life and improved safety of the treated food products. Additionally, PEF offers advantages in terms of maintaining the nutritional quality of foods. Unlike traditional thermal processing methods, PEF operates at lower temperatures, minimizing the impact on heat-sensitive nutrients and preserving the sensory attributes of the food [144]. Another notable advantage of PEF is its impact on enzymatic activity. PEF can selectively modulate enzyme activity, providing opportunities to control certain enzymatic reactions that contribute to quality changes in food [149]. This allows for tailored processing that maintains the desired characteristics in the final product. Furthermore, PEF can facilitate the extraction of valuable compounds from raw materials, such as juices from fruits, by disrupting cell structures and enhancing mass transfer [150]. In an industrial setting, PEF can be used to enhance the texture and quality of fresh-cut potatoes, especially for frying applications, as it helps reduce oil uptake and improves crispness. Additionally, PEF can aid in shelf life extension by controlling microbial levels. However, along with its advantages, PEF technology also presents some challenges and disadvantages. The scalability of PEF systems for large-scale food processing remains a technical challenge, and the development of cost-effective and efficient equipment is crucial for widespread adoption [144]. Moreover, the impact of PEF on the overall sensory attributes of food products is still an area of research and development [151]. The potential alterations in texture, color, and flavor need to be thoroughly understood and controlled to meet consumer expectations. Furthermore, the capital investment required for implementing PEF systems in existing food processing facilities can be substantial, posing a barrier to adoption for some companies [144].

PEF technology achieves a rupture of the cell membranes and forms pores (electroporation) in the cellular structure of plant tissues without compromising the quality of the food. Generally, PEF causes a smoother, softer texture and a lower cutting–breaking force of plant tissues. The temperature of PEF-treated potatoes increases by less than 1 °C [152]. Therefore, cell membrane electroporation, which increases cell membrane permeability, is the main mechanism of PEF processing. The application of PEF ($E$ = 1.5 kV/cm and 20 pulses) to potato slices induced pore formation in the cell membrane, altering diffusion characteristics and leading to an enhanced release of intracellular molecules and an improved uptake of low-molecular substances [8].

The application of PEF in the development of healthier fried potato products with a lower fat content has been investigated [3]. In this context, the treatment of potato slices with PEF at a strength of 5 kV/cm reduced the oil absorption of fried potato chips by up to 20.6% due to changes in the cellular microstructure and porosity [3]. However, higher electric field strengths (5–20 kV/cm) had an adverse effect, increasing the average pore diameter and total pore volume. Another work investigated the effect of PEF treatment followed by air drying at 60 °C on the mechanical properties (maximum cutting force) of fresh-cut potato cylinders [153]. The maximum cutting force, as an expression of fresh-cut potato firming (hardness), was found to increase after PEF treatment at 1 and 1.5 kV/cm [153]. A different study found that the starch properties (thermal stability, gelatinization behavior, susceptibility to digestive enzymes) inside shredded potatoes were not altered after PEF processing [147].

Potato chips prepared by PEF-treated slices were found to contain less acrylamide (approximately 10 ng/g fresh weight) [154]. PEF treatment of steam-peeled tubers can also affect the texture and kinetics of in vitro starch digestibility of French fries [103]. Specifically, the outer crust of PEF-treated fries was significantly harder compared to the crust of fries made from untreated tubers [103]. Other researchers applied PEF prior to vacuum drying (VD) at a fixed pressure of 30 kPa in order to notably reduce the drying time of potato disks [146]. In Table 5, the parameters of PEF applied to fresh-cut potatoes are presented.

PEF has also been tested as a pretreatment for potato freeze-drying [142]. The results showed a decrease in drying time by 31.5% and specific energy consumption [electricity consumption (kJ) per initial potato mass (g)] by 16.6%, as well as an improvement in drying rate by 14.3% under optimal PEF conditions [142]. Concluding, PEF as a non-thermal method can enhance potato drying.

**Table 5.** Parameters of PEF applied to fresh-cut potatoes.

| Electric Field Strength (kV/cm) | Optimal Processing Conditions | Reference |
| --- | --- | --- |
| 0.75 | 9000 pulses, Q * = 18 kJ/kg | [155] |
| 2.50 | 800 pulses, Q = 18 kJ/kg | [155] |
| 0.6 | 100 µs, T < 50 °C | [15] |
| 1.1 | 20 µs pulse width, 200 Hz pulse frequency, Q = 10 kJ/kg, | [3] |
| 5 | 5 µs pulse width, 100 Hz frequency, 2000 pulses, Q = 3.42 kJ/kg | [3] |
| 10 | 5 µs pulse width, 20 Hz frequency, 2000 pulses, Q = 3.42 kJ/kg | [154] |
| 1 | 30 kV pulse voltage, 4 µs pulse width, 2000 µs treatment time, 100 Hz, Q = 1.25 kJ/kg | [156] |
| 1 and 1.5 | 8 kV voltage, 10 µs pulse width, 1 s total time, 100 Hz frequency | [153] |
| 1.1 | 20 µs pulse width, 100 Hz frequency, 900–6250 pulses, Q = 50.1 kJ/kg | [147] |
| 1.1 and 1.9 | Energy input 10–50 kJ/kg, electrode gap = 13 cm, 900–1100 µS/cm, pulse duration = 20 µs, 200 Hz frequency, fried at 185 °C for 50 s, frozen at −20 °C for 18 min | [103] |
| 0.6 (PEF + vacuum drying) | n = 100 pulses, pulse duration = 100 µs, time interval (Δt) = 10 ms, total time = 0.1 s | [15] |
| 0.4 (PEF + OD) | Total time ($t_t$) = 0.3 s pulse repetition time = 100 µs, pulse duration = 1000 µs, T = 25 °C OD: 4% *w*/*w* NaCl (0.69 mol/L), solid/liquid = 1:20, 25 °C | [145] |
| 1.5–2.5 | n = 20 pulses, electrode distance (d) = 8 cm, pulse form: exponential, pulse duration = 400 µs, 2 Hz frequency | [8] |
| 0.74–1.01 | $W_T \leq 0.6$ kJ/kg, immersion in standardized water: NaCl (0.6156 g/L) and $CaCl_2 \cdot 2H_2O$ (0.0923 g/L), EC: 1400 µS/cm at 25 °C, potato/liquid medium = 1:3, vacuum packed | [143] |
| 30, 40, 50 ** | Potato starch–water suspension = 8 *w*/*w*, 1008 Hz frequency, pulse duration = 40 µs, electrode diameter = 0.30 cm, n = 20.16 pulses, total treatment time: T = 806 µs | [141] |
| 5 ** | Starch concentration: 35%, 1000 Hz frequency, pulse duration = 40 µs, electrode gap = 0.30 cm, chamber (cylinder) diameter = 0.30 cm, sample flow rate = 60 mL/min | [157] |
| 1.5 | Pulse width = 120 µs, pulse number = 40, pulse duration = 500 ms | [142] |
| 0.04 | Low DC electrical field, platinum (Pt) electrodes, sample chamber filled with distilled water, 1 min exposure of potato cylinders | [96] |

* $Q$ or $W_T$ is the total specific energy input expressed in J/g or kJ/kg; ** potato starch treatment.

Although PEF is considered an efficient non-thermal food technology, the complexity of the system and the interdependency of operational parameters hinder the upscaling of the process from a pilot to an industrial scale [144]. Accordingly, any alteration to one process parameter may consequently impact others, highlighting the importance of a comprehensive understanding of various engineering aspects.

*5.4. Ohmic Heating (OH)*

The principle of this technique is based on electrical current passing through a conductive food—i.e., a food that contains a substantial amount of water, ions, or other polar compounds—allowing electricity to flow effectively. Fresh-cut potatoes, for instance, are well-suited for OH due to their high water content and natural salts, which facilitate conductivity [125]. As a result, the ions contained in the aqueous phase and salts of the food0 move to the electrodes of opposite charges [95]. Then, the energy generated due to the electrical resistance of the food leads to a rapid and uniform temperature increase (volumetric heating) [158]. The OH process is mostly affected by the electrical conductivity (EC) of the sample, which increases in the presence of ionic (polar) compounds such as acids, bases, and salts [95]. In contrast, non-polar molecules such as fats and oils do not affect the EC of the food product [95].

Ohm′s law defines the passage of electrical current (voltage) through the food sample according to the following equation [95]: $V = I \times R$, where $V$ is the voltage (V), $I$ is the current intensity (A), and $R$ is the resistance (Ω or Ohm). The main parts of an ohmic heating system are a power source of alternating (AC) or direct current (DC), a non-electroconductive heating chamber (cell), stainless-steel electrodes, a thermocouple, a voltage control unit (current sensor), and a data monitoring and acquisition system (data logger and personal computer) [114]. The heating cell (chamber) can be in the form of a rectangle or cylinder [159,160]. To increase the electrical conductivity of the food sample, the sample chamber is filled with water or salt solution [159].

The advantages of OH processing include rapid heating and a uniform temperature profile, reduced energy usage and high energy conversion efficiency, low maintenance cost, high retention of nutrients and bioactive compounds in the final dried food, and shorter heating times compared to traditional heating techniques, which give the treated samples an equivalent or longer shelf life [114,160]. Specifically, the energy consumption of OH has been estimated to be 4.3–5.6 times lower than that of conventional heating [95]. OH can be applied as a pretreatment for solid food drying. In an industrial setting, OH is suitable for pretreating fresh-cut potatoes by inactivating browning enzymes, which helps prevent discoloration. This method is particularly useful for potatoes that will undergo further processing, like frying or baking. The disadvantages of OH are the corrosion of electrodes in ohmic cells due to electrochemical reactions, contamination of food by metals, low efficiency in food containing fat granules, higher initial cost to establish an OH system than conventional heating processes, and problems in upscale adaption [95,159]. So far, OH has mainly been applied to liquid products such as fruit juices, aiming for juice concentration and resulting in a higher polyphenolic content than after traditional heating [95,160]. The non-thermal effects of OH treatment refer only to the inactivation of metal-containing enzymes such as PPO (Cu), lipoxygenase (Fe), and alkaline phosphatase (Zn and Mg) [114].

Slices of purple-fleshed potato (PFP) subjected to OH at a voltage of 40 V/cm for 4 min were found to contain more anthocyanin and total phenolics than the control samples [159]. In addition, the ascorbic acid content decreased when the voltage gradient was 20 V/cm and the duration increased from 2 to 4 min [159]. In another case, OH with a moderate electric field (15 and 30 V/cm) was applied at various temperatures and times to extract phytochemicals (anthocyanins and phenolic compounds) from the purple potato cultivar Vitelotte [161]. In brief, OH gave promising results as a green extraction method for industrial applications, avoiding organic solvents.

Another study investigated the simultaneous use of OH and convectional air drying by changing the operational parameters (applied voltage, temperature and air velocity) to minimize the drying time by 32–38% [160]. This novel method provided a partial pre-gelatinization of starch molecules, which appeared to be an advantage for the food industry [160]. Besides the drying time, the authors investigated the effective moisture diffusivity, the enzymatic activity (peroxidase), the browning index, the starch gelatinization degree, and the content of ascorbic and total phenolics in potato samples [160].

### 5.5. Miscellaneous Technologies

This subsection presents and discusses other emerging technologies for potato processing, with a very limited number of research articles so far (Table 6), including ultrasound, irradiation, and plasma treatment.

**Table 6.** Other technologies for processing fresh-cut potatoes *.

| Materials | Processing Conditions | Storage Conditions | Reference |
| --- | --- | --- | --- |
| OH | 20 and 40 V/cm, exposure: 2 and 4 min, final temperature after 4 min at 40 V/cm: 65 °C, electrode distance: 10 cm, electrode size: 6 cm × 10 cm, | - | [159] |
| OH | 15 and 30 V/cm, time: 5 and 10 min at 30, 60 and 90 °C, anthocyanin and extraction | - | [161] |
| OH with convective drying | Applied voltage: 112 V, needle-shape electrodes: 3 mm in diameter, air velocity: 1.07–1.98 m/s | - | [160] |
| Ultrasound | 20 kHz frequency, 500 W/cm$^{-2}$ power intensity, 2 and 4 min, final temperature = 23 °C | - | [159] |
| Ultrasound | 40 kHz, 200 W, immersion: 1, 5 and 10 min, 20 g/L citric acid | 12 d, 3 ± 1 °C | [116] |
| Ultrasound | 40 kHz, 5 min, 20 g/L citric acid | 12 d, 3 ± 1 °C | [98] |
| Ultrasound | 40 kHz, 480 W, 10 min | 8 d, 4 °C | [162] |
| Ultrasound | Acoustic intensity 0.75 W/m$^2$ for 5 min, frequency: 40 kHz, potato slices packed in PE bags | 8 d, 4 °C | [163] |
| Ultrasound-assisted OD | Osmotic solution: NaCl + maltodextrin (30% *w/w*), 60 min immersion at 45 °C, potato cubes/solution = 1:40 (20 g/L), electrical power: 130 W, frequency: 20 kHz | - | [6] |
| Ultrasound + cactus polysaccharide (CP) | 40 kHz, 480 W, 10 min, 1% *w/w* CP, potato slices to solution = 1:4 | 8 d, 4 °C | [162] |
| Ultrasound + *Portulaca oleracea* (purslane) extract | Ultrasound: 40 kHz, 630 W, 10 min, purslane extract 0.02 *w/w*, packaged in PE self-sealing bags | 8 d, 4 °C | [164] |
| UV-C irradiation | Immersion of slices in sodium ascorbate (2% *m/v/*) for 3 min, vacuum-packed in PA/PE bags, UV-C irradiation: 2.70 kJ/m$^2$ for 5 min | 15 d, 6 °C | [11] |
| UV-C irradiation | 2–5 min irradiation time, packed in PE bags | 5 d, 4 °C | [165] |
| UV-C irradiation | Irradiation dose: 13.68 kJ/m$^2$, packed in closed plastic boxes | 10 d, 4 °C | [166] |
| UV-C irradiation +ascorbic acid + $CaCl_2$ | 1% *w/v* ascorbic acid and 0.1% *w/v* $CaCl_2$, dipping for 5 min at 4 °C, irradiation dose: 6.84 kJ/m$^2$, packed in closed plastic boxes | 10 d, 4 °C | [166] |
| PPA | 10 min, vacuum-packed | −80 °C | [94] |
| CP | Power = 900 W, treatment time = 40 min | - | [110] |
| PAW process | 200 Hz-PAW, optimized discharge time = 10 min | 5 d, 4 °C | [167] |

* PE: polyethylene.

#### 5.5.1. Ultrasound

The operating principle of ultrasound treatment in food preservation involves the application of high-frequency ultrasound waves, typically exceeding 20 kHz, with high-intensity (10–1000 W/cm$^2$) and low-frequency (18–100 kHz) characteristics. Ultrasound treatment is based on the phenomenon of cavitation, which refers to the formation, oscillation, and collapse of microbubbles in a liquid [168]. The output power (W) divided by the beam area ($cm^2$) defines the power intensity of the ultrasonic probe. This process generates localized extreme conditions, including high temperatures and pressures, which have various effects on the food matrix. This process facilitates the inactivation of enzymes by inducing the leakage of cell membranes, making ultrasound technology integral in mitigating the effect of browning on fresh-cut potatoes [98]. Notably, ultrasonication plays a dual role in facilitating wound healing and maintaining the membrane integrity of fresh-cut produce [163]. The versatility of sonication in the food industry holds immense potential for enhancing sustainability in production. One of the major advantages of ultrasound is its relatively low energy requirement compared to conventional thermal treatments, which makes it a cost-efficient and environmentally friendly process. Additionally, ultrasound reduces the need for chemical preservatives, enhancing food safety and consumer appeal [16]. In an industrial setting, ultrasound can be used to inhibit enzymatic browning and enhance the firmness of fresh-cut potatoes, making it ideal for vacuum-packaged or minimally processed potato products with extended shelf life requirements. However, there are some disadvantages to ultrasound treatment, as prolonged exposure or high intensity can cause cell structure damage, negatively affecting the texture of sensitive produce. This sensitivity requires a careful optimization of treatment parameters to avoid overprocessing and ensure product quality. Amaral et al. (2017) showed that the use of ultrasound (40 kHz, 5 min) as an alternative to blanching can improve the quality attributes and shelf life of vacuum-packaged potato strips [98]. In another study, ultrasound treatment revealed high potential as an innovative pretreatment applied before the drying of purple-fleshed potato slices, which exhibited enhanced quality attributes with respect to the control [159]. Furthermore, Amaral et al. (2015) investigated the impact of different ultrasound exposure durations on the quality parameters of fresh-cut potatoes. Sonication for 5 min resulted in a 50% inhibition of PPO activity during the initial 4 days of storage. Samples treated with ultrasound for 5 and 10 min exhibited sustained and consistent firmness after frying throughout the storage period, while an extended immersion time of 10 min induced cell damage in the potatoes [116]. Qiao et al. (2021) investigated a new way to prevent browning in fresh-cut potatoes by employing a combination of *Sonchus oleraceus* L. extract and ultrasound. The study demonstrated the effectiveness of this method in preserving the quality of fresh-cut potatoes, reducing browning, and retaining their texture [163]. Zhu et al. (2021) explored the application of ultrasonic treatment to lower the minimum effective concentration of purslane extract on fresh-cut potato slices throughout storage. The findings indicated that a more effective anti-browning outcome could be achieved through the combined application with a lower purslane extract concentration (0.02%, $w/w$) compared to the optimal concentration of purslane extract alone (0.05%, $w/w$) [164].

#### 5.5.2. Irradiation

The irradiation of food products with short-wave ultraviolet light (UV-C) is a promising non-thermal method already used to disinfest water, air, packaging, and solid surfaces [166]. The germicidal mechanism of UV-C is attributed to the disruption of nucleic acids (DNA, RNA) of pathogens at a wavelength of 254 nm [166]. One of the key advantages of UV-C irradiation is its effectiveness in reducing microbial populations on the surfaces of fresh-cut produce, which can enhance food safety without the use of chemicals. Additionally, UV-C treatment maintains the nutritional attributes of produce, as it is a non-thermal method that minimizes nutrient degradation [165]. In an industrial setting, UV-C irradiation can be employed to reduce surface microbial load on fresh-cut potato slices, helping to extend shelf life. This treatment is beneficial for potatoes stored in packaging where surface decontamination is critical. However, the disadvantages of UV-C irradiation include its limited penetration depth, as UV-C light only affects surface layers, making it less effective for products with complex shapes or denser structures [169]. Another potential downside is the formation of acrylamide in fried potato products treated with UV-C, a concern that has been observed in raw tubers [170] and potato slices [11]. However, the effect of UV-C treatment on fresh-cut potato products has been poorly studied (Table 6). While irradiation with UV-C has been effective in sterilizing other fresh-cut vegetables during storage by reducing bacterial populations, it did not significantly extend the shelf life of fresh-cut potato slices beyond 5 days [165]. In another study, the combination of dipping in an ascorbic acid and calcium chloride solution with UV-C exposure at 6.84 kJ/m$^2$ was observed to be effective in maintaining lower enzymatic activities (POD, PPO and PAL) and higher total phenolic content in potato slices during storage period compared to untreated or UV-C-treated samples [166]. This suggests that UV-C irradiation may be more effective when used as part of a combined treatment strategy rather than as a standalone method for fresh-cut potatoes.

#### 5.5.3. Plasma Treatment

Non-thermal plasma (NTP) decontamination technology has emerged as a prominent and verified non-thermal processing method for microbial inactivation. NTP is a state of ionized gas characterized by the presence of electric fields, charged particles, ultraviolet photons, and reactive species, including reactive oxygen species (ROS) and reactive nitrogen species (RNS) [171]. The generation of plasma occurs when electrical energy is applied to a gas present or flowing between two electrodes with a high electrical potential difference, leading to gas ionization as a result of free electrons colliding with gas molecules [172]. Various methods are employed for generating plasma in food processing, and these methods are broadly classified into dielectric barrier discharge (DBD), plasma jet (PJ), corona discharge (CD), radiofrequency (RF), and microwave (MW) [172,173]. ROS and RNS are identified as the primary bactericidal agents in plasma inactivation [174]. These components contribute to the breakdown of cell membranes, DNA, and microbial proteins [171,175,176].

NTP offers several advantages for food processing, including low application costs, short treatment times, and broad applicability across various food types, including packaged foods. Additionally, NTP is considered an environmentally sustainable technique, as it avoids the use of chemicals and requires minimal energy, making it a promising technology for enhancing microbiological quality, decontaminating packaging materials, and sterilizing food contact surfaces [177]. In an industrial setting, plasma treatment can be used for surface sterilization of fresh-cut potatoes, reducing microbial contamination and enzymatic browning. It is particularly effective when combined with other methods to further enhance shelf life. However, there are disadvantages to plasma treatment as well. One challenge is the potential for oxidative damage to the sensory and nutritional quality of certain foods due to the high reactivity of ROS and RNS, which can affect the texture, color, and flavor of delicate food products. Furthermore, the effectiveness of plasma can be limited by its penetration depth, as it primarily acts on the surface, making it less effective for foods with complex shapes or dense structures [178].

This technology has been explored for the decontamination of various fresh fruits and vegetables, including grapes, tomatoes, vegetable leaves, strawberries [179–182]. Plasma-processed air (PPA) is an indirect non-thermal plasma treatment involving remote exposure. This treatment is produced by a discharge device and then indirectly supplied to the samples undergoing exposure. Bußler et al. (2017) explored the potential application of PPA in fresh-cut potatoes and found that the activity of PPO and peroxidase (POD) was reduced by 77% and 89%, respectively, after exposure of fresh-cut potatoes to PPA for 10 min [94].

Cold plasma (CP) is formed when ionized gas is generated with relatively low energy (1–10 eV) and electronic density (up to $10^{10}$ cm$^{-3}$) [183]. In CP, there exists a thermodynamic non-equilibrium between electrons and heavy species, causing a temperature difference between them due to the significantly lighter nature of electrons compared to ions and neutral molecules. The gas maintains a low temperature as the cooling of ions and uncharged molecules is more effective than energy transfer from electrons [184]. Kang et al. (2019)

examined the effect of microwave CP treatment on the inactivation of PPO in potato. The study identified the optimal conditions for PPO inactivation, achieving the highest rate (49.5%) at a CP generation power of 900 W and a treatment duration of 40 min [110].

The direct exposure of water to NTP results in the generation of Plasma-Activated Water (PAW) process, with relevant antimicrobial properties that persist for long periods of time [185]. This phenomenon is attributed to the chemical species produced in the plasma, which diffuse and interact with each other or with water molecules, giving rise to new chemical species. This novel approach represents a completely new approach in the application of NTP, presenting intriguing possibilities for its application in food treatment and processing [186]. Aihaiti et al. (2023) explored the efficacy of PAW generated at a frequency of 200 Hz in treating fresh-cut produce, using fresh-cut potatoes as the experimental model. PAW treatment resulted in the inactivation of PPO and peroxidase enzymes associated with browning, leading to a reduced browning index. Among the tested parameters, 200 Hz-PAW demonstrated the most significant inhibitory effect on browning during storage [167].

To provide a comprehensive overview of each technology's strengths and limitations, Table 7 summarizes the key advantages and challenges associated with each non-thermal and natural preservation method discussed. This comparison highlights the practical considerations—such as scalability, energy requirements, and potential regulatory constraints—that influence the feasibility of these methods for fresh-cut potato preservation in the food industry.

**Table 7.** Comparison of non-thermal technologies for fresh-cut potato shelf life extension: advantages and limitations.

| Technology | Pros | Cons |
|---|---|---|
| OD | Retains sensory qualities (texture, flavor); supports microbial stability with minimal heat application | Nutrient loss due to osmotic process; requires large volumes of osmotic solution, increasing costs |
| HPP | Effective microbial inactivation without nutrient loss; preserves sensory qualities | High equipment and packaging costs; limited suitability for small facilities |
| PEF | Enhances texture and reduces oil absorption in fried products; energy-efficient | Scalability challenges; requires optimization of parameters for consistent results |
| OH | Rapid, uniform heating with lower energy consumption than conventional heating; environmentally friendly | Challenges with electrode corrosion; scalability issues in large industrial settings |
| Ultrasound | Enhances mass transfer; can be combined with other treatments for increased effectiveness | Limited by high-power requirements; potential tissue damage in sensitive products |
| Irradiation | Strong microbial inactivation; prolongs shelf life effectively | Consumer perception issues; regulatory restrictions in certain regions |
| Plasma Treatment | Effective in reducing microbial load; no chemical residues left on products | Scalability issues; equipment costs and technical complexity |

## 6. Effect of Anti-Browning and Antimicrobial Agents, Probiotics, and Edible Coatings on Fresh-Cut Potato Shelf Life

### *6.1. Conventional and Novel Anti-Browning Agents*

Inorganic and organic compounds have been tested as anti-browning agents in order to slow down PPO activity and prolong the durability of fresh-cut potatoes. Typically, fresh-cut potatoes undergo immersion in anti-browning solutions, composed of either a single substance or a combination of compounds, to mitigate discoloration. This preventive action occurs through three main mechanisms: firstly, by lowering the pH to levels below 4; secondly, by chelating copper from PPO molecules, thereby disrupting their structure; and thirdly, by reducing o-quinones back to phenolics [187]. This reduction inhibits oxidation and the subsequent polymerization of phenolics into colored melanins. It is worth noting that the effectiveness of an anti-browning agent relies on factors such as its concentration and the pH of the solution [18].

Chemicals such as ascorbic acid, sodium bisulfate, potassium bisulfite, and sodium metabisulfite are considered low-cost products and are readily available on the market; they have been certified as safe food additives by the U.S. Food and Drug Administration [165,188]. Their acidity differs since sodium bisulfate is a stronger acidic medium ($pK_a$ = 2.0) than citric acid ($pK_a$ = 3.1) and ascorbic acid ($pK_a$ = 4.1) [165]. Immersion of fresh-cut vegetables in acidic solutions leads to a pH decrease at the cut surface and a reduction in browning, since pH values below 4 mark the limit of PPO activity, thus inhibiting enzymatic browning. While acidic solutions reduce browning, citric acid is particularly effective, setting the limit for PPO activity around pH 3.5, thus offering a more potent browning inhibition. Other studies have investigated acidification and alkalization using sulfuric acid or sodium hydroxide for browning control, finding that citric acid is more efficient than these alternatives due to its ability to lower the pH more effectively without adversely affecting texture or flavor. Notably, citric acid does not significantly alter the sensory properties of the treated vegetables, making it an ideal choice for browning prevention in fresh-cut produce [189].

Other researchers found that the potato cultivar (Birgit and Laidy Claire) affected the durability and quality properties of fresh-cut potato slices that received the same treatment [190]. This finding suggests the need for further studies focusing on appropriate cultivars. In addition, sodium ascorbate (2% $w/w$) was observed to be more efficient as an anti-browning agent than sodium chloride (1% $w/w$), whereas the vacuum packaging of both treated samples enhanced their durability up to 8 days of storage [86]. On the other hand, storage temperature (3 and 10 °C) did not significantly affect the examined sensory and quality parameters [86].

Natural substances and extracts of plant and animal origin have been used as anti-browning agents (Table 8). Their ability to reduce PPO activity and enzymatic browning in potatoes is attributed to the presence of bioactive compounds such as polyphenols, flavonoids, anthocyanins, and vitamin C [191]. The positive effect of these agents is reflected by increasing the whitening index (WI) value and reducing that of BI after treatment [187]. The bioactive phenolic compounds detected in plant extracts include protocatechuic acid, vanillic acid, p-coumaric acid, ferulic acid, and sinapic acid [192]. On the other hand, the potato phenolic profile consists mainly of chlorogenic acid derivatives such as chlorogenic acid (5-O-caffeoylquinic acid), neochlorogenic acid (3-O-caffeoylquinic acid), and cryptochlorogenic acid (4-O-caffeoylquinic acid) [193]. Kasnak (2020) investigated the effects of ascorbic acid and collagen hydrolysate treatments on the quality of fresh-cut potatoes during cold storage. The treatment of collagen hydrolysate (0.22% $w/v$) and ascorbic acid (0.30% $w/v$) in fresh-cut potatoes was successful in slowing PPO activity at the end of storage [187]. Another study demonstrated that sea buckthorn leaf extract, characterized by its abundance in catechin, hypericin, gallic acid, casuarinin, and isorhamnetin, effectively suppressed browning in fresh-cut potatoes. This inhibition was attributed to the extract's ability to reduce the activities of peroxidase and phenylalanine ammonia-lyase, lower the levels of phenolics, and enhance antioxidant capacity [152]. Furthermore, Feng et al. (2022) remarked the potential use of S-Ethyl thioacetate, which naturally exists in durian, beer, and wine, as a natural anti-browning agent to inhibit the browning of fresh-cut potatoes by decreasing PPO [194]. In another study, certain phenolic compounds like ferulic acid and p-coumaric acid, present in rice bran, demonstrated a more pronounced anti-browning effect on potatoes compared to the conventional industrially produced agent, 100 ppm citric acid [192]. Guan et al. (2024) concluded that tea polyphenols can inhibit the occurrence of enzymatic browning in fresh-cut potatoes by regulating phenylpropanoid and ROS metabolism [195]. Similarly, Liu et al. (2019) concluded that purslane aqueous extract is a promising nutritive anti-browning agent for fresh-cut potato [196]. Kasnak (2022) investigated the effects of quercetin treatment on the browning of cut potatoes. The results showed that quercetin treatment had an inhibitory effect on the enzymatic and oxidative activity of the potatoes, which led to a reduction in browning [197]. Finally, Bobo et al. (2022) investigated the impact of fifteen aqueous plant extracts, including cinnamon, clove, garlic, ginger, green tea, marjoram, mint, nutmeg, oregano, pepper (black and white), rosemary, sage, thyme, and wheat bran, on PPO to identify the most effective in preventing browning in minimally processed potatoes. Following the study, green tea extract was singled out for further assessment due to its consistent ability to inhibit PPO activity, irrespective of solution concentration. Green tea extract successfully managed to control browning in fresh-cut potatoes for a period of 14 days when stored at 4 °C [198].

**Table 8.** Anti-browning agents and edible coatings applied to fresh-cut potatoes *.

| Substance | Processing Conditions | Storage Conditions and Time | Reference |
|---|---|---|---|
| Acetic acid | Immersion in 0.8% acetic acid at 25 °C for 18 h, potato slices to solution ratio = 2/3 *w*:*w*, vacuum packed aluminum foil pouches | - | [199] |
| Acidified $NaOCl_2$ | 500 mg/L, 5 min washing, (pH 2.5–2.9), mixing $NaOCl_2$ and citric acid at 50:50 *w*/*w*, potato/solution = 1:10 *w*/*v*, vacuum packed in PE bags | 5 d, 4 and 10 °C | [200] |
| Ascorbic acid + vacuum packaging | 3 min immersion, 5 g/L, vacuum packed in PE and PA, vacuum time: 30 s | 5 d, 4 °C | [57] |
| Ascorbic acid | 5%, 3 min dipping, MA packaging for 3 min (9% $CO_2$, 3% $O_2$, 87% $N_2$) | 13 d, 2 °C | [73] |
| Ascorbic acid | 3% *w*/*w*, 3 min dipping, potato slices packed in PE bags | 14 d, 4 °C | [101] |
| Ascorbic acid + $CaCl_2$ | 2% *w*/*w* + 1% *w*/*w* $CaCl_2$, 3 min dipping, potato slices packed in PE bags | 14 d, 4 °C | [101] |
| Ascorbic acid + citric acid + modified atmosphere | 1.25% AA + 1.25% CA, 3 min immersion at 7.5 °C, potato/solution = 1:10, MA: 3% $O_2$ + 12% $CO_2$ | 8 d, 5 °C | [201] |
| Ascorbic acid + citric acid | 5% *v*/*w* AA + 2.5% *v*/*w* CA, 2 min immersion, sliced potato/solution = 1:3, packed in plastic pouches under MA ($O_2$) of 55 and 100 kPa | 10 d, 5 °C | [105] |
| Ascorbic acid | 0.08% *w*/*w* AA | - | [202] |
| Ascorbic acid | 0.2% *w*/*v* AA, 5 min immersion, 3 slices packed in PE bags | 5 d, 4 °C | [203] |
| Aspartic acid | 5 min immersion, potato/solution = 1:4 (g/mL), chips packed in PE bags | 7 d, 2–4 °C | [204] |
| Aronia berries extract | Solution/sample = 15:1 | - | [6] |
| Citric acid | 1% CA (pH 2.42) or 2% CA (pH 2.24), 2 min immersion, packed in plastic bags | 6 d, 5 °C | [189] |
| Citric acid | 2% CA, different cut shapes: slices, wedges, cubes, dice | 12–60 d, 4 °C | [34] |
| *Centella asiatica* extract | 5 min dipping, extract concentration: 250 mg/mL | 4 d, 4 °C | [63] |

**Table 8.** *Cont.*

| Substance | Processing Conditions | Storage Conditions and Time | Reference |
|---|---|---|---|
| Chlorogenic acid | 2.8 × $10^{-5}$ mol/L, immersion for 10 min at 25 °C, potato/solution = 1:5, packed in PE bags | 12 d, 4 °C | [205] |
| Cod peptides | 0.1% *w*/*w* cod peptide, 5 min immersion at 25 °C, potato/solution = 1:4, packed in PE bags | 8 d, 4 °C | [206] |
| Green tea (*Camellia sinensis*) extract | 7 min immersion at 4 °C, 50 mL/L tea extract, potato slices/solution = 1:3 *w*/*w*, packed in LDPE bags and sealed in 30% vacuum | 14 d, 4 °C | [198] |
| Glutamic acid | 15 g/L, 4 min, | 5 d, 2–4 °C | [19] |
| Methyl jasmonate (MeJA) | 260 µmol/L MeJA, 15 min immersion | 6 d, room temperature | [207] |
| NaCl + ascorbic acid | 1% NaCl + 2% AA (*w*/*w*), immersion for 3 min at 18 °C, potato slices/solution (g/mL) = 1:4, vacuum and MA packaging (10 $CO_2$, 3% $O_2$, 87% $N_2$) | 8 d, 10 °C | [190] |
| NaCl | 1% *w*/*v* NaCl, immersion for 3 min at 18 °C, potato slices/solution (g/mL) = 1:4, vacuum and MA packaging (10 $CO_2$, 3% $O_2$, 87% $N_2$) | 10 d, 3 and 10 °C | [190] |
| NaOCl | 100 mg/L, 5 min washing (pH 6.5–7.0), potato/solution = 1:10 *w*/*v*, vacuum packed in PE bags | 5 d, 4 and 10 °C | [200] |
| Nisin (bacteriocin) | Potato slices inoculated with *Bacillus subtilis*, 10 min immersion in 0.25% *v*/*v* formic acid and 0.016 mg/mL Nisin | 10 d, 37 °C | [208] |
| Onion essential oil | 0.5 mg OEO/mL, 2 min immersion | 15 d, 4 °C | [23] |
| Orange peel essential oil | Potato slices placed on a Petri dish and inoculated with 50 µL of fungal spore suspension, incubated at 28 °C | 4 d, 4 °C | [209] |
| Potassium metabisulfite | 0.3%, different cut shapes: slices, wedges, cubes, dice | 12–60 d, 4 °C | [34] |
| Potassium metabisulfite | 0.1%, 3 min dipping, MA packaging for 3 min (9% $CO_2$, 3% $O_2$, 87% $N_2$) | 13 d, 2 °C | [73] |
| Peanut seed oil + rosemary essential oil | Dipping in peanut seed oil (150 mL) and rosemary essential oil (0.5% *v*/*v*), packed in vacuum sealed *sous vide* bags | 4, 7, and 11 d, 4 °C | [75] |
| *Portulaca oleracea* extract | 0.05% *w*/*w*, 5 min immersion, packed in PE bags | 8 d, 4 °C | [196] |
| Proline | 90 mmol/L, 1 h, 30 °C | 4 d, 2–4 °C | [210] |
| Rosemary oil enrichment by vacuum impregnation | Immersion for 30 min in 12% *w*/*v* rosemary oil and sub-atmospheric pressure of 60 mbar, potato/solution = 1:1.5, placed in PP tray and sealed with PE film | 14 d, 4 °C | [211] |
| Rice bran extract | 100 µg/mL, blended for 20 s at 1:1 *w*/*w* ratio and room temperature | 6 h | [192] |

**Table 8.** *Cont.*

| Substance | Processing Conditions | Storage Conditions and Time | Reference |
| --- | --- | --- | --- |
| Sodium ascorbate | 2% *w*/*v*, immersion for 3 min at 18 °C, potato slices/ solution (g/mL) = 1:4, vacuum and MA packaging (10 $CO_2$, 3% $O_2$, 87% $N_2$) | 10 d, 3 and 10 °C | [86] |
| Sodium metabisulfite | 0.5% *w*/*v*, 30 min immersion, vacuum packed | 15 d, room temperature | [188] |
| Sodium metabisulfite + ascorbic acid | 0.25% *w*/*v* + 0.25% *w*/*v* AA, 30 min immersion, vacuum packed | 15 d, room temperature | [188] |
| Sodium bisulfate | 2.5% *w*/*v*, 2 min immersion, packaged in PE bags | 25 d, 4 °C | [165] |
| Sodium bisulfite + modified atmosphere | 0.025% *w*/*w*, 3 min immersion at 7.5 °C, potato/solution = 1:10, MA: 3% $O_2$ + 12% $CO_2$ | 8 d, 5 °C | [201] |
| S-Ethyl thioacetate (S-Et) | 0.14 and 0.20 mmol/L S-Et, 15 min immersion, potato/solution = 1:2 *w*/*w*, 200 g potato chips packed in PE bags | 5 d, 2–4 °C | [194] |
| *Sonchus oleraceus* extract + ultrasound | 5 min immersion, 0.1 g/L extract, US: acoustic intensity 0.75 W/m$^2$ for 5 min, frequency: 40 kHz, potato slices packed in PE bags | 8 d, 4 °C | [163] |
| Sprayable double-stranded RNA (dsRNA) | 0.1 g/L dsRNA solution, 20 µL dsRNA solution was sprayed on each potato slice, 3 slices packed in PE bags | 5 d, 4 °C | [203] |
| γ-aminobutyric acid (GABA) | 20 g/L GABA, 10 min immersion, air-dried | 6 d, 4 °C | [212] |
| 3-mercapto-2-butanol | 25 µL/L, 5 min immersion, packed in PE bags | 5 d, 5 °C | [213] |
| Carboxymethyl cellulose | 1% *w*/*v*, immersion for 30 min at 24 °C, 1:10 *w*/*v* | 4 °C | [123] |
| Carboxymethyl cellulose | Dipping for 0.5–10 min containing 1% *w*/*v* olive leaf extract or 1% *w*/*v* sodium ascorbate, potato strips vacuum packed in PA/PE bags | 7 d, 10 °C | [214] |
| Cactus polysaccharide | 1% *w*/*w*, 10 min dipping, potato slice (g)/solution (mL) = 1:4 | 8 d, 4 °C | [162] |
| Chitosan | 1.5% *w*/*v*, immersion for 30 min at 24 °C, 1:10 *w*/*v* | 4 °C | [123] |
| Chitosan | Dipping for 0.5–10 min containing 1% *w*/*v* olive leaf extract or 1% *w*/*v* sodium ascorbate, potato strips vacuum packed in PA/PE bags | 7 d, 10 °C | [214] |
| Cactus polysaccharide (*Opuntia dillenii*) | 3 min immersion at 5 °C, 1% polysaccharide *w*/*v* | 5 d, 5 °C | [215] |
| Fish collagen hydrolysate (CH) + ascorbic acid (AA) | 0.22% CH and 0.30% AA, 5 min immersion at room temperature, potato (g)/solution (mL) = 1:5, potto cubes placed in PE plates and covered with stretch film | 9.5 d, 4 °C | [187] |

**Table 8.** *Cont.*

| Substance | Processing Conditions | Storage Conditions and Time | Reference |
| --- | --- | --- | --- |
| Gellan gum (GN) + cranberry extract (CE) + *Lactococcus lactis* (LA) probiotic film | GN + 0.5% CE + 2.0% LA, 2 g GN powder/100 mL distilled water, 2 min immersion, potatoes placed in boxes | 6 d, 4 °C | [191] |
| Gum arabic (GA) | Dipping for 0.5–10 min in GA containing 1% *w*/*v* olive leaf extract (OLE) or 1% *w*/*v* sodium ascorbate (SA), potato strips vacuum packed in PA/PE bags | 7 d, 10 °C | [214] |
| L-cysteine (L-cys) | 0.02% *w*/*w* | - | [202] |
| L-cysteine | 0.5% L-cys, 3 min dipping, MA packaging for 3 min (9% $CO_2$, 3% $O_2$, 87% $N_2$) | 13 d, 2 °C | [73] |
| L-cysteine + citric acid | 0.5% L-cys + 2% CA, 3 min dipping, MA packaging for 3 min (9% $CO_2$, 3% $O_2$, 87% $N_2$) | 13 d, 2 °C | [73] |
| Monosodium glutamate | 2.5% *w*/*v*, immersion for 30 min at 24 °C, 1:10 *w*/*v* | 4 °C | [123] |
| Pectin (PEC) | Dipping for 0.5–10 min in PEC containing 1% *w*/*v* olive leaf extract (OLE) or 1% *w*/*v* sodium ascorbate (SA), then dipped in $CaCl_2$ (0.1% *w*/*v*) for 30 s, potato strips vacuum packed in PA/PE bags | 7 d, 10 °C | [214] |
| Pectin/sodium alginate (SA)/xanthan gum (XG) (composite film) | 6 g/L pectin, 5 g/L SA, 4 g/L XG, 18 g/L glycerol, 20 g/L $CaCl_2$, potato cylinders | 8 d, 4 °C | [16] |
| Sodium alginate | 20 g/L | 12 d, 3 °C | [98] |
| Sodium alginate-based coating (AEC) + thyme essential oil (TEO) | (i) Immersion in AEC (1.29% *w*/*v*), glycerol (1.5% *w*/*v*) and TEO (0.05% *v*/*v*) solution for 2 min, (ii) immersion in $CaCl_2$ for 2 min | 16 d, 4 °C | [216] |
| Transglutaminase-crosslinked whey protein/pectin edible film | Whey protein/pectin: 4:1 *w*/*w*, 5 min dipping, thermally sealed LDPE bags | 2–10 d, 4–6 °C | [217] |

* AA: ascorbic acid; CA: citric acid; MA: modified atmosphere; PE: polyethylene; PA: polyamide; PP: polypropylene; LDPE: low-density polyethylene.

Essential oils, naturally derived from various plants, have gained recognition for their antioxidative and antimicrobial properties, making them valuable agents in enhancing the shelf life and quality of fresh-cut potatoes. Among the essential oils explored in food preservation, rosemary oil (*R. officinalis* L.) is particularly noteworthy due to its potential in delaying enzymatic browning and reducing microbial growth [75,211,218]. Additionally, studies have identified certain essential oils, such as cinnamon oil, as highly effective against common foodborne pathogens, which underscores the broad applicability of essential oils in improving food safety [66]. For fresh-cut potatoes, coatings that incorporate essential oils, like thyme oil in alginate-based formulations, have shown promising results in maintaining quality and microbial stability. Such applications, particularly at low concentrations, suggest that essential oils could serve as clean-label alternatives to synthetic preservatives, meeting both consumer demands for natural ingredients and industry needs for shelf life extension [216]. Particularly, Vázquez Armenta et al. (2014) evaluated the effect of onion essential oil (OEO) on microbial growth, browning decay, and sensorial appeal of cut potatoes stored for 15 days at 4 °C. The study found that OEO at a concentration of 0.5 mg $mL^{-1}$ effectively prevented the browning (38.5% inhibition respect to control) during storage and inhibited PPO activity (39% respect to control) after the treatment [23]. Zhang et al. (2021) investigated the impact of varying concentrations of ginger essential oil within a chitosan-based edible coating on the microbiological and sensory attributes of fresh-cut sweet potatoes during a 6-day storage period at 4 °C. Findings revealed that incorporating 0.3% (*w*/*v*) ginger essential oil into the chitosan coating displayed significant potential in extending the shelf life and maintaining the quality of fresh-cut sweet potatoes. However, the addition of 0.5% (*w*/*v*) ginger essential oil to the coating resulted in a notable deterioration in their sensory attributes [219]. Finally, Shi et al. (2018) demonstrated the efficacy of navel orange peel essential oil to significantly improve the microbiological quality of potato slices [209].

In summary, a wide range of anti-browning agents, from inorganic compounds to plant-based extracts and essential oils, have proven effective in inhibiting enzymatic browning and extending the shelf life of fresh-cut potatoes. Chemical agents like ascorbic and citric acid offer affordable and efficient browning control, while concerns over health and safety drive interest in natural alternatives. Plant extracts, phenolic compounds, and essential oils not only inhibit browning but also enhance microbial stability, offering promising clean-label solutions that align with consumer demand for natural ingredients. These innovative approaches, particularly when tailored to specific potato cultivars and applied at optimal concentrations, provide a versatile foundation for future developments in fresh-cut potato preservation.

### *6.2. Edible Films and Coatings*

Edible films and coatings can be used as barrier layers to oxygen and carbon dioxide, as well as carriers of antioxidant or antimicrobial agents, to extend the shelf life of fresh food against oxidation and microbial spoilage [220,221]. Polysaccharides, proteins, and lipids derived from agricultural feedstocks (maize, wheat, potato, cassava, soy bean) are the main ingredients used to produce edible films and coatings [222,223]. Natural biopolymers for the production of edible films and coatings can also be recovered by valorizing waste from food processing, contributing to the concept of circular economy [220]. Edible coatings have been applied to fresh-cut vegetables and fruits as an immersion solution, whereas edible films in solid sheet form are wrapped around the product [220]. The mechanical properties, transparency, and oil resistance of polysaccharide films are better than those of protein-based films [223]. On the other hand, protein films exhibit lower water transmission [223]. Lipid films (fatty acids, beeswax) are fragile but more hydrophobic, reducing water permeability [223].

Alginate, chitosan, pectin, carrageenan, and starch are the most abundant polysaccharides in nature after cellulose and are mostly used as edible coatings of fresh-cut vegetables and fruits [49,220]. Polysaccharides can be extracted from microorganisms, algae, and crustacean cells (shrimps, crabs), as well as from the fruits, stems, and cladodes of wild or cultivated crops [49,162,220]. Recently, there has been an interest in extracting polysaccharides from cladodes, which are flattened leaf-like stems in cactus genera such as *Opuntia* sp. [162,215]. The biomacromolecules of polysaccharides, consisting of arabinose, xylose, fructose, glucose, galacturonic acid, and rhamnose, exhibit antioxidant and antibacterial activities [162,215].

Polysaccharide films, in native or modified form, are functional and promising materials to employ in food preservation as active packaging [224]. The modification of edible films can be achieved via salt pretreatment, esterification, etherification, ozonation, electron beam irradiation [225], and impregnation of nanoparticles [224] or antimicrobial/antioxidant proteins [221]. For example, the treatment of alginate with calcium ($CaCl_2$) produced a flexible and water-insoluble biopolymer [49]. Bioplastics produced from starch and other renewable resources are proposed as an alternative to non-biodegradable plastics, which are accumulated in the environment [221]. The addition of plasticizers such as glycerol to raw starch is necessary to improve the thermal, physical, and microstructural attributes of edible films, giving them thermoplastic properties [221].

On the other hand, the incorporation of antioxidant and antimicrobial agents, such as metal nanoparticles (selenium) or proteins (lactoferrin, lysozyme), in low concentrations makes starch-based films an active packaging material [221,224]. Organic or inorganic active compounds can be released into the food from the biodegradable film, augmenting the preservation efficiency [221]. Additionally, the application of proteins and nanoparticles to fresh-cut potatoes, either incorporated in edible films or used in dipping solution, is a novel research topic. In addition, consumers show a greater preference for natural agents such as essential oils [211], plant extracts [192], polysaccharides [162], and probiotic microbial strains [191].

Recent research on edible coatings as preservation strategies for fresh-cut potatoes highlights the effectiveness of natural anti-browning and antimicrobial agents in extending shelf life. Essential oils, such as rosemary essential oil (REO), combined with antioxidants like ascorbic acid (AA), have shown substantial promise. For instance, edible coatings formulated from polysaccharides, like those derived from potato peels, create protective barriers that maintain quality by reducing enzymatic browning, minimizing microbial growth, and preserving texture over extended storage periods [64]. Garden cress seed mucilage, as another edible coating, has demonstrated similar potential by delaying browning, reducing weight loss, and preserving texture in fresh-cut and fried potato strips, which suggests applications for both shelf life extension and reduced oil absorption in processed potato products [226].

Various types of coatings have been evaluated for their unique benefits. Biodegradable coatings made from gelatin and gelatin–rice starch mixtures retain moisture effectively and can improve the structural integrity of fresh-cut potatoes during storage [227]. Crosslinked whey protein and pectin films further enhance quality by reducing weight loss, limiting microbial proliferation, and preserving sensory characteristics [217]. Similarly, cassava starch-based coatings with added ascorbic acid help prevent browning and quality deterioration in root vegetables, such as sweet potatoes [228].

The versatility of edible coatings is evident in studies that focus on optimizing antioxidative activity and moisture retention. For example, coatings containing soy protein isolate (SPI), particularly those fortified with carboxymethyl cellulose, have shown notable antioxidative properties that minimize browning and moisture loss in fresh-cut potatoes [49]. Other investigations highlight the critical role of coating materials in determining functionality; formulations using zein, alginate, and potato starch perform differently across potato varieties, indicating that coating effectiveness can vary with polymer composition and potato cultivar [49].

In addition to enhancing storage quality, some coatings have been developed with functional benefits aimed at fried potato products. Coatings like carboxymethyl cellulose and gum arabic, enriched with olive leaf extract or sodium ascorbate, successfully reduce oil uptake and fat content in deep-fried potato products without compromising key sensory attributes [214]. Similarly, a combination of carboxymethyl cellulose and flaxseed mucilage, supplemented with nanoencapsulated burdock extract, has been shown to improve the texture, color, and antioxidant activity of fresh-cut and fried potatoes while decreasing oil absorption during frying [229].

Novel advancements in edible coatings include probiotic films incorporating natural extracts and functional compounds. For instance, a gellan gum-based film with cranberry extract and Lactococcus lactis has demonstrated optimal preservation effects for fresh-cut potatoes, combining probiotic benefits with microbial stability [191]. Additionally, antibacterial films formulated with sodium alginate, gum arabic, glycerol, and natamycin have been applied to sweet potatoes, effectively slowing down physiological changes and maintaining product quality during storage [230].

In summary, edible films and coatings provide versatile, natural options for extending the shelf life of fresh-cut potatoes by offering barriers to oxidation and microbial spoilage.

Polysaccharide-, protein-, and lipid-based coatings demonstrate unique properties that cater to various preservation needs, with polysaccharides showing superior transparency and oil resistance and proteins offering reduced water transmission. Recent advancements in coating formulations, particularly those incorporating essential oils, antioxidants, and nanoparticles, show great promise in enhancing both microbial stability and sensory quality. These natural and biodegradable coatings not only address consumer demand for clean-label products but also support sustainable practices by leveraging renewable and waste-derived materials. Overall, edible films and coatings represent a valuable approach for fresh-cut potato preservation, with ongoing research driving further innovations in this field.

## 7. Future Directions and Current Challenges in Non-Thermal Processing of Fresh-Cut Potatoes

The field of emerging non-thermal technologies for processing fresh-cut potatoes presents both exciting opportunities and notable challenges, each with significant implications for advancing food preservation techniques. While substantial progress has been made in applying methods such as PEF, HPP, and ultrasound, there remain several critical gaps that require further exploration. One major challenge lies in understanding the long-term effects of these technologies on the organoleptic qualities—such as flavor, texture, and appearance—of fresh-cut potatoes, as well as their impact on nutritional integrity over extended storage periods. Non-thermal methods often aim to minimize nutrient loss compared to conventional thermal methods, yet optimizing conditions to consistently achieve this outcome remains complex.

Standardizing and optimizing operating conditions across different non-thermal techniques poses additional challenges. Each technology requires specific parameters, such as electric field strength in PEF or pressure levels in HPP, that need to be finely tuned to preserve quality and extend shelf life without compromising the sensory or nutritional properties of fresh-cut potatoes. However, this tuning process is intricate due to the diversity of potato cultivars and variations in processing equipment, which makes it difficult to develop universal standards. Addressing this issue will require extensive research, with an emphasis on developing comprehensive guidelines and protocols for each technique that consider not only the food matrix but also environmental sustainability and energy efficiency.

Additionally, non-thermal methods need to be assessed in terms of their scalability and economic feasibility for the food industry. While these methods offer significant benefits in quality retention, their high initial costs, equipment demands, and maintenance requirements can limit their accessibility for smaller processing facilities. Collaborative efforts from industry, academia, and government agencies could help mitigate these barriers by exploring cost-effective solutions, promoting knowledge sharing, and supporting subsidies or incentives for adopting sustainable processing practices.

An emerging area of interest in non-thermal processing is the potential for synergistic combinations of multiple methods to enhance preservation outcomes. Combining PEF with HPP, for instance, has shown promise in achieving superior bacterial inactivation, color retention, and texture preservation compared to either method alone. Such synergistic applications could enable the preservation of fresh-cut potatoes with fewer chemical preservatives, aligning with consumer demand for cleaner labels and minimally processed foods. However, these combinations require careful control to avoid unintended interactions or excessive processing, which could negate the benefits of individual technologies. More research is needed to understand the underlying mechanisms of these interactions and to optimize combined treatments for commercial application.

Moreover, sustainability remains a pressing concern. Non-thermal technologies generally consume less energy than traditional methods, yet their overall environmental impact has not been thoroughly evaluated. Future studies should incorporate life-cycle assessments to evaluate the environmental footprint of each non-thermal method, particularly in terms of energy consumption, water use, and waste generation. These insights could contribute to a more sustainable approach to fresh-cut potato processing by identifying the greenest and most efficient methods.

By addressing these current gaps, particularly in areas of standardization, feasibility, and sustainability, future research in non-thermal processing can drive significant advancements. Ultimately, these efforts could facilitate the broader adoption of non-thermal technologies, enabling the food industry to offer high-quality, safe, and environmentally friendly fresh-cut potato products that meet evolving consumer preferences.

## 8. Conclusions

This review highlights the evolving landscape of fresh-cut potato preservation, underscoring the role of non-thermal processing technologies and natural preservation methods as promising alternatives to traditional chemical treatments. With growing consumer demand for minimally processed, safe, and convenient food products, the food industry is increasingly turning to innovative techniques that preserve quality, extend shelf life, and cater to health-conscious preferences.

Among the methods explored, OD offers potential for fresh-cut potato preservation due to its ability to retain sensory qualities and support microbial stability with minimal heat application. However, nutrient loss and the need for significant osmotic solution volumes may limit its feasibility. Used in combination with non-thermal technologies, OD can further enhance shelf life, contributing to a sustainable, energy-efficient preservation strategy. Additionally, HPP has proven effective in maintaining the sensory qualities of fresh-cut potatoes by inactivating spoilage microorganisms without nutrient loss associated with heat-based treatments. However, high equipment costs and the need for specialized packaging limit HPP's immediate adoption, especially in smaller facilities. PEF offers unique benefits, such as improved texture and reduced oil absorption in fried products, though challenges remain in terms of scalability and the need to optimize processing parameters for consistency. OH presents a sustainable option, achieving rapid, uniform heating to inactivate spoilage enzymes efficiently. While OH requires less power than conventional heating, it faces challenges with electrode corrosion and scaling up for industrial use. Despite these hurdles, OH holds strong potential as an environmentally friendly solution.

Natural preservatives, including plant extracts, essential oils, bioactive compounds, and edible coatings enriched with these agents, offer compelling alternatives to synthetic chemicals, addressing the demand for clean-label products. These agents, when combined with edible coatings or used alone, have shown effectiveness in reducing browning and microbial growth, particularly when paired with non-thermal methods like HPP or PEF. Edible coatings provide a physical barrier to minimize moisture loss and oxygen exposure, enhancing shelf life when infused with natural preservatives. However, the effectiveness of these additives and coatings can vary depending on the potato cultivar and processing conditions, underscoring the need for targeted research to optimize application strategies across product types.

In conclusion, the integration of non-thermal methods with natural anti-browning and antimicrobial agents shows considerable promise for advancing fresh-cut potato preservation. These approaches align with the broader shift toward sustainable, health-conscious food processing, with the potential to reshape industry standards. While technical and economic challenges remain, optimizing these technologies and addressing scalability will pave the way for delivering safer, longer-lasting, and environmentally friendly fresh-cut potato products that meet evolving consumer expectations. By preserving nutritional quality and reducing the need for synthetic additives, these technologies directly address consumer demand for healthier, minimally processed, and clean-label food products, reinforcing their relevance in modern food processing.

Limitations and feasibility for industry use: Although promising, each discussed technology faces limitations that impact its scalability and feasibility in the food industry. OD, while beneficial for retaining sensory qualities and microbial stability, has limitations due to nutrient loss and the need for large volumes of osmotic solution, which can increase operational costs and reduce practicality for large-scale applications. HPP, while effective in microbial inactivation, involves high costs for equipment and specialized packaging, which may hinder its adoption in smaller facilities. PEF, although energy-efficient, requires further research to optimize processing parameters and achieve consistent results on a larger scale. OH offers a sustainable heating alternative but faces technical challenges like electrode corrosion, which complicates its durability and scalability. Natural preservatives, such as plant extracts, essential oils, bioactive compounds, and edible coatings, provide a clean-label alternative to synthetic chemicals but can have variable effects depending on the potato cultivar, processing conditions, and interactions with non-thermal methods. Furthermore, regulatory approval for certain natural preservatives varies by region, which could affect their broader adoption in commercial settings. Moreover, the adoption of these technologies may be influenced by regulatory considerations that vary by region, particularly in terms of permissible processing methods and labeling requirements for clean-label products. Addressing these limitations through targeted research and technological advancements will be essential to support the industry-wide adoption of non-thermal methods in fresh-cut potato preservation. Future potential and research directions: Among the technologies reviewed, HPP, PEF, and OH hold the most immediate commercial potential due to their proven effectiveness in microbial inactivation and shelf life extension, as well as consumer acceptance of minimally processed foods. HPP and PEF, in particular, have been widely studied and applied in various fresh-cut products, making them strong candidates for broader commercial adoption in the fresh-cut potato industry. However, future research should focus on improving the energy efficiency and reducing the equipment costs of HPP to make it accessible for smaller-scale operations. Additionally, optimizing processing parameters for PEF is critical to ensure consistency and scalability, especially in terms of texture and sensory quality. Research should also prioritize refining OH technology to address electrode corrosion issues and improve the technology's durability for large-scale applications. In addition, edible coatings and natural preservatives, such as plant extracts and essential oils, offer another promising approach for extending shelf life. These natural additives meet the demand for clean-label alternatives to synthetic chemicals and have shown effectiveness in reducing browning and microbial growth, which are key issues for fresh-cut potatoes. Future studies should explore how to best apply these methods across different potato cultivars and processing conditions to maximize shelf life and maintain quality.

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