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Review

Maintaining the Quality and Safety of Fresh-Cut Potatoes (*Solanum tuberosum*): Overview of Recent Findings and Approaches

Branka Levaj [1,*], Zdenka Pelaić [1], Kata Galić [1], Mia Kurek [1], Mario Ščetar [1], Milan Poljak [2], Draženka Dite Hunjek [3], Sandra Pedisić [1], Sandra Balbino [1], Zrinka Čošić [1], Filip Dujmić [1] and Maja Repajić [1,*]

[1] Faculty of Food Technology and Biotechnology, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia; zpelaic@pbf.hr (Z.P.); kata.galic@pbf.unizg.hr (K.G.); mkurek@pbf.hr (M.K.); mscetar@pbf.hr (M.Š.); sandra.pedisic@pbf.unizg.hr (S.P.); snedjer@pbf.hr (S.B.); zcosic@pbf.hr (Z.Č.); filip.dujmic@pbf.unizg.hr (F.D.)
[2] Faculty of Agriculture, University of Zagreb, Šimunska bb, 10000 Zagreb, Croatia; mpoljak@agr.hr
[3] Intersnack Adria Ltd., Bukača Pepe 11, 43284 Hercegovac, Croatia; drazenka.dite@intersnack.hr
* Correspondence: blevaj@pbf.hr (B.L.); maja.repajic@pbf.unizg.hr (M.R.)

Abstract: Fresh-cut potatoes (FCP), like other fresh-cut (minimally processed) vegetables, are a convenient but highly perishable product. Unlike most fresh-cut vegetables, which are "ready-to-eat", FCP must be cooked before consumption. Therefore, in addition to the safety (chemical and microbiological), quality and sensory characteristics of raw FCP, the same requirements should be applied for cooked potatoes. It is known that many factors play a role in meeting all these requirements: (i) selection of cultivars less susceptible to browning; (ii) use of anti-browning and antimicrobial agents and/or certain physical methods against browning and microbial growth; (iii) packaging and cold storage conditions. In recent studies on FCP, scientists have attempted to deepen their knowledge of the mechanisms of browning prevention to better understand changes at the molecular level as well. The main objective of this review is to provide a comprehensive overview of recent research, which aimed at deepening knowledge of the various changes that occur in potatoes during processing, and to develop new approaches that could help improve quality and extend FCP shelf life. It also discusses the effects of subsequent cooking of FCP on sensory and other properties, as well as on chemical constituents.

Keywords: potato; minimal processing; innovation; cultivar; agriculture

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1. Introduction

Potatoes (*Solanum tuberosum* L.) have been one of the basic sources of human nutrition for centuries and are the most important food plant [1]. Moreover, the potato is a year-round available crop, which makes it attractive for fresh market sales or for processing. Another advantage of the potato as a raw material is its suitability for consumption in various forms or for diverse processing (dehydration, freezing, and minimal processing) with many possibilities and various final products [2]. Minimally processed or fresh-cut potatoes (FCP) are very convenient products that reduce the time needed to prepare meals at home or in restaurants. Customers appreciate this due to the accelerated lifestyle in today's world; therefore, the demand for FCP has increased in recent years. Consequently, FCP is the focus of manufacturers, but also of scientists, whose interest in this topic continues to grow. When reviewing the scientific literature in the Web of Science with the keywords "potato × fresh-cut", it was found that almost two hundred articles published in the last 30 years have been listed, of which almost 30 were published in 2020 and 2021, almost 40 in 2022 and already three in 2023 (https://www.webofscience.com, accessed on

10 January 2023). This review presents the latest findings on fresh-cut potatoes and related topics, as well as other (older) related findings, selected by the citation hand search and using the authors' expertise, necessary to explain, understand, and contextualize the latest findings. FCP like other fresh-cut fruits and vegetables, are convenient but highly perishable products. Unlike most fresh-cut vegetables, especially salads (various types of lettuce, cabbage, etc.), which are ready to eat immediately, FCP must be cooked before consumption. Therefore, in addition to the safety (chemical and microbiological), quality and sensory characteristics of raw FCP, the same requirements should be applied to cooked FCP. In general, processing includes washing, peeling, cutting, pretreatments, dewatering, and packaging [3]. A key quality problem for FCP of peeled and sliced potatoes is susceptibility to rapid browning and microbial growth due to the loss of the potatoes' natural protection. This physical stress can initiate chemical and biochemical spoilage processes. In addition to that, temperature fluctuations often occur during distribution and storage, which can also greatly affect the quality of the potatoes. Therefore, peeled and packaged potatoes have a limited shelf life, usually 5–7 days at 4–5 °C, due to browning and microbiological, sensory, and nutritional deterioration [4].

Browning, one of the major problems for the shelf life of FCP, is a very complex process involving several enzymes and classes of compounds. Enzymatic browning is an adverse phenomenon of cutting potatoes and other fruits and vegetables. During cutting, the integrity of the tissue is disturbed, leading to the contact of oxidative enzymes with phenolic compounds (substrate for browning). In the presence of oxygen and enzymes, the oxidation of endogenous phenolics to quinones is catalyzed, which can further polymerize with other phenolics or with amino or sulfhydryl groups of amino acids or soluble proteins and with sugars, forming polymeric melanoid brown pigments. The responsible enzymes are mainly polyphenol oxidase (PPO) and peroxidase (POD). However, phenylalanine lyase (PAL) is damage-induced and a key enzyme in polyphenol synthesis [5–7]. Due to the complexity of the browning process, a better understanding of the mechanism of all these reactions in the potato has long been a challenge for many scientists, whose main goal is to develop a successful anti-browning treatment or strategy and to preserve the authentic color of the potato and the quality of the products. Considering that three main factors are involved in browning reactions, namely enzymes PPO and POD, phenolics, and oxygen, the main principle of anti-browning treatments is to exclude one of them [6]. However, recently Liu et al. (2019) [7] found the fourth factor, namely the increase in antioxidant capacity and PAL activity, which trigger reactions in advance to increase stress resistance. Common anti-browning methods include thermal methods or recent emerging technologies to inactivate enzymes, the use of certain (multifunctional) chemicals or natural agents (anti-browning and antimicrobial agents), as well as the use of suitable packaging methods (edible coatings, suitable packaging material and modified atmosphere), all of which can be used individually or in combination due to their known synergistic effects [3,8,9]. Bobo-Garcia et al. (2020) [6] gave an overview of anti-browning agents (ABA) applied to FCP.

In addition to the FCP production process itself, the browning and shelf life of FCP is also influenced by other factors, including the cultivar, harvest time, tuber handling, storage conditions and duration.

Many studies have shown that individual cultivars vary in their susceptibility to browning, but recent studies are deepening our understanding of these differences at the molecular level [10–12].

In post-harvest handling, in addition to the importance of curing treatments and appropriate storage conditions [13,14], certain treatments applied immediately prior to processing in fresh-cut products have been studied and have shown promising results. With such treatments, certain metabolic processes or chemical compositions in the potato tuber are specifically altered prior to wounding to increase the resistance of FCP to stress and subsequent color changes [7].

The mentioned influences are presented in Figure 1.

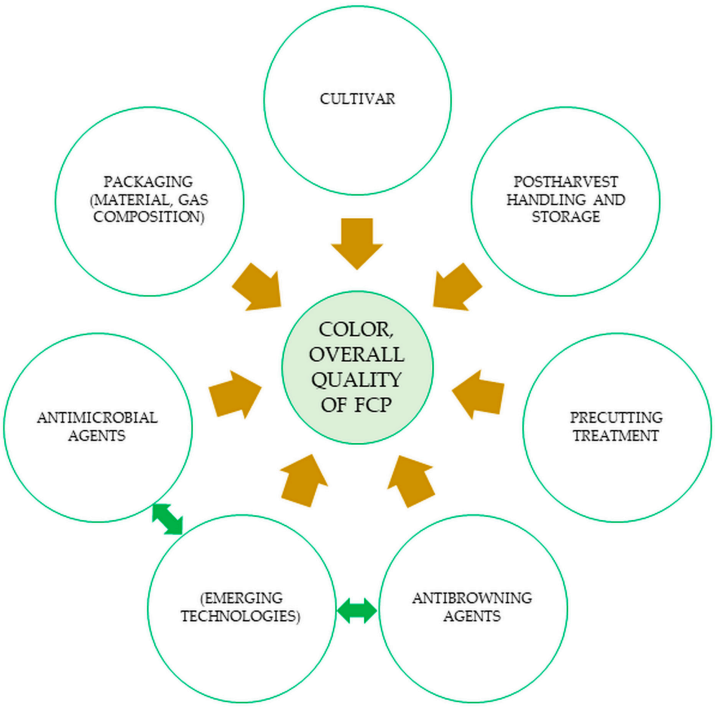

Figure 1. Overview of the factors that affect the quality of fresh-cut potatoes.

Furthermore, considering the chemical composition, potatoes contain about 80% water, and the rest refers to dry matter, of which almost 60 to 80% is indigestible starch, which has no nutritional value for humans. To make it digestible, it should be heated, such as boiled, fried, baked, or microwaved before consumption. However, heat treatment can result in the loss of certain constituents (e.g., phytochemicals). In addition, certain interactions may occur during cooking between sugars and amino acids in the potato, known as non-enzymatic browning or the Maillard reactions, which are primarily responsible for developing the pleasant taste of fried and baked potatoes. Unfortunately, these reactions can also lead to the formation of toxic acrylamide when reducing sugars react with the amino acid asparagine at temperatures above 120 °C for a prolonged period of time and low water content [1]. Therefore, with regard to the safety of FCP, another approach should also be considered, i.e., to investigate whether the treatments used in the production of FCP and its storage time may alter the chemical composition and consequently may have an impact on acrylamide formation during the subsequent frying or baking of FCP and on the sensory properties as well.

The main objective of this review, in addition to a brief introduction to the potato as a crop, is to provide a comprehensive overview of recent research that have focused on deepening knowledge of potato changes during storage and production of FCP, including the application of new processing approaches, all with the aim of improving the quality of FCP and extending its shelf life. In addition, the effects of the subsequent cooking of FCP on the chemical constituents as well as on the sensory properties will be discussed.

2. Potato as a Crop

2.1. Origin

The potato is a perennial herbaceous plant from the Solanaceae family, which includes many cultivated species such as tobacco, tomatoes, eggplant, and peppers, but also some poisonous plants such as nightshade (*Atropa belladonna*), and at least 1500 other species [15]. The *Petota* (potato) section consists of seven species cultivated for human consumption and 199 wild species [16]. Within the species *Solanum tuberosum* subsp. *tuberosum*, a distinction can be made between diploid and tetraploid species that are cultivated. Diploid species from the *Andigenum* group, which are adapted to short-day conditions, originated in the

Andean region of South America [17], where they have been cultivated for more than 6000 years [18]. The Chilean potato tetraploid species (*Solanum tuberosum* subsp. *tuberosum*) was obtained by crossbreeding; it develops tubers in longer day time conditions, gives higher yields, and has spread through cultivation throughout South America, thus suppressing the displacement of its Andean predecessors [16,19]. Today, the Chilean potato is an important crop grown around the world [20], and most modern hybrid varieties do not have a strict need for short days to form tubers [21]. The potato was brought to Europe in 1567 (Gran Canaria) and then to other parts of Europe (Belgium, Spain, France and England) and from Europe to other parts of the world in the early 17th century (India, Si Lanka, Bermuda, Virginia–United States, Taiwan and China) [22]. Therefore, Europe can be considered the second homeland of the potato. The potato has transformed the former European society, as its cultivation allows for higher yields on a smaller area [22]. Today, the potato is the most important tuber crop with tuberous roots in the global food and the most consumed crop in the tuber family. Due to its agronomic adaptability, the potato is grown in more countries and agroecological zones than any other crop [21]. Depending on the climatic conditions, potatoes can be grown as a summer, winter, spring, or fall crop, or as a year-round crop [16,18]. Although the potato is a cold climate crop plant and can be optimally grown where the average daily temperature is between 5 and 20 °C and where rain or irrigation water is available [16], its cultivation is widespread in approximately 150 countries at altitudes from between sea level and 4000 m [23]. Potatoes are a fast-growing species, and tubers can be harvested in less than 75 days under favorable conditions. In most cases, they are harvested within 120–150 days after planting [22]. Depending on the intended use of the potatoes, harvesting can occur in two different stages. In the production of mature potatoes, it is important to harvest them after the above ground part has died, dried or removed by cutting, and the tubers must have a firm skin. Immature tubers are harvested in the production of "young potatoes".

2.2. Cultivation

Its ease of cultivation and high nutritional value make it a leading crop, with production increasing in developing countries and exceeded production in developed countries for the first time in 2005 (http://faostat.fao.org, accessed on 20 January 2023). Potatoes are grown on all continents with an area of about 18 million ha and are the fourth largest crop in the world after wheat, corn, and rice. The world's largest potato producer is China with 90.3 million tons of potatoes in 2018, followed by India and Russia. In 2019, China's total production was the highest, of 370.4 million tons on 17.4 million ha (http://faostat.fao.org, accessed on 20 January 2023). To be sustainable, it is important to possible maximum yield per unit area, as this reduces energy consumption per yield [24]. Total production in the EU-28 amounted to 56.40 million tons and was obtained in 2019 on an area of 1.75 million ha. Potato production is mainly concentrated in some EU-28 member states, which account for 3/4 (77.8%) of the total area and 3/4 (78.9%) of the total amount of potatoes (http://faostat.fao.org, accessed on 20 January 2023). Germany is the leading EU-28 country with 10.6 million tons (18.8% of total EU production), followed by France (15.2%), the Netherlands (12.3%), Poland (11.5%), the United Kingdom (9.3%), Belgium (7.1%), and Romania (4.7%).

2.3. Potato Market

After harvest, potatoes are sold raw and processed, and used for various purposes for human consumption, for animals as seed, and for industrial purposes. In fact, less than 50% of the total potato production seems to have been used for human consumption as table potatoes, prepared in various ways (boiling, baking, steaming, roasting, and frying). Today, a significant amount of the potatoes are processed into frozen products (crisps and fries), dehydrated products (flour, starch, and flakes), and various food ingredients (sauces, soups, and pancakes). In any case, the consumption of potatoes as food is increasingly shifting from unprocessed to processed or partially processed products. Potatoes also have

a wide range of industrial applications and due to the high quality of potato starch, it can be used in the production of ethanol as a fuel, alcoholic beverages, pulp for the paper industry, additives, adhesives, or as a raw material for the pharmaceutical and chemical industries as a substitute for plastics [25].

The history of potato processing began more than 500 years ago [26], but industrial production is much younger and began with dehydration in the 19th century, followed by the development of frozen products in the second half of the 20th century and the processing of pre-peeled (minimally processed) potatoes in the later 20th century. In parallel, the production of other potato products such as crisps, flour, starch, etc., developed. Crisps, probably the most famous potato product, date back to 1853 when chef George Crum invented them [27]. According to Willard (1993) [27], "the industry is market-driven—developing unique or improved products is a high priority" and so he suggested certain strategies that would favor the following: increasing awareness of the importance of environmental impact (waste reduction, processes with minimal impact on the environment and automatization), health-promoting potato products (e.g., low fat or additive-free) and the development of new potato cultivars (e.g., less prone to browning or more stable with reducing sugars). It seems that the development of the potato sector follows the strategies recommended at that time.

3. Chemical Composition

The potato (*S. tuberosum* L.) has been one of the basic sources of human nutrition for centuries. It is the most important food crop after cereals. The raw tuber without skin contains approximately 81.1 g/100 g of water. In the dry matter of the edible part, carbohydrates predominate (16 g/100 g), followed by total dietary fiber (13.8 g/100 g), simple sugars (0.65 g/100 g), proteins (1.81 g/100 g), lipids (0.26 g/100 g), ash (0.89 mg/100 g), minerals (approximately 0.6 g/100 g) and vitamins (approximately 27 mg/100 g). Of the minerals, potassium (446 mg/100 g) and phosphorus (57 mg/100 g) are the most abundant, along with magnesium, sodium, iron, zinc, manganese and copper in lesser amounts. Vitamins present in potatoes include vitamin C (19.7 mg/100 g) and, to a lesser extent, niacin, thiamine, and vitamin B6 (https://fdc.nal.usda.gov, accessed on 17 January 2023). Although the potato is a modest source of ascorbic acid, its contribution to the diet is not negligible, considering that it is widely consumed in large quantities in the Europe (except Italy) [28]. The exact chemical composition depends on the cultivar but also on environmental and climatic differences. Potato consumption, with lower added fat or sodium, can improve the intake of certain nutrients [29].

Potatoes yield more carbohydrates, macronutrients, B vitamins, and protein than cereals, and do so much faster and in smaller areas than any other crop because approximately 85% of the plant is a food source for humans, unlike cereals, where the use of plants is about 50% [30].

Starch (made up from glucose units) is the main carbohydrate in potatoes (approximately 90% of dry matter) and consists of amylose (linear chain structure) and amylopectin (branched structure) in a ratio of approximately 1:3 [31]. Potato fibers are mostly insoluble and they consist of pectin, cellulose, and hemicellulose [32]. Glucose, fructose, and sucrose are the sugars present in potatoes [22,33]. Their content is strongly dependent on pre- and post-harvest factors, especially storage temperature, in addition to cultivars. Among the organic acids available in the potato, the content of citric acid is the highest, followed by malic, lactic, fumaric, and formic acids [34].

The protein content of the potato is low, but has a high biological value (90) (proportion of protein absorbed from food and incorporated into the proteins of the body) [35] compared to whole egg, which has 100, and beans 73. Although the potato is gluten-free, its main protein (glycoprotein), patatin, is also a potential allergen [36]. However, patatin can be considered as a nutritionally valuable tuber protein. In the tuber, it partly plays a defense role and partly a role as a storage protein [37]. Patatin can be isolated from potato juice in food-grade purity, and its application as a lipase in the food industry is promising [38]. It

should be noted that the amino acid composition of potato proteins has a higher content of leucine, lysine, and methionine compared to many other plant proteins [39]. In addition, the following amino acids were identified in potato proteins in descending order (generally, but with some differences between cultivars): asparagine (from 8.9 to 34.5 g/kg dry weight), aspartic acid, glutamic acid, glutamine, lysine*, valine*, leucine*, serine, phenylalanine*, arginine, isoleucine*, threonine*, tyrosine, alanine, glycine, proline, histidine*, cysteine, methionine* (*essential) [34,40].

The potato tuber is not rich in essential lipids and contains about 0.15–0.5% of fresh weight. Linoleic acid is dominant, followed by palmitic acid and linolenic acid. It may contain bioactive lipid compounds such as glycolipids, phospholipids, sterols, and carotenoids, which are desirable for their health-promoting effects [35]. Potatoes contain a significant content of carotenoids called xanthophylls, particularly lutein (2.92–6.66 mg/kg fresh weight), followed by zeaxanthin (1.44–3.05 mg/kg fresh weight) and varying amounts of violaxanthin, neoxanthin, and β-carotene depending on the cultivar. The total carotenoids content in potato tubers depends on the color of the tubers, and in yellow one it ranged from 5.57 to 20.20 mg/kg fresh weight [41,42].

Among phenolics (5.9–155 μg/g dry weight) [43], chlorogenic acid (2.1–66.5 μg/g dry weight), known for its beneficial health impact-promoting effect, is the predominant phenolic acid in the inner flesh [44]. Phenolics are distributed in tubers in descending order as follows: peel > outer part flesh > inner part flesh. The purple tubers have the highest content of phenolics and their profile is different from that of the white and yellow tubers. (Generally, topics related to purple cultivars are not included in this review). In addition to chlorogenic acid, neochlorogenic, cryptochlorogenic, caffeic, ferulic, vanillic, gallic, and protocatechuic acid (phenolic acids), (+)-catechin (flavan-3-ols), kaempferol 3-*O*-rutinoside, quercetin-3-*O*-rutinoside, quercetin-3-*O*-sophoroside (flavonols), and vanillin have been found in potatoes, and their presence and amount depend on the cultivar [43,44] and maturity [45], as well as many other factors.

In addition to health-promoting constituents, potatoes can also contain antinutritive substances, namely glycoalkaloids: α-chaconine and α-solanine, which can be toxic and can cause poisoning [46]. As part of the natural defense of the potato plant against fungi and insects, its leaves, stems, and shoots contain a high amount of glycoalkaloids. Glycoalkaloids are usually found in small amounts in the tuber and occur in the highest concentrations just below the skin. The glycoalkaloids content should be less than 20 mg/100 g of fresh potatoes. Potatoes should be stored in a dark and cool place to keep glycoalkaloids levels low. When exposed to light, potatoes turn green due to an increase in chlorophyll content, which may also indicate an increase in solanine and chaconine content [47]. Peeling and cutting the green parts of potatoes before cooking ensures their significant reduction, but boiling alone destroys them to a lesser extent, with frying being more powerful than boiling [46,48]. Nitrites form another group of potentially harmful compounds that occur naturally in potatoes. The permissible level of nitrites in table potatoes is 200 mg NO_3/kg of potatoes, but potatoes grown in Central Europe usually contain less than 100 mg $NaNO_3$/100 g of fresh weight. Nitrate is not toxic to humans, but can be converted by the intestinal microflora into nitrate III, which participates in the formation of carcinogenic nitrosamines. The thermal processes of blanching, boiling, and frying reduce the content of glycoalkaloids and nitrates [46].

4. Cultivars

As mentioned above, there are differences in the chemical composition between cultivars, which may affect their properties during processing or preparation of dishes, as well as the quality of the final products and their shelf life (e.g., FCP). Therefore, it is necessary to know the chemical composition of the potato in order to select the optimal cultivar for the production of a particular product. This can reduce both the losses during processing and the amount of waste of the final product due to its longer shelf life. FCP are particularly sensitive products, prone to browning; what depends largely on the quality

and characteristics of the cultivar. Numerous studies have been conducted to investigate the suitability of certain cultivars for the production of FCP by monitoring their resistance to browning [2,4,49–54]. A potato cultivar that is resistant to disease and mechanical tissue damage and has a lower respiration rate is preferred for FCP [3]. The appearance (color and surface) influences the quality perception of fresh horticultural products and FCP, as well as consumer purchase decisions. Firmness and texture, as attributes of "mouthfeel", as well as all attributes related to taste (sweetness, acidity, aroma/flavor, and astringency), are also quality parameters [55], but influence consumers' repurchase decisions. In addition, it is desirable that FCP are suitable for the preparation of various dishes at home or in restaurants. Therefore, the sugar content in the potato should be controlled to minimize the formation of acrylamide during frying.

Consequently, a recent study addressed the chemical composition of potatoes to estimate the optimal cultivar for a particular product. Ingallina et al. (2020) [34] found significant differences in the chemical composition of 20 Italian cultivars, for example, cv. Jelly contained high levels of monosaccharides, which is undesirable for potatoes intended for frying in terms of possible acrylamide formation. Higher levels of citric acid were found in cv. Roseval and Rubra Spes, and the authors concluded that these cultivars are desirable for the production of FCP because citric acid is involved in the inhibition of enzymatic browning. Cv. Rouge des Flandres, Blue Star, Bergerac, Roseval, and Ratte had high levels of amino acids, possibly related to the formation of pleasant-smelling volatile compounds during potato cooking. It seems that a particular cultivar is predisposed to certain industrial products and that appropriate selection of the cultivar facilitates the obtaining of quality products.

Quiao et al. (2022) [56] used transcriptomics and metabolomics analyzes to deepen the knowledge at the molecular level of differences between cultivars with different susceptibility to surface browning after cutting. Cultivar sensitive to browning (Yunshu 505) showed higher PPO and POD mRNA accumulation and enzymatic activity, but lower catalase (CAT) and ATP citrate lyase mRNA accumulation, altered lipid and amino acid metabolism, increased reactive oxygen species (ROS), and increased respiration. All observed changes contributed to the browning process. On the other hand, the cultivar less susceptible to browning (Kexin 13) had higher levels of jasmonic acid, glutamate, and gibberellins (metabolites associated with signal transduction). The authors also pointed out that L-aspartic acid and kynurenic acid (produced in tryptophan metabolism) were responsible for a lower browning and generally proved that PPO activity on phenolics was responsible for the browning process in FCP.

Wang et al. (2023) [57] made a similar observation when they compared the two cultivars, Minshu and Huangjin. Huangjin showed a higher browning index and higher activity of browning-related enzymes (PPO, tyrosinase, POD, PAL, phospholipase D, and lipoxygenase), while Minshu potatoes showed lower browning and lower activity of browning-related enzymes. The authors also found that the ultrastructure of Huangjin cells was severely damaged and therefore susceptible to browning, while the cells of Minshu potatoes remained intact 7 h after cutting, indicating a tough cell structure more resistant to browning. The differences between cultivars in browning susceptibility are presented in Figure 2. Simplot International designed genetically modified potatoes (named Innate potatoes) with reduced expression of four of the potatoes' own genes (silenced PPO as an alternative to the use of ABA and silenced invertase and asparagine synthetase to lower acrylamide in fried products) [53,58].

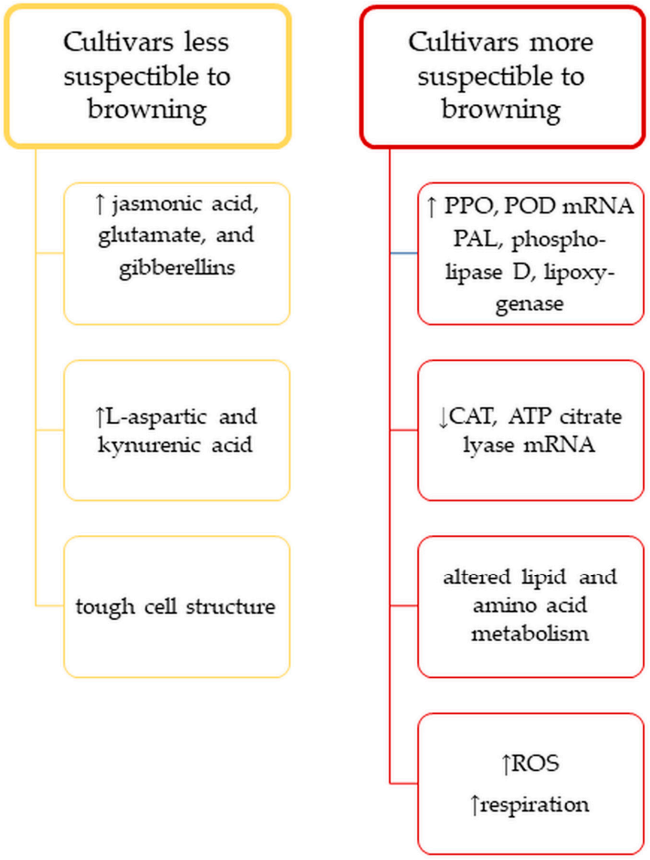

Figure 2. Differences between cultivars in terms of brown sensitivity (↑ = increase, ↓ = decrease) [56,57].

5. Post-Harvest Handling and Storage (Influence on FCP)

In addition to cultivar characteristics, harvesting and post-harvest handling have a major impact on the quality of potato tubers and FCP. The potato is a crop suitable for long-term storage, but post-harvest handling and storage conditions have a major impact on tuber shelf life and quality. To maintain the original quantity and quality of stored potatoes, recommended postharvest procedures (including wound healing, cooling, and maintaining the optimal temperature, and warming up before use) must be followed and/or special treatments applied. Following standard postharvest procedures, potatoes are placed in warehouses and exposed to curing treatment at 15 °C and high relative humidity for about 10 days. During this time, the damaged parts of the potatoes that have occurred during harvest and in storage are healing [14]. After the post-harvest curing treatment, the temperature in the warehouse is lowered by 0.5 °C every day until the optimal conditions for long-term storage are reached. It is important to gradually lower the temperature in the warehouse to avoid stress to the potatoes and to keep them in dormancy to prevent sprouting [13]. Dormancy is a very complex process that depends on the cultivar, environmental, and management conditions during growing, and temperature as well as gas composition during storage. Endogenous plant hormones are involved in the whole dormancy process, and it seems that cytokinin is involved in dormancy breakdown, as well as high temperatures or anaerobic conditions during storage [59,60].

In addition to the usual physical features of tubers, such as size and shape, health, being without damage and sprouting, their chemical composition is also important, and the storage temperature. When potatoes are stored at temperatures below about 9 °C, starch is converted to reducing sugars, and so-called "low temperature sweetening" occurs [53]. On the contrary, at higher temperatures, the reducing sugars are converted to starch during the reconditioning process. Furthermore, another sweetening process occurs during storage, called "senescence sweetening" as a result of prolonged storage at relatively

high temperatures [14]. Higher levels of reducing sugars are not desirable because they contribute to the development of a dark color of fried or roasted products, along with a bitter taste and the formation of harmful acrylamide during frying or roasting [61].

The recommended storage temperature for table potatoes is usually 3 °C, and for processed potatoes 6–10 °C [13] with relative humidity above 95% [14]. This well-known relationship between the quality of the raw material, i.e., the tuber, and the final product is particularly emphasized of FCP, since FCP should be suitable for various types of preparation (boiled, fried, roasted, baked, etc.) [33]. A better understanding of the biochemical mechanisms that occur in potatoes during post-harvest treatment, such as wound healing, i.e., curing treatment, is the subject of many scientific works. A better understanding of the potatoes' defense mechanisms and their triggers is of a great importance in the search for possible treatments to accelerate wound healing and increase the potatoes' resistance in general and during processing.

Wound Healing

Many studies have addressed a better understanding of the wound healing process, with the aim of accelerating it and reducing losses. Yang et al. (2020) [62] investigated the treatment of wounded potatoes by immersion in hot water (45 °C/10 min) and found that such treatment reduced losses and accelerated wound healing by activating phenylpropanoid metabolism and stimulating the synthesis of suberin and lignin, among other effects. Suberin is a domain of multilamellar areas composed of polyaliphatic (lipid polyester) and polyaromatic (polyphenolic) layers [63]. A recent study showed that wound healing can be accelerated by *Kloeckera apiculata*, a biocontrol yeast, which also accelerates phenylpropanoid metabolism and the synthesis of suberin, phenolics and lignin, and reduces weight loss of wounded tubers [64].

In addition, Ozeretskovskaya et al. (2009) [65] found positive effects of arachidonic acid and chitosan on wound healing in potato tuber tissues by accelerating the development of phellogen and inducing proteinase inhibitors, with jasmonic acid playing a crucial role as a signaling molecule.

Zhou et al. (2019) [66] reported the positive effect of dipping potato cubes in methyl jasmonate at 250 µM for 15 min on the wound healing process. This treatment improved gene expression and enzyme activity of resistance and phenylpropanoid metabolism, e.g., increased activity of PAL, PPO, POD, CAT, cinnamate-4-hydroxylase and 4-coumarate-CoA ligase, and promoted the accumulation of suberin and thickening of the cell wall. On the other hand, it had negative effect on color of the potato cubes.

Furthermore, application of chito-oligosaccharide, a chitosan degradation product, to injured potatoes accelerated wound healing and reduced postharvest losses [67]. Chito-oligosaccharide-induced ROS metabolism, increased gene expression and activities of CAT, POD and enzymes responsible for the synthesis of ascorbic acid and glutathione. Additionally, chito-oligosaccharide improved antioxidant capacity, which contributes to maintaining cell membrane integrity, and reduced cell membrane permeability as well as malondialdehyde (MDA) content.

Wang et al. (2015) [68] explored the behavior of FCP from potatoes taken immediately after harvest and from potatoes previously stored at 16 °C for 10 days (post-harvest curing treatment). The results showed an increase in the content of phenolics such as chlorogenic acid, an increase in the activity of PPO and a decrease in PAL activity in the cured FCP samples, which also showed better color and sensory properties compared to the control samples. PAL is an enzyme responsible for the conversion of phenylalanine to cinnamic acid, which is the beginning of the phenylpropanoid pathway in which phenol biosynthesis occurs [69]. Although phenolics are a substrate for browning reactions, chlorogenic acid is a strong antioxidant that improves the resistance of low-density lipoproteins to lipid peroxidation and inhibits DNA damage [70]. Therefore, the authors speculated that chlorogenic acid with such abilities may be helpful in protecting against browning and suggested to better understand gene expression, the enzyme activity and metabolism of potatoes should

be systematically studied. Another study on the same post-harvest cure treatment at 16 °C for 10 days was published by the same team [71], in which they more or less confirmed the results of the above study of Wang et al. (2015) [68].

Furthermore, Hou et al. (2014) [71] found that curing treatment inhibited gene expression of PAL at the mRNA level during the storage of FCP previously cured and associated this with lower PAL enzyme activity and retarding browning.

6. Anti-Browning Agents and Their Mechanism of Action

ABA are the most searched topic on FCP in the last 12 years, especially in the last 3 years according to Web of Science. More than half of the published papers with the keyword "potato × fresh-cut" dealt with the unpleasant phenomenon of potato browning, which can be prevented or slowed by treatment with ABA. In view of the fact that three review papers [6,8,9] have recently been published dealing with the prevention of potato browning, only a brief overview will be given here, focusing on the publications on FCP of the last few years.

6.1. Inhibition of PPO

Many methods are based on the inhibition of PPO, which is generally considered to be the enzyme most responsible for enzymatic browning. In general, PPO can be inhibited in several ways. Indirectly, by ABA, which act on the substrate by reducing quinones to phenolics (ascorbic acid and sulfites) or react with quinones, for example, cysteine, and form a colorless adduct. Furthermore, PPO can be directly inhibited by lowering the pH of the optimal enzyme's activity (by organic acids) [6,72]. In general, the optimal pH for PPO activity is 6.5 [73] and can be prevented by using solutions with pH below 4 [74]. Furthermore, PPO can be directly deactivated by ABA which has chelating properties and binds metal ions (Cu^{2+}) of the enzyme such as citric acid, quercetin, amino acids, peptides or proteins, etc. [6,72]. For example, aspartic acid showed an inhibitory effect on PPO activity by lowering pH and acting as a chelating agent for Cu^{2+}, preventing the formation of brown products of tyrosine and chlorogenic acid [75]. Similarly, citric acid is also an acidifier and chelating agent, and it seems that both effects are unavoidable in evaluating its efficacy, since the reduction in browning by citric acid was much better when compared to sulfuric acid at the same pH [74]. Another direct way of PPO deactivation can be by the formation of complexes of PPO and ABA due to their structural similarity (benzoic acid, cinnamic acid, ferulic acid, etc.) [72]. The influence of ABA is presented in Figures 3 and 4.

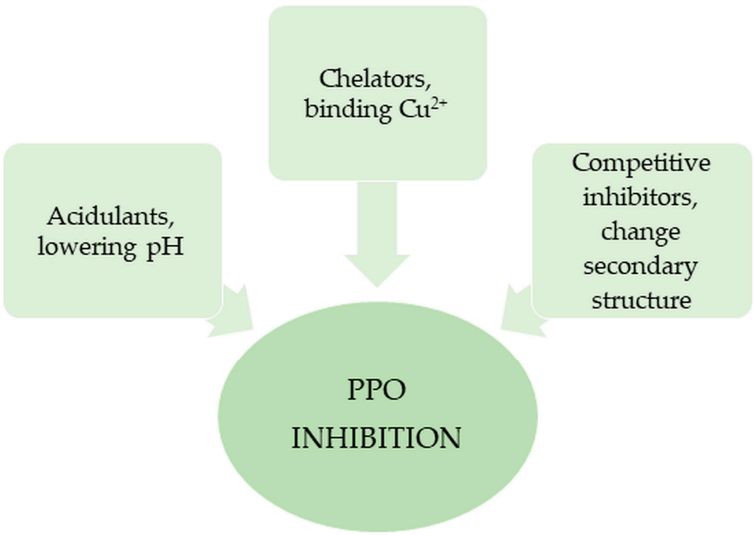

Figure 3. Influence of anti-browning agents on polyphenol oxidase (PPO) inhibition.

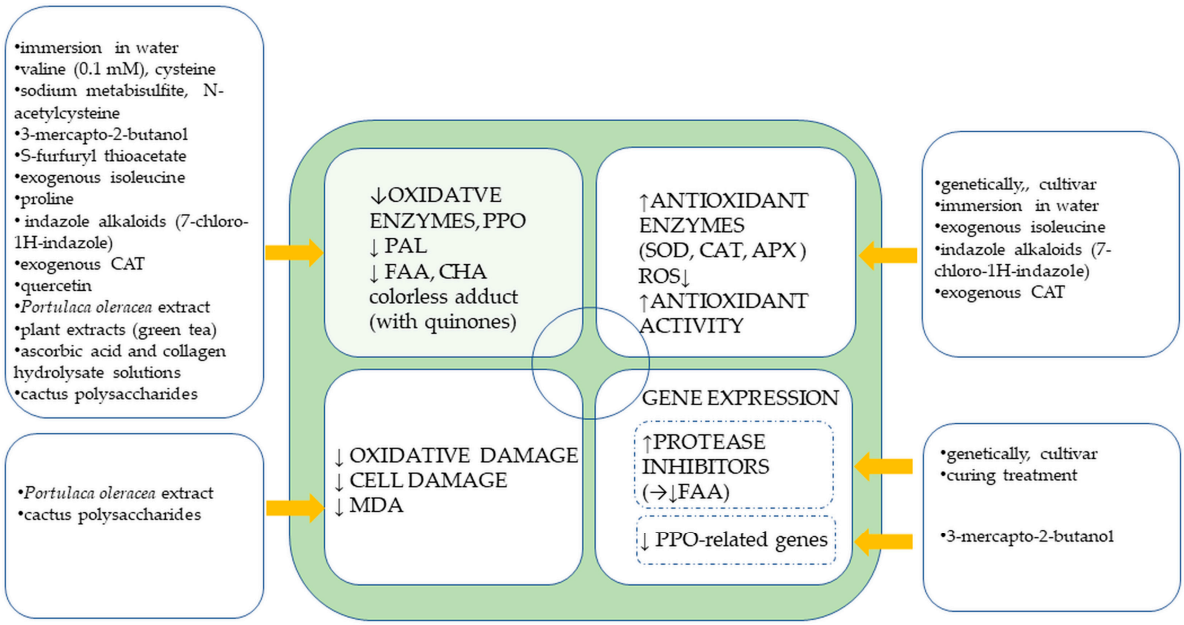

Figure 4. Overview of changes in plant cells of fresh-cut potatoes responsible for resistance to browning due to use of the latest anti-browning agents or due to cultivar characteristics (↑ = increase, ↓ = decrease) [11,12,72,76–88].

6.2. New Approaches in Browning Prevention

In contrast, Dong et al. (2020) [12] found that browning inhibition was not related to PPO activity, but to the activity of protease inhibitor activity, especially two cysteine protease inhibitors (cysteine StPI 143 and cysteine StPI 146). These inhibitors can reduce protease activities and the accumulation of total free amino acids, as well as tyrosine, a phenolic amino acid associated with potato browning. The authors found that the activity of protease inhibitors was a characteristic of the cultivar, but also a result of curing treatment. In the next study, Dong et al. (2021) [11] compared wild and transgenic potatoes and found that overexpression of the new aspartic protease inhibitor gene (StASPI) also reduced enzymatic browning and free amino acids content in transgenic potato, but also reduced PPO activity. In addition, in transgenic potatoes they found an increased activity of antioxidant enzymes superoxide dismutase (SOD) and CAT, which can scavenge ROS (superoxide radical O_2^- and hydrogen peroxide), decreasing their levels. Similar mechanisms to prevent browning were reported by Gong et al. (2019) [76], who investigated the effect of immersing potato slices in water during different time periods from 0 to 30 min. The best browning inhibition during 12 days at 5 °C, was obtained after 15 min of immersion. In response to and with the aim of overcoming water stress, various reactions were induced in the potato, which subsequently had an anti-browning effect. In these samples, the levels of SOD, ascorbate peroxidase, glutamic acid, and proline increased, while hydrogen peroxide and superoxide radical (O_2^-) were lowered. Furthermore, in these samples, the activities of chlorogenic acid, tyrosine, and tyrosinase (PPO) were lower. The proposed mechanism of inactivation of PPO occurs through the binding of chlorogenic acid and amino acid residues of PPO, disrupting the natural balance of hydrogen bonds and destroying the secondary structure of the enzyme. However, results on the role of chlorogenic acid in enzymatic browning are contradictory. According to some results, it can promote [73] or inhibit PPO activity [76,89], depending on the concentration. Similar to chlorogenic acid, certain amino acids and proteins may have a dual effect on browning: as a stimulator of browning in reaction with quinones or as an inhibitor as a chelating agent, also depending on their concentration [72]. In a study by Ali et al. (2016) [72] valine at a concentration of 0.1 mM reduced browning and at a concentration of 1 M it increased browning. Furthermore, a concentration of ≥1 mM for glycine, and ≥1 M

for methionine and phenylalanine increased browning due to the formation of colored catechol-amino acid adducts, while a lower concentration reduced browning. Cysteine, on the other hand, reduced browning at all these concentrations. The thiol group of cysteine is characterized by higher nucleophilicity, so that at higher concentrations cysteine reacts with quinones to form colorless adducts, while at lower concentrations it acts as a competitive PPO inhibitor [72]. Unfortunately, its use is limited due to its unpleasant odor [90]. In general, the amino acid that was the most effective in reducing the browning process was valine at low concentrations (0.1 mM) and cysteine at high concentrations (1.0 M) while the least effective was glycine [72]. Other endogenous thiol compounds, in addition to cysteine, glutathione, and N-acetylcysteine, which contains a reduced form of very reactive sulfur, the sulfhydryl group, could play an important role as an anti-browning agent [77]. Cerit et al. (2020) [77] compared the efficacy of sulfur compounds and found that sodium metabisulfite as well as L-cysteine and N-acetylcysteine reduced PPO activity, while glutathione did not. Sulfites are often avoided due to their potential health risk, especially among sensitive consumers, e.g., consumers suffering from bronchial asthma, who show intolerance to sulfites in foods [91–93], so scientists are searching for a substitute. Furthermore, Zhou et al. (2013) [94] concluded that a combination of 0.45% $CaCl_2$ + 0.1% EDTA-2Na + 0.15% L-cysteine + 0.6% citric acid could be a sulfite substitute for potatoes. Another sulfur compound, 3-mercapto-2-butanol, was found to be similarly effective to sulfites [78]. This compound occurs naturally in humans and is recognized by the Flavor by Extract Manufacturers' Association (FEMA) as a safe (GRAS-Generally Recognized as Safe) flavoring agent (https://www.femaflavor.org, accessed on 5 March 2023). This is a potential ABA due to its ability to reduce PPO activity directly in a competitive manner (by competing with tyrosine for the binding site of PPO) and indirectly by inhibiting the expression levels of PPO-related genes (POT32 and POT33) [78]. In general, many endogenous sulfur compounds play a defensive role in the plant [95]. In addition, Feng et al. (2022) [96] found that S-furfuryl thioacetate, a naturally derived sulfur compound, was very effective at very low concentrations. At concentrations as low as 0.04 and 0.07 mM at 2–4 °C, S-furfuryl thioacetate prevented the browning of FCP sticks for up to 10 days. For comparison, the anti-browning effect was comparable to that of sodium bisulfite at 2.40 mM. Treatment with S-furfuryl thioacetate seems to inhibit PPO by bonding with Cu^{2+} and its amino acid residues and causing changes in the secondary structure of the enzyme [79]. Similarly, Meng et al. (2022) [80] found that when exogenous isoleucine (1.0%) was used to reduce browning on potato crisps. PPO activity was reduced by chelating Cu^{2+} and interacting with PPO amino acid residues. In addition, it improved the antioxidant capacity. Liu et al. (2022) [81] found that treatment with 90 mmol/L proline for 1 h at 30 °C effectively inhibited the browning of FCP slices for 4 days at 2–4 °C by decreasing PPO activity, phenolic content and the content of certain amino acids (tyrosine, aspartic acid, glutamic acid, serine, glycine, histidine and valine), while increasing the accumulation of endogenous proline content and antioxidant capacity of FCP. The efficacy of indazole alkaloids known for their biological activities [97] was also investigated in a study by Öztürk et al. (2022) [82], where 7-chloro-1H-indazole showed the highest potential to inhibit PPO activity. Qiao et al. (2021) [83] showed that the use of exogenous CAT treatment (immersion in 0.05% CAT/5 min) is an efficient biological approach to delay the browning of FCP at 4 °C for 8 days. Lower levels of phenolics, H_2O_2 and O^{2-} and lower activities of PPO, POD and PAL were found in samples with better color, while activities of antioxidant enzymes (CAT, ascorbate peroxidase and glutathione peroxidase) were higher.

6.3. Ascorbic Acid

In addition to the fact that new ABA are continuously sought, the efficacy of already known effective ABA is also still being tested. Zhou et al. (2021) [98] studied the impact of ascorbic acid (5 or 10 g/L) on FCP strips during storage at 20 °C/4 days and a relative humidity of 80–90% and demonstrated that ascorbic acid (5 g/L) can retard browning. It also preserves texture by reducing hardening (delayed lignin formation) and improving

flavor (for 3 days), as well as reducing weight loss and respiration rate. These results were confirmed in another study by the same group in which they investigated the combined effect of ascorbic acid (5 g/L) and vacuum-packaging (VP) and storage of FCP for 5 days at 4 °C [99].

Dite Hunjek et al. (2019) [100] studied the effect of treatment with sodium chloride solution (1%) and sodium ascorbate solution (2%) on potato slices of cv. Birgit and Lady during storage under air, vacuum, and active modified atmosphere. The influence of these treatments on color, texture, and other properties was compared with samples dipped in water for 2 min. In general, sodium ascorbate showed a higher efficiency in preventing browning, but also in retaining sensory and other properties, and vacuum-packaged samples were more acceptable.

6.4. Natural ABA

Recently, numerous studies have been conducted on natural constituents with anti-browning activity. Some of these components also show antimicrobial activity and health benefits. Although their main purpose is to preserve color and extend shelf life, they should not have a negative impact on other properties and components or sensory characteristics and should not be harmful to health.

Among natural agents, several groups are studied as ABA or antimicrobials, e.g., antioxidants such as quercetin or phenolic extracts of plant, or essential oils and aroma compounds, natural peptides, proteins such as collagen, polysaccharides, etc. Kasnak (2022) [84] found that treatment with 25 mg of quercetin per 100 mL of water effectively lowered the browning index for 7 days at 4 °C, inhibited PPO and PAL activities, decreased MDA formation, and reduced the accumulation of phenolics. In another study, Kasnak and Palamutoglu (2021) [101] investigated the effects of yogurt serum treatment and showed its positive effect on the suppression of the browning process. Liu et al. (2019) [85] investigated the efficacy of water extract of the biologically valuable plant purslane (*Portulaca oleracea*) as an ABA for FCP. This is a widely used wild plant that is very popular in China, where it is traditionally used in folk medicine. Phenolics and alkaloids are mainly responsible for its antioxidant activity, and the alkaloid betaine [85] has been of interest as an osmoregulator and can act against oxidative stress [102]. A lower concentration (0.05%, *w*/*w*) of aqueous purslane extract was more effective than a higher concentration (0.1%, *w*/*w*) in suppressing browning, the degree of oxidative damage (lower MDA content), cell membrane damage and the activity of PAL, PPO, and POD. It seems that a higher concentration was not as effective because a higher concentration could have negative effects on ROS balance and redox biological system [103]. It is speculated that a higher concentration of aqueous extract could lead to higher osmotic pressure and consequent cell damage and it also contains higher content of quinine and glycine, compounds that could be involved in the browning process and be converted into colored adducts [104]. Another promising plant extract, sea buckthorn leaf extract, was studied by Zhang et al. (2022) [105]. Catechin, hypericin, gallic acid, casuarinin, isorhamnetin, and pedunculagin were identified as the main constituents of this extract. The extract showed a possible anti-browning effect on FCP, while casuarinin, isorhamnetin, gallic acid and pedunculagin showed a synergistic effect. The extract had the ability to decrease the content of phenolics and the activities of PPO, POD, and PAL, and to increase the antioxidant capacity. Bobo et al. (2022) [86] studied the influence of 15 plant extracts (black pepper (*Piper nigrum*) powder, cinnamon (*Cinnamomum verum*) sticks, clove (*Eugenia caryophyllus*) dehydrated, garlic (*Allium sativum*) minced and dehydrated, ginger (*Zingiber officinale*) powder, green tea (*Camellia sinensis*) and marjoram (*Origanum majorana*), dehydrated leaves, nutmeg (*Myristica fragrans*) powder, oregano (*Origanum vulgare*), peppermint (*Mentha piperita*), rosemary (*Rosmarinus officinalis*), sage (*Salvia officinalis*) and thyme (*Thymus vulgaris*) dehydrated leaves, wheat bran (*Triticum* spp.) leaflets and white pepper (*Piper nigrum*) powder). Although the clove extract had the highest total phenolic content and the highest antioxidant capacity, green tea extracts showed strong inhibition of PPO, regardless of the extract water ratio (1:12.5 to

1:1, *v*:*v*). Therefore, green tea was selected for further study of effects of the extracts on FCP, while it was found that it successfully retarded browning during 14 days at 4 °C.

6.5. Essential Oils

Among essential oils, the use of rosemary oil (*R. officinalis* L.) has been studied [106–108] and promising results have been obtained. Essential oils are liquid, concentrated mixtures of volatile compounds (mostly short hydrocarbon chains complemented by oxygen, nitrogen, and sulfur atoms) with distinct aroma isolated from plants. They also have various functional properties as a result of highly reactive atoms in their composition. For both reasons, they have the potential to be widely used in food processing [109]. In the past and even today, rosemary has been traditionally used in folk medicine as well as in cooking for its distinctive flavor. Jiang et al. (2011) [110] identified 1,8-cineole, α-pinene, camphor, camphene and β-pinene as the main constituents of rosemary essential oil and noted its antimicrobial activity. Additionally, the oil showed higher antibacterial and antifungal activity than 1,8-cineole or α-pinene alone. The use of such aromatic plants in potato processing could lead to the production of new innovative products [109]. Luo et al. (2019) [106] immersed the cut potatoes in a solution of water and oil, and vacuum impregnation was performed before packaging to improve the penetration of essential oil into the potato tissue. They found that rosemary oil slightly deteriorated the color of the potato, did not affect the texture and moisture content, but contributed to the microbiological stability of the product. Rizzo et al. (2018) [107] and Amaroso et al. (2019) [108] used VP (French *sous vide*) for potatoes treated by dipping in rosemary oil. No negative effects on potato color were observed with less microbial growth during storage. Liu et al. (2018) [104] found that certain cod fish peptides (identified 1765), were more effective at a lower concentration (0.1%) than at a higher concentration (1%). Liu et al. (2019) [85] found similar observations for aqueous purslane extract. Kasnak (2020) [87] found that immersion of FCP in ascorbic acid and collagen hydrolysate solution (with an optimal concentration of 0.22% collagen and 0.30% ascorbic acid) preserved color and antioxidant capacity, and reduced PPO activity. Cheng et al. (2022) [88] studied the effect of cactus polysaccharides (immersion in 1%, *w*/*w* for 10 min) alone and in combination with ultrasound (kHz, 480 W, 10 min) on the stability of FCP, which was stored at 4 °C for 8 days. The samples treated with combined treatment were the brightest during storage, followed by those treated with cactus polysaccharides, while the color of the control samples (immersed in distilled water for 10 min) was the most unacceptable. The same sequence was observed in the decrease in the activity of PPO and POD and in the increase in the activity of PAL, furthermore, in the inhibitory effect on the MDA content, and in the decrease in the loss of cell membrane integrity measured by the relative conductivity. Moreover, the combined treated samples showed the least decrease in antioxidant capacity during storage.

Finally, it should be mentioned that the effect of ABA also depends on the origin of the enzymes. Kuijpers et al. (2014) [111] studied the potential of 60 plant extracts to inhibit PPO isolated from mushrooms or potatoes. They found that different plants had different abilities depending on the origin of the enzyme, and the opposite results were obtained with the extract of mate (*Ilex paraguariensis*), which inhibited PPO from mushrooms but not potatoes.

6.6. Potatoes' Response to Cutting

Recent research approaches the problem in a different way, studying the changes that occur in potatoes immediately after cutting to gain knowledge and develop better strategies to improve the shelf life of FCP and breeding potato plants that are resistant to enzymatic browning [112]. Wang et al. (2023) [57] investigated the physiological changes in FCP at molecular level 4, 12 and 24 h after cutting. The authors made a hypothetical model of the potatoes' response to cutting based on the results obtained: after cutting potato tubers, tissues produce ROS and plant hormones (gibberelin, cytokinin, ethylene, auxin, jasmonic acid, and salicylic acid) and activate genes encoding enzymes for the biosynthesis of secondary metabolites (including phenolics and lipids). Genes related to enzymatic

browning (PPO, POD, CAT, etc.) were then also activated. The higher initial activity of CAT may reduce the enzymatic browning caused by PPO and POD by degrading H_2O_2. Therefore, the authors concluded that it may be helpful not only to reduce the activity of PPO, but also to directly or indirectly reduce the activity of POD and SOD, or to improve the activity of CAT by genetic engineering or other physical or chemical methods to inhibit enzymatic browning.

7. Microflora

FCP are products that are highly susceptible to microbial growth, which not only leads to spoilage, but can also pose a potential health risk to consumers. Despite the fact that the natural microbial flora of vegetables is not generally contaminated with pathogenic microorganisms, disease outbreaks have been reported in whole and fresh-cut vegetables because the vegetables can become contaminated during growth, harvest, and post-harvest processes [113]. Potato tubers are naturally exposed to soil microorganisms, bacteria, and fungi that can cause certain potato diseases. For example, potatoes can be infected in the field with the filamentous fungus *Phytophthora infestans*, which causes late blight, or *Alternaria solani*, which causes late blight under irrigation. In addition, soil is generally considered an important habitat for the *Clostridium* spp. [114]. Additionally, tubers can be injured during harvest and handling, which may be the cause of infections and diseases that develop during storage, such as dry rot and wilt caused by *Fusarium*, brown rot caused by *Pseudomonas solanacearum*, or scab caused by *Streptomyces scabies*. Bacterial soft rot can be caused by some subspecies of *Erwinia*, *Pseudomonas* and *Clostridium*, and the potato can be infected in the field and the infection can spread during storage [115]. Several human pathogenic bacteria have been isolated from raw potatoes or from the potato field: *Listeria monocytogenes* from soil [116], *Escherichia coli* O157:H7 [117], *Clostridium botulinum* [118] and *Clostridium difficile* [119,120] from potato tubers. Today, the global food market (e.g., potato market) represents a potential transmission of infections, which can even be transcontinental [120]. To minimize the risk of foodborne illness, strict standards are established and rigorous controls are implemented regarding the cultivation, handling, transportation, and marketing of fresh vegetables. This practice also applies to food processing lines and facilities through good manufacturing practice (GMP) and Hazard Analysis and Risk-Based Preventive Controls (HARPC) explained in adequate guidance e.g., Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards of Fresh-cut Fruits and Vegetables by Food and Drug Administration (FDA). Adherence to the food safety protocols contained in this guidance can significantly help reduce the risk of foodborne illnesses According to Butt et al. (2022) [121], the number of disease outbreaks caused by *E. coli* has decreased over time. On the contrary, Desai et al. (2019) [122], based on data collected by the ProMED search engine for the period 1996–2018, concluded that an increasing number of international *Listeria* outbreaks have been recorded in the last decade. They also noted that there was an increase in the number of foods contaminated with *Listeria* that are not normally contaminated, such as mashed potatoes. As mentioned above, minimally processed (fresh-cut) fruits and vegetables are a particularly sensitive category of processed foods. It is not subjected to the heat treatment, which generally guarantees safe products, although not completely if the preservation or storage is not adapted to potential infection by, for example, *C. botulinum* [114]. Therefore, it is necessary to produce fresh-cut products under high hygienic conditions (including equipment, facilities, and labor) to maintain the cold chain and to establish cold rooms in their retail stores. Minimal processing, especially peeling and cutting, damages plant tissue, exposing FCP to cross-contamination, including human pathogens. Leakage of nutrient-rich juices from damaged tissue, large surface of the product, and high humidity in the packaging also increase susceptibility to microbial growth during storage [123]. FCP are particularly susceptible due to its generally weak acidity at pH 6 [74,100,124,125]. Under such circumstances and conditions, the number of colony-forming units per gram (CFU/g) of natural microbial flora can rapidly increase from an initial level of approximately 10^4 to 10^5 CFU and more [100,109]. Beltran et al. (2005) [126] determined that the natural microflora of FCP (after washing with water) is aerobic mesophilic bacteria (approximately 3.5 log CFU/g),

psychotropic bacteria (approximately 3.5 log CFU/g), anaerobic bacteria (approximately 2.0 log CFU/g), yeasts and coliforms (approximately 1.2 log CFU/g), and lactic acid bacteria (less than 1.0 log CFU/g). Coliform bacteria (from the *Enterobacteriaceae* family) are indicators of fecal contamination and include potentially pathogenic species such as *E. coli*. Anaerobic bacteria include spoilage bacteria and the foodborne pathogen *C. botulinum*. Lauridsen and Knøchel (2003) [127] studied the natural microflora of potatoes and demonstrated the absence of *L. monocytogenes*, *Bacillus cereus*, and *C. botulinum*, while *Enterobacteriaceae*, particularly *Enterobacter amnigenus*, were predominant. Gunes et al. (1997) [128] demonstrated the predominant presence of *Pseudomonas* spp. (especially *Pseudomonas fluorescens* and *Vibrio fluvials*). Recently, Li et al. (2022) [125] showed the presence of the following bacteria: *Ralstonia* (43.08%, previously included in the genus *Pseudomonas*), *Pseudomonas* (13.66%), *Pantoea* (8.48%), *Comamonas* (5.37%), *Enterobacteriaceae* (3.24%), *Brevundimonas* (2.63%), *Lysobacter* (2.59%), *Delftia* (2.31%), *Limnobacter* (2.1%), *Serratia* (1.43%), *Bacillus* (1.2%) and others (13.77%) in peeled potatoes.

Another problem associated with microbiological contamination of fresh-cut products is the detection of contamination. The shelf life of the products is relatively short, and analytical methods, especially the traditional ones, are relatively time-consuming and complex, while the new and advanced methods are technically demanding, so there is a need for rapid, simple, and accurate methods. Li et al. (2021) [129] established models for predicting *E. coli* on the surface of FCP slices based on the full spectrum and characteristic wavelengths in the visible and near-infrared range (Vis-NIR, 400–1000 nm) using the hyperspectral imaging system and developed an optimal backpropagation neural network model. They demonstrated that hyperspectral imaging measurement of contamination on the surface of FCP could provide a rapid and non-destructive method for the detection of *E. coli*.

The usual antibacterial treatment involves washing both the whole and the cut potato. Immersing the potato after peeling and cutting it in water or in water solutions containing disinfectants (antimicrobial chemicals, including ABA) can reduce the microbial load and therefore the growth of microorganisms [130].

Scientific research to find efficient antimicrobials is mainly addressing two approaches. One approach is to monitor the effectiveness of the applied treatment on the natural microflora. Another approach is to monitor the effectiveness of treatment on a specific microorganism (culture medium) or inoculated product.

In addition to the application of antimicrobials, which is known as a chemical method, physical methods are inevitable, such as the packaging process, including the selection of appropriate material and atmosphere. Recently, many studies have been conducted on the effects of non-thermal techniques (e.g., irradiation, ultraviolet light, pulsed light, high-pressure, ultrasound, cold plasma) on maintaining the food safety of FCP. Moreover, these techniques are usually combined with certain common and harmless ABA such as ascorbic acid and its salts, or some others and show synergistic effects (hurdle technique) in retarding browning and microbial growth. Therefore, they have great potential to maintain food safety in FCP industry without the use of chemical disinfectants such as sulfur or chlorine compounds.

8. Antimicrobials

The effectiveness of antimicrobial agents depends on the treatment method, including their concentration, but also on the potato cultivar used, packaging conditions (material and gas composition), storage temperature, etc. According to Zhao S. et al. (2022) [131], 0 °C is optimum for the storage of FCP pretreated with chlorine dioxide solution (100 mg/L), citric acid solution (1.5%) and potassium sorbate solution (0.1%), and packaged with polyvinylidene chloride plastic film.

Giannuzi 1995 [132] tested the antimicrobial activity of citric and ascorbic acids individually and in combination on pre-peeled potatoes that were vacuum-packaged and stored at 4 °C for 20 days. Individual acids also showed antimicrobial activity, but for the required efficacy (total plate count of less than 10^6 CFU/cm for 20 days), the concentrations were so

high that they negatively affected the taste of the subsequently boiled potato. However, acids in combination, even at lower concentrations, had good antimicrobial activity for 8 days, with no adverse taste effects.

Juneja et al. (1998) [133] tested the antimicrobial activity of sodium bisulfite and a commercial browning inhibitor without sulfite on peeled potatoes inoculated with *L. monocytogenes* during storage at 4, 15 and 28 °C. They found that *L. monocytogenes* did not grow for 21 days only at 4 °C, regardless of the agents used. These results show the importance of temperature control throughout the production chain and especially in retail stores, where variation is common.

Ajingi et al. (2020) [134] found that the combination of nisin peptide (0.0016 mg/mL) and formic acid (0.025%, *v*/*v*) inactivated the proliferation of the *Bacillus subtilis* food spoilage bacteria in vitro and showed their synergistic effect. They also found the synergistic effect of nisin and another organic acid (citric, lactic, malic, fumaric, and tartaric) not only on non-pathogenic *B. subtilis*, but also on pathogenic bacteria *Pseudomonas aeruginosa*, *E. coli*, *Salmonella typhimurium*, *Staphylococcus aureus*, and *Streptococcus faecalis*. They also inoculated peeled and cut potatoes and immersed them in 0.125% (*v*/*v*) formic acid combined with 0.0016 mg/mL nisin and 0.02 N HCl (nisin diluent) for 10 min, which successfully suppressed the survival and proliferation of all of the tested bacterial strains in this study.

Vazquez-Armenta et al. (2014) [135] studied the antimicrobial influence of onion essential oil (0, 0.5, 2.5, and 5 mg/mL) on potato slices packaged in a polystyrene tray at 4 °C during 15 days of storage. In onion oil, dipropyl disulfide and dipropyl trisulfide were identified as the main components. Aerobic mesophilic bacteria and these two sulfur compounds were negatively correlated. The immersion of slices in onion essential oil (5 mg/mL) effectively suppressed microbial growth during 15 days of storage at 4 °C.

Shi et al. (2018) [136] investigated the efficacy of Navel orange peel essential oil in controlling mold growth in potato slices. They found about 74, 74, 73, and 69% protection against *Aspergillus niger*, *Mucor wutungkiao*, *Penicillium funiculosum*, and *Rhizopus oryzae*, respectively, at a concentration of 2.00 µL/mL air, although a significant effect was also shown at a lower concentration (0.50 µL/mL air). The authors suggested that D-limonene, β-myrcene, γ-terpinene, and 3-carene, as constituents of the oil studied, could be responsible for this inhibitory effect. The proposed mechanism of action of citrus oils and their volatiles is that they disrupt the membrane integrity of microbes and consequently reduce pH, which could negatively affect ATP synthesis and certain enzymes [137]. Since essential oil citrus volatiles do not affect the sensory properties of food, the authors concluded that the essential oil of Navel orange peel can be used as a fumigant in the storage of fresh-cut vegetables to prevent the spread of fungi [137].

Sarengaowa et al. (2022) [138] tested 18 essential oils of cinnamon (*Cinnamomum cassia*), oregano (*O. vulgare*), clove (*E. caryophyllus*), tea tree (*Melaleuca alternifolia*), pomelo (*Citrus maxima* (Burm.) Merr.), jasmine (*Jasminum sambac* (L.) Ait.), eucalyptus (*Eucalyptus globulus*), sweet orange (*Citrus sinensis* (Linn.) Osbeck), sea buckthorn pulp (*Hippophae rhamnoides* L.), sweet osmanthus (*Osmanthus fragrans* (Thunb.) Lour.), lavender (*Lavandula angustifolia*), petitgrain (*Citrus sinensis* L. Osbeck), grapefruit (*Citrus paradisi* Macf.), rose (*Rosa rugosa* Thunb.), citrus (*Citrus reticulata* Blanco), blumea (*Blumea balsamifera*), rosemary (*R. officinalis*), and valeriana (*Valeriana officinalis*) against *L. monocytogenes*, *S. typhimurium*, *S. aureus*, and *E. coli* O157:H7. Cinnamon oil was the most effective against all four bacteria tested.

Rizzo et al. (2018) [107] treated peeled sliced potatoes with 0.5% rosemary oil, vacuum-packaged them in *sous vide* cooking bags, and stored them at 4 °C. Rosemary oil was effective in controlling the growth of mesophilic bacteria and *Enterobacteriaceae* over a 12 day period.

Luo et al. (2019) [106] found that vacuum impregnation with rosemary essential oil (already mentioned in the previous section) had an antimicrobial effect on the natural potato microflora (total aerobic plate count, yeasts and molds, and psychrophilic bacteria)

proportional to concentration applied. Potato sticks were packaged in polypropylene trays and stored at 4 °C for 14 days.

Yu et al. (2021) [139] investigated the effect of the photodynamic sterilization technique using 420 nm light-emitting diodes and curcumin (30 µmol/L) as a photoactive compound (photosensitizer) on FCP. This is a novel non-thermal treatment to inactivate bacteria by cytotoxic ROS generated by the photosensitizer after irradiation with visible light. Curcumin is a natural phenolic compound derived from the rhizomes of turmeric (*Curcuma longa*) and is known for its health-promoting properties. Recently, it has been used as a photosensitizer with promising results. In this study, the growth of *E. coli* and *S. aureus* was reduced in intentionally infected FCP, while other properties were largely preserved.

Cheng et al. (2022) [88] found a positive effect of combined treatment with cactus polysaccharides and ultrasound (already mentioned in the previous section) on reducing the total number of microbial colonies, mold and yeast in FCP during 8 days of storage at 4 °C.

Irfan et al. (2020) [140] studied the influence of different cut types or forms (slices, dices, cubes and wedges) on the shelf life of potatoes. Potato pieces were treated with calcium chloride, citric acid, and potassium metabisulfite (3, 2, and 0.3%, respectively) and stored in plastic boxes at 4 °C for 60 days. In the evaluation of physicochemical parameters (firmness, weight loss, pH, titratable acidity, total soluble solids and ascorbic acid content) and microbial activity, the dice cut type showed the best results, i.e., minimal changes in the above parameters. The microbial activity increased over time in all forms, with an increasing difference between them, so that at the end of the storage period the slices were the most unacceptable cut samples and the dices, which had a lower microbial load, were shown to be the best cut type.

9. Packaging in FCP Production

Packaging is of a great importance for proper handling and distribution of fresh-cut products. These products are generally packaged in (i) flexible polymeric bags, (ii) rigid plastic trays, sealed with cover polymeric films (iii) or in overwrapped trays. Polyolefins, such as polyethylene (PE) and polypropylene (PP), are the dominant polymeric materials used for the packaging of fresh fruits and vegetables (Table 1). The most recent research recommended polyvinylidene chloride (PVDC) plastic film for the best preservation effect of FCP [131]. If the package containing fresh product is sealed with a permeable film, the headspace atmosphere is modified because of the balance between the respiration process of the product and the exchange of gases through the polymeric film. Stable-state concentrations of O_2 and CO_2 are established at a given temperature when the O_2 consumption and CO_2 production rates are identical to the rates of permeation of these gases through the package [141].

Table 1. Examples of different packaging materials and methods used for the storage of fresh-cut potatoes.

Packaging Material	Packaging Method	Storage Conditions	Reference
PA/PE, 100 µm PCO_2 (23 °C, 50% RH): 145 mL/m^2 bar 24 h PO_2 (23 °C, 50% RH): 35 mL/m^2·bar·24 h WVP (23 °C, 50% RH): 7 g/m^2·24 h, peeled whole tuber	Vacuum *	4–6 °C, 7 days	Rocha et al., 2003 [124]

Table 1. *Cont.*

Packaging Material	Packaging Method	Storage Conditions	Reference
PA/PE bags, PCO_2: 0.121 mL/m^2 d atm PO_2: 0.024 mL/m^2 d atm WVP (90% RH): 22.1 g mm/m^2 d atm, slices previously treated with pressurized Ar * and N_2	MAP (4% O_2, 2% CO_2, 94% N_2)	4 °C, 12 days	Shen et al., 2019 [142]
Coex.PA/PE-HD, 22 µm OTR: 8 × 10^4 cm^3/m^2 Pa, previously edible coating (alginate) on strips	vacuum	3 ± 1 °C, 12 days, no positive effect	Amaral et al., 2017 [143]
OPA/CPP (15/60 µm) two-component polyurethane as adhesive, previously slices treated with rosemary essential oil	*Sous vide* packaging–vacuum	4 ± 2 °C, 11 days	Rizzo et al., 2018 [107]
PP trays, sealed with PE film, 200 µm, previously sticks dipped in rosemary oil suspension under a sub-atmospheric pressure of 60 ± 10 mbar/30 min (vacuum impregnation)	-	4 °C, 14 days	Luo et al., 2019 [106]
Edible coatings on slices based on Cactus *Opuntia dillenii* polysaccharide (0.5%, 1% * and 1.5% ODP)	edible coating (slices on racks)	5 °C, 5 days	Wu, 2019 [144]
PE-LD -previously edible film (crosslinked whey protein/pectin film) * on sticks	-	4–6 °C, 6 days	Marquez et al., 2017 [145]
Edible coating on whole tuber: chitosan (CH) + whey protein (WP) + coconut oil (CO): 1. CH 0.5% 2. CH 0.5% + CO 0.1% 3. CH 0.5% + WP 5% 4. CH 0.5% + WP 5% + CO 0.1% *	-	20 ± 1 °C, 75–80% RH, 60 days	Saha et al., 2014 [146]
Polystyrene trays wrapped in PVC films, previously edible coating on cubes based on chitosan containing cinnamon oil (0.2 *, 0.4, and 0.6%)	-	4 °C, 16 days	Sarengaowa et al., 2022 [138]
Coex. PP, 19 µm OTR: 1.91 × 10^{-6} mol/m^2 s PPcast, 30 µm; OTR: 1.55 × 10^{-6} mol/m^2 s previously edible coating on sticks based on Locust bean gum *	-	4 ± 1 °C, 90–95% RH, 8 days	Licciardello et al., 2018 [147]
alginate coating on cubes		no positive effect	Ceroli et al., 2018 [148]

Table 1. *Cont.*

Packaging Material	Packaging Method	Storage Conditions	Reference
PP trays covered by a cling wrapper, slices previously wrapped by active packaging film by sodium alginate, carboxymethyl cellulose, glycerol, calcium chloride and citric acid by addition of extract of peel shallot onion waste		4 °C, 5 days no positive effect	Thivya et al., 2021 [149]
1. Biodegradable film (30 µm) PO_2: 55 c^3/m^2 24 h atm PCO_2: 95 c^3/m^2 24 h atm WVP: 200 g/m^2 24 h 2. PA/PE, 85 µm * PO_2: 79 c^3/m^2 24 h atm PCO_2: 347 c^3/m^2 24 h atm WVP: 8 g/m^2 24 h Slices packaged	standard atmosphere conditions	4 °C, 9 days	Ierna et al., 2017 [150]

* treatment/conditions showed positive impact.

In order to maintain the quality of the potato product, appropriate conditions must be ensured inside the package. Due to the product respiration (reduction in O_2 and increase in CO_2 concentrations inside the package), the packaging material with specific permeability (gases and water vapor) characteristics should be selected. Different types of plastic packaging material polypropylene (PP), low density polyethylene (PE-LD), medium density polyethylene (PE-MD) and high-density polyethylene (PE-HD) assessed by Abassi et al. (2016) [151] had a significant impact on weight loss of non-peeled potato tuber during storage. The weight loss was influenced by the type and thickness of the material (increased weight loss in PE-HD packaging compared to those packaged in PE-LD). In addition, the better mechanical properties (tensile strength) of PP made it better for the storage of FCP, helping to avoid potential losses during shipping and sale [151]. Siracusa et al. (2012) [152] pointed out the importance of the permeability parameters of the biaxially oriented polypropylene/polyethylene (BOPP/PE) film used for packaging FCP for 20 days. The authors found some changes in the properties of the barrier film after 5 days of direct contact with the packaged product. In fact, food packaging material should be inert to the permeants that come from packaged food. In certain circumstances, especially in polymers with polar groups, moisture from the atmosphere or food juices could cause swelling or plasticizing of the packaging material and harm barrier properties [153].

It is of great importance that immediately after washing and removal of surface water, packaging is done under vacuum (VP) or under modified atmosphere (MAP). VP reduces oxidative reactions and inhibits the growth of aerobic microorganisms, which generally lead to deterioration of foods during storage. The use of VP is an alternative to chemical treatment to maintain the quality of FCP [124,125], but most often both are combined [99,100,126,154]. Rocha et al. (2003) [124] used 0.01 cm thick polyethylene/polyamide (PE/PA) bag for VP, by which PPO activity was greatly inhibited and the 'fresh-like' quality of potatoes was effectively preserved. Shireesha et al. (2018) [155] studied the effect of potato cube size, polyethylene thickness, and lack of oxygen on weight loss, color changes, firmness, spoilage, and organoleptic properties of FCP. The authors demonstrated that the best solution was to pack 2 cm^3 rather than 1 cm^3 cube sizes and that 0.005 cm PE bags were better than 0.0025 cm PE bags when packaged in vacuum conditions.

The vacuum-packaged potatoes were also shown to receive slightly higher scores than those packaged in inert atmosphere (100% N_2) in BOPA/PE pouch (thickness of 0.012 cm). It seems that more consumers are willing to purchase vacuum-packaged products due

to greater external firmness, less internal moisture and moisture in the mouth, and less pastiness. The samples were analyzed before and after boiling [154].

Rizzo et al. (2018) [107] studied the effect of the *sous vide* packaging method combined with essential oil of rosemary as a strategy for preservation of sliced potatoes (a study mentioned study in the previous section). Vacuum conditions and the presence of rosemary essential oil had a positive effect on texture, total phenolics, and antioxidant capacity, and it limited the growth of mesophilic bacteria and *Enterobacteriaceae* over 11 days of storage.

Ultrasound as a non-thermal processing technology in combination with alginate coatings did not have a positive effect on potato strips stored in refrigerator (3 ± 1 °C) and vacuum-packaged in coextrude polyamide/high-density-polyethylene (PA/PE-HD) bags for 12 days [143]. Alginate improved the browning of potato samples, reduced pH, and did not reduce microbial growth. The authors reported that the combination of applied techniques was not suitable for improving the shelf life of FCP under given storage conditions.

Another packaging method which can be used for FCP is MAP. With MAP, the composition of gases inside the package is altered and thus it reduces the respiration rate of the fresh product. The success of MAP depends on the barrier (O_2, CO_2 and water vapor) properties of polymeric films.

Rapid establishment of low O_2 and/or elevated CO_2 conditions is critical for the prevention of browning. A package suited for this product would create an equilibrium gas composition of 1 to 2% O_2 and 3 to 5% CO_2 to prevent enzymatic browning [156,157]. O_2 levels were noticed to be affected by potato cut type with values of 3 to 5% for chips or cubes, respectively [2]. Furthermore, it was shown that the effect of high O_2/CO_2 gas combinations significantly lowered respiration rates in FCP stored at 4 °C compared with potatoes stored in low O_2/low-high CO_2 atmospheres. The best results were obtained using gas combinations of 80 O_2/10 CO_2 and 80 O_2/20 CO_2 (kPa/kPa; N_2 balance). The best results for anti-browning activity were observed for the same gas combinations, although browning was still visible at the end of the 14 day storage. Low O_2 treatments (without the presence of CO_2) resulted in increased acidity, while low O_2/high CO_2 and high O_2/high CO_2 conditions lowered acidity. For these experiments, potato slices were placed in hermetically closed 3.25 L glass jars with a flow-through system to create the different modified atmospheres [158].

According to Ma et al. (2010) [159], modified atmosphere only slightly delayed the quality loss of FCP (cv. Pacific Russet), but effectively suppressed PAL activity and increased the content of phenolics. The analyzed potato slices were packaged in vented PE bags that were stored in polycarbonate (PC) containers with a humidified air or modified atmosphere (0.3, 3 and 21% O_2 in combination with 0, 6 or 12% CO_2).

In addition to MAP, inert gases (argon and nitrogen) can also be used to extend the shelf life of a fresh-cut produce. Shen et al. (2019) [142] reported the effects of pressurized treatments with Ar and N_2 (concentration ratio of 1:1) in combination with MAP (4% O_2, 2% CO_2, 94% N_2) on the shelf life of FCP during refrigeration (4 °C). The results indicated a positive impact of packaging treatment, as well as the edible coating (ε-polylysine/chitosan) during storage period compared to control group.

Compared to MAP, VP was also recommended for storing FCP (cv. Agata, Altesse, Franceline, Manon, and Monalisa) to preserve vitamin C (89% of the initial content) and color at 4 °C [160]. Fresh cutting was found to increase L-galactono-*g*-lactone dehydrogenase activity from 4.7- (VP) to 11-fold (air) after 6 days. For the rest of the packaging conditions, after 6 days of storage, vitamin C decreased in the following order: VP (89% retention) > 100% N_2 (78%) > 20% CO_2 (63%). In the case of air and MAP (20% CO_2, 100% N_2,) FCP was placed in 250-mL jars, while for VP a multilayer film bags (BB4L Cryovac) were used [160]. Beltrán et al. (2005) [126] also concluded that VP preserved fresh-cut cv. Monalisa potatoes up to 14 days at 4 °C better than MAP.

9.1. Edible Coatings

In order to preserve original food quality, to avoid weight loss, water loss and nutrient loss, edible film preservation technology has become hot topic. In addition to VP or MAP, edible coatings confer barriers properties of the final package [161]. Moreover, due to the improvement of people's health awareness and vigorous promotion of harmless packaging, in some instances, these coatings applied on food surface might serve as a tool for delivery of functional and active compounds such as antioxidants, vitamins, bactericides, immunomodulatory, gastro protective agents, etc. [144,162].

As coatings could be made from different naturally occurring polysaccharides (starch, chitosan, pectin, etc.) [163,164], gums [147], proteins, and lipids, there are numerous possible combinations.

Wu et al. (2019) [144] reported that treating potatoes with a polysaccharide extract isolated from *Opuntia dillenii* cactus could suppress browning, microbial counts, respiration rate, loss of weight and total sugars content in FCP stored at 5 °C for 5 days. Similar observations were also made by coating with transglutaminase crosslinked whey protein/pectin blends during 6 days of storage [145].

Saha et al. (2014) [146] showed that chitosan/whey protein/coconut oil blends coated on potato strips increased shelf life of potatoes up to 60 days (in comparison with 45 days in control group) when stored at 20 ± 1 °C. The results showed that coated potatoes had a reduced weight loss rate, respiration rate, percentage of decay, soluble solids, shrinking, and wrinkle development when compared with uncoated.

Licciardello et al. (2018) [147] noted that if edible coating made of locust bean gum is applied and the tubers packaged in PPcoex or PPcast and stored in refrigerated conditions at 4 ± 1 °C for 8 days, the reduction in color changes occurred only in samples obtained with intermediate fertilizer levels, due to limited microbial contamination. Ceroli et al. (2018) [148] showed that the alginate coating did not improve the quality of the potato cubes compared to combined osmotic dehydration technology and/or antioxidants. Similarly, Thivya et al. (2021) [149] prepared an active packaging film by mixing sodium alginate, carboxymethyl cellulose, glycerol, calcium chloride citric acid and the extract of peel shallot onion waste. The coatings were applied on the FCP, but the L^* value decreased from 66.40 to 47.88 in 5 days at 4 °C.

Sarengaowa et al. (2022) [138] showed that coating FCP with chitosan containing cinnamon oil (0.2, 0.4, and 0.6%) and packaged in polystyrene trays (255 mL) wrapped in PVC films, and stored at 4 °C for 16 days had a positive impact on reducing browning and microbial growth.

Edible coatings are also used to improve the appearance quality of fried food products and to reduce lipid migration of lipids [165–167].

9.2. Biodegradable Packaging

Although it is evident that it is impossible to replace plastic packaging materials, the extensive use of plastic packaging raises serious environmental concerns. Recent trends include growing interest in packaging with biodegradable and compostable materials. Ierna et al. (2017) [150] compared the influence of bio-based (cellulose based) compostable film against conventional coextruded polyamide/polyethylene (PA/PE) films used for 9 days of storage of minimally processed potato tubers. The authors reported that the bio-based film resulted in poorer quality (i.e., higher browning, weight changes, and microbial proliferation) of that packaged in PA/PE bags. These differences were mainly due to the completely different and lower barrier properties of the compostable bags. Furthermore, the barrier of these bags was shown to be even worse during storage due to the migration of water from the potatoes. In order to find commercial applications, biodegradable films must have customized characteristics, such as barrier properties to gases and water vapor, for a specific food packaging [168].

10. Emerging Technologies

Consumer habits have changed in terms of increasing demand for healthy, natural, and safe food, as well as in terms of their distrustful attitude toward additives [169,170], but unfortunately, they are usually used as ABA or antimicrobial agents (sanitizers) for minimally processed fruits and vegetables. To obtain safe products with a lower quantity or without additives and without thermal treatment, which is in contradiction with freshness, the main characteristics of these products, the use of non-thermal technologies is studied. For this reason, non-thermal food processing technologies such as ultraviolet (UV) radiation, high hydrostatic pressure (high pressure processing) (HHP), ultrasound (US) among others are being investigated to develop adequate processing methods for the production of FCP.

Food treated with UV-C radiation may be considered as a novel food in EU. Novel food is, among others, food to which an applied production process which did not exist in Europe before 1997, "which gives rise to significant changes in the composition or structure of a food affecting its nutritional value, metabolism or level of undesirable substances" [171,172]. Because such food must pass a safety assessment before being placed on the EU market to ensure human health [172] and due to the lack of regulatory approvals and high investment costs, the widespread use of UV technology in industry is delayed [173]. Regarding HHP, the European Food Safety Authority (EFSA) announced in 2022 that HHP food processing does not pose additional problems in terms of microbial or chemical food safety compared to other routine procedures such as pasteurization, and made some recommendations on the use of HHP [174]. However, the application of HHP in the food processing in EU can be affected by many factors such as, among other things, the innovation of companies, high investment costs, and the profitability [175].

10.1. UV-C Radiation and Its Effect on FCP

UV radiation causes structural changes in DNA [176,177], thus preventing cell replication. The UV-C wavelength of 254 nm has the most effective germicidal effect. Numerous studies have reported effective UV-C inactivation of microorganisms, when applied to fresh or fresh-cut fruits and vegetables [178–180]. UV-C may also positively affect the storage of fresh and fresh-cut fruits and vegetables by reducing oxidative or cell wall-degrading enzyme activities [181,182]. Compounds that have a beneficial effect on health, such as anthocyanins or flavonoids, can be increased by exposure to UV-C light [183]. Furthermore, UV-C can increase firmness, improve flavor, or preserve color in UV-C treated fruits and vegetables [178,179,181,184]. However, some negative effects are observed, such as reduced vitamin C content in pineapple slices or impaired ripening and increased browning of tomatoes at higher doses [184,185]. Although UV-C radiation can lead to physiological and biochemical changes that can positively affect the quality of fruit and vegetable products and extend their shelf life, its effect depends on many factors, such as intensity and exposure time (dose), plant material and the type of microorganisms present, the topography of processed surface, minimal processing and transparency of packaging [186–189].

There is a relatively small number of studies on the effect of UV-C radiation on FCP (Table 2). Teoh et al. (2016) [182] monitored enzyme activity in irradiated potato slices. Although UV-C treatments (2.28, 6.84, 11.41 and 13.68 kJ/m^2) reduced enzyme activity, the lowest PPO, POD and PAL activity during storage (in darkness 10 days/4 °C and packaging in permeable plastic boxes after radiation) was observed when combined treatment of ascorbic acid, calcium chloride solution and 6.84 kJ/m^2 was applied. However, Xie et al. (2017) [190] reported that UV-C radiation did not significantly affect PPO activity during the early storage period, but less activity was observed after 13 days of storage at 4 °C compared to the control. In addition, UV-C did not prolong the durability of the product, while sodium acid sulfate treatments had the best effect on microbial inhibition, color parameters and PPO activity during storage.

Table 2. Recent studies on the effect of UV-C, HHP and US on fresh-cut potatoes.

Potato Treatment/Processing/Packaging	Storage	Reference
UV-C 2.28, 6.84 *, 11.41 and 13.68 kJ/m^2–slices pretreated with ascorbic acid and calcium chloride solution, in permeable plastic boxes	4 °C, 10 days	Teoh et al., 2016 [182]
UV-C 3 min, sodium acid sulfate, and their combination–slices in PE bags	4 °C, 25 days	Xie et al., 2017 [190]
UV-C 0, 3, 5 * and 10 min (0, 1.62, 2.70 * and 5.40 kJ/m^2, respectively)–slices pretreated with sodium ascorbate solution in PA/PE vacuum bags	6 °C, 23 days	Pelaic et al., 2021, 2022 [191,192]
UV-C 0–10.08 kJ/m^2–tubers UV-C 0–2.70 kJ/m^2–slices *	10 °C, 24 h	Čošić et al., 2021 [193]
HHP 400 MPa/3 min–slices in plastic jars filled with sodium ascorbate solution	6 °C, 15 days	Levaj et al., 2020 [194]
HHP 600 MPa/3 min/10.6 °C peeled tubers, vacuum packaging (PA/PE)	4 ° C, 14 days	Tsikrika et al., 2021 [195]
HHP 200 MPa/2, 6 and 10 min 400 MPa/1, 2 and 6 min sticks, packaged in PP bags + distilled water	4 °C, 12 days	Procaccini et al., 2022 [196]
US (bath, 53 kHz, 200/5, 10 min, 500 W/5, 10, 15 at 20 °C–sticks packaged in bags 500 W/15 min *	4 °C, 12 days	Procaccini et al., 2022 [196]
US 630 W, 40 kHz/10 min, room temperature slices dipped in 0.00, 0.01, 0.02 *, 0.05% purslane solution, packaged in PE self-sealing bag	4 °C, 8 days	Zhu et al., 2021 [197]
US (bath, 0.75 W/cm^2/5 min, 40 kHz), slices simultaneously dipped in *Sonchus oleraceus* L. extract (0.1 g/L); treatments alone or in combination *	4 °C, 8 days	Qiao et al., 2021 [198]
US (180–900 W/5–25 min, 20–60 °C, 20 kHz, titanium probe, Φ20 mm, inserted approximately 2 cm) whole tuber dipped in distilled water (PPO deactivation 540 W/15 min, 20 °C) *	-	Erihemu et al., 2021 [199]
US (28 kHz, 100–500 W/0–10 min) slices dipped in 0.5–2.5 g/L L-cys solution, packaged in PE bags; 360 W/6 min/2 g/L *	4 °C, 48 h	Erihemu et al., 2022 [200]
US 40 kHz, 480 W, 10 min–slices, control, dipped in cactus polysaccharides (CP), US, US + CP *	4 °C, 8 days	Cheng et al., 2022 [88]
US (40 kHz, 200 W, 3 min) slices dipped in ascorbic acid (0.2%, *w*/*v*) treatments alone or in combination *		Xu et al., 2022 [201]
US (35 or 130 kHz) slices dipped in Natureseal® 7.5% (*w*/*v*) and green tea 5% (*w*/*v*), US-no significant enhancement	4 °C, 9 days	Nicolau-Lapeña et al., 2022 [202]

* observed the best positive effect; US—ultrasound, HHP—high hydrostatic pressure, UV-C—ultraviolet-C radiation (100–280 nm).

Pelaić et al. (2021, 2022) [191,192] examined the effect of UV-C radiation (0, 1.62, 2.70 and 5.40 kJ/m^2) on potato slices vacuum-packaged in PA/PE vacuum bags during storage 23 days/6 °C. The initial effect of UV-C on aerobic mesophilic bacteria was not significant, but during storage its effectiveness was significant, especially for the treatment of 2.70 and 5.40 kJ/m^2 which reduced the growth of bacteria throughout storage time (reduction of 2 log CFU/g compared to control). These treatments also increased brightness (L^*) and positively affected sensory properties such as color, odor, and firmness of raw potatoes. Boiled and fried potatoes treated with UV-C had a more pronounced characteristic odor and taste. Furthermore, UV-C treatment increased the content of simple sugars and the acrylamide content in fried samples. Acrylamide is a potentially carcinogenic compound, which is formed by frying potatoes at temperatures above 120 °C, where the reducing sugars and the amino acid asparagine act as precursors. However, the acrylamide content in these studies was below the maximum allowed limit for potato products (750 µg/kg fried sample) [203].

The effect of UV-C on unpackaged potato tubers (0–10.08 kJ/m^2) and unpackaged potato slices (0–2.70 kJ/m^2) during storage for 24 h/10 °C was investigated by Čošić et al. (2021) [193]. Applied doses caused a significant reduction in the number of aerobic mesophilic bacteria. Although the initial number of bacteria was similar for potato tubers and slices, a similar reduction in the number of bacteria (1–1.5 log CFU/g) required a much higher dose for potato tubers (5.40 kJ/m^2) compared to potato slices (1.08 kJ/m^2), probably as a result of natural surface topography [173] and possible shading of microorganisms. Furthermore, UV-C increased the chlorogenic acid content especially in tubers, which decreased with increasing dose. The increased phenolic content can be stress-related (excessive UV light or wounding by minimal processing) [68]. On the contrary, Pelaić et al. (2021) [191] observed a slight decrease in chlorogenic acid content, which was more expressed with higher applied doses.

Some noticeable differences in the results in these studies are probably due to the application of different radiation doses and UV-C radiation conditions [171,189], different cultivars and minimal processing of potatoes and ultimately different packaging and storage of products. Therefore, it is important to examine and apply the radiation conditions that will ensure the inactivation of microorganisms but also preserve quality of FCP under certain conditions of minimal processing, packaging, and storage.

10.2. HHP and Its Effect on FCP

Inactivation of microorganisms and enzymes can be successfully achieved by using HHP as a substitute for thermal pasteurization in the production of fruit and vegetable-based foods, resulting in an extension of the shelf life of the product. The complex effect of HHP on microorganisms affects the structural organization of the cell, metabolic processes, leads to denaturation of proteins and disintegration of ribosomes, ultimately leading to cellular death [204,205]. Usually, products are packaged before HHP treatment under vacuum conditions to prevent recontamination of the product, and the isocratic pressures vary from 400 to 600 MPa and common hold times from 1.5 to 6 min [174]. HHP affects secondary, tertiary and quaternary structures, but not covalent bonds; therefore, compounds such as vitamins and flavor components remain largely unchanged, maintaining food quality [206]. According to some previous research on fresh-cut fruits and vegetables, the use of HHP has resulted in the inhibition of polygalacturonase in jujube fruits [207], delayed microbial growth in potatoes [195] or improved the content of β-carotene in packaged fresh-cut melon [208]. The effectiveness of HHP treatment on food depends on the pressure and processing time used, intrinsic factors such as water activity and pH, microorganism-related factors such as type, taxonomic unit, strain and physiological state, as well as on the type of enzymes present [174,209].

According to Levaj et al. (2021) [194], the initial reduction in aerobic bacteria was 15% when HHP was applied to potato slices in comparison with HHP untreated samples. However, the effectiveness of HHP treatment was more noticeable during storage,

significantly slowing bacterial growth and resulting in a reduction of approximately 53% after 15 days of storage. On the contrary, Tsikrika et al. (2021) [195] noted a significant initial reduction (>3 log CFU/g) of aerobic plate count in HHP treated vacuum-packaged peeled tubers, but after 14 days of storage, there were no significant differences between HHP treated and untreated potatoes. Also, according to Tsikrika et al. (2021) [195] HPP completely inactivated *Enterobacteriaceae* in examined cultivars (Maris Piper and Rooster). The same authors reported a significant decrease in glycoalkaloids, reduced chlorogenic acid content, and unchanged total phenolic level in HHP treated samples. However, in their previous study, the results showed an increase in the content of total phenolics under the same conditions (600 MPa/3 min) [210]. As noted by the authors, a number of factors can affect the phenolic content and therefore the impact of applied processing technology, such as, inter alia, cultivar, maturity, or growing and storage conditions. Firmness is an important factor for food acceptability, and therefore, it is important not to be degraded by food processing. HHP causes damage to the structure of tubers and cell walls and therefore can lead to a reduction in firmness [196,211]. Dourado et al. (2020) [212] observed that the firmness of potatoes did not change significantly for 100 MPa, but decreased when pressures of 200 and 400 MPa were applied (water and asparaginase solution). Similarly, Procaccini et al. (2022) [196] reported a lower hardness of HHP treated samples compared to control during storage of potato sticks for 6 days, where a reduction in firmness was also noticeable with a longer treatment time, although not significant. According to the same authors, HHP treatments had negative effects in terms of enzymatic browning, resulting in the lowest L^* value and increased PPO activity, higher with prolonged treatment time. Due to cellular changes caused by the action of HHP, the release of membrane-bound enzymes is possible, but also a better interaction of enzymes and substrates as a result of the applied pressure for a longer time [211]. As a result, a more pronounced browning may occur. On the contrary, Eshtiaghi and Knorr (1993) [213] observed complete inactivation of the PPO enzyme, which was achieved when 400 MPa was applied for 15 min at 20 °C, using diluted citric acid solution as immersion medium. Regarding the color changes in the treated potatoes, Tsikrika et al. (2021) [195] also found a decrease in lightness (L^*) during storage in FCP treated with HHP.

10.3. US and Its Effect on FCP

The US is one of the non-thermal techniques that have been widely used in the food industry where a wide positive influence has been confirmed in a wide range of processing techniques [214–216]. A more resentful trend in the food industry is the application of high-intensity US as pretreatment for fresh-cut and ready to cook/eat products [8]. In this new trend there are several studies that investigated the beneficial influence of US on the anti-browning effect, inhibition of PPO [198,200–202]. Zhu et al. (2021) [197] elucidated that the combination effect of US and natural extract could prevent PPO activity significantly enhancing the antioxidant capacity and better maintaining the integrity of the cell membrane of FCP. The synergistic effect of US and natural extract would be a promising method for the fresh-cut industry because of its simplicity, safety, low cost and convenience for anti-browning and strong effect of sterilization for FCP. Furthermore, Qiao et al. (2021) [198] investigated the mutual influence of US and anti-browning treatments with *Sonchus oleraceus* L. extracts as a strategy to increase the shelf life of FCP, and successfully and efficiently controlled the activities of PPO, POD, PAL, lipoxygenase, soluble quinones, as well lowered MDA content and increased antioxidant capacity in FCP slices. These results and conclusions are consistent with other research [197]. Erihemu et al. (2021) [199] investigated the influence of US on the PPO activity of whole potatoes and determined that the PPO activity of whole potatoes treated with US was lower than that of untreated whole potatoes. In addition, the power and time of US have a large impact on the microstructures of the whole potatoes and the most effective ultrasound power and time was 540 W/15 min, and temperature 20 °C. Procaccini et al. (2022) [196] implemented and investigated the use of US treatment as a possibility to prolong shelf life and reported a positive effect of

US on PPO activity, and moderate influence on the preservation of microbiological quality in terms of shelf life. Cheng et al. (2022) [88] investigated the combined effect of cactus polysaccharides and US treatment and found their positive effect in increasing the shelf life of FCP.

11. Chemical Changes in FCP during Storage

During the storage period of FCP, many chemical and biochemical reactions can occur in the potato in addition to color and microbial decay. Among other things, the content of phenolics, sugars, or volatiles may change. A wide range of factors such as cultivar, harvest time, handling, storage conditions and duration, and the processing itself (treatments applied) influence the chemical composition of FCP. This section provides an overview of studies that addressed some of these issues.

Meng et al. (2020) [80] found a differential susceptibility to browning in potatoes harvested at three stages of maturity (the third was commercial mature), and was higher with increasing maturity, although PPO activity showed a decreasing trend and antioxidant capacity showed an increasing trend. On the other hand, the content of free amino acids, especially tyrosine, increased with maturity, which could be responsible for the browning of the more mature potato. Additionally, the content of total phenolics was highest, while the content of MDA was lowest in the last harvested potatoes. The total phenolic content and antioxidant capacity also increased with increasing tuber weight.

11.1. Phenolics and Sugars

Although it is desirable to preserve phenolics in FCP due to their health-promoting properties, many studies showed that their content showed decreasing trend during FCP storage [7,84,139,147]. Considering that they are substrates for enzymatic browning, their decrease may be associated with browning reactions.

Therefore, during storage, the content of phenolics undergoes qualitative and quantitative changes depending on many factors. The phenolic content increases according to some studies [7,98,104]. Wang et al. (2015) [68] recorded that it could depend on potato pre-treatment. They found that the phenolic content was higher in FCP produced from potatoes that were subjected to curing treatment (16 °C/10 days) before cutting and showed increasing trend of phenolics during 12 days storage, which was not the case with non-cured potatoes. Chlorogenic acid was found to have the highest content, and it showed an increasing trend during storage. Protocatechuic acid also showed an increasing trend, while gallic acid decreased. Similar results on chlorogenic acid were obtained by Gong et al. (2019) [76], but in their study protocatechuic acid showed a decreasing trend at 5 °C/12 days. Furthermore, they identified gallic acid, which first increased and then it decreased. In this study, potato slices were immersed in deionized water (25 °C, pH 5.0) for 15 min. Furthermore, the content of gallic acid was higher in control samples, but the trends during storage were similar.

Dite Hunjek et al. (2021) [33] studied the content of phenolics and sugars in FCP. The potato was peeled, sliced, immersed in sodium ascorbate (2%, w/v) and vacuum-packaged. Two cultivars (Birgit and Lady Claire) with different tuber ages (1, 5, and 9 months) during storage (8 days at 10 °C) were examined. Cv. Birgit contained less phenolics (5.77 mg/100 g of dry weight) than cv. Lady Claire (10.13 mg/100 g of dry weight), while sugar content (sum of glucose, fructose, and sucrose) was 1.75 and 0.65 g/100 g of dry weight, respectively. The phenolic content, with chlorogenic acid as the predominant component, showed a decreasing trend, while the sugar content increased with tuber age; content of phenolics and sugars did not change significantly during the storage time of FCP. Similarly, Tsouvaltzis and Brecht (2017) [74] also did not find a significant change in phenolics in FCP (cv. Russet Burbank) during 6 days at 5 °C.

Xu et al. (2022) [99] reported that the sugar content (glucose, fructose, and sucrose) in FCP (cv. Holland No.7) pretreated with ascorbic acid and vacuum packaged also showed an increasing trend during 5 days at 4 °C, while the content of starch and phenols decreased.

Furthermore, Zhao et al. (2022) [131] studied the treatment of ascorbic acid and calcium ascorbate not only by dipping, but also by vacuum impregnation and found delayed formation of phenolics, especially chlorogenic acid.

Rizzo et al. (2018) [107] treated potato slices with peanut oil and rosemary essential oil, vacuum packaged and stored them at 4 °C/11 days. Phenolic content, ascorbic acid content, and antioxidant capacity were different between the studied cultivars (Arinda, Elodie, Erika, Fontane, Marabel, and Ranomi) and showed a decreasing trend during 11 days. The addition of rosemary essential oil resulted in some maintenance of phenolic and ascorbic acid content and antioxidant capacity. Cv. Marabel showed a higher phenolic content and the least decrease in ascorbic acid content during storage.

Hu et al. (2021) [217] investigated the influence of cutting style (pieces, strips, and slices) on the quality and other properties of FCP. Vitamin C content was gradually reduced, while glutathione content and phenolic content (40.48, 74.88 and 108.86% in pieces, strips, and slices, respectively) increased compared to the control (whole potatoes). The increase in phenolics was related to the increase in PAL activity, which was also induced by cutting. Furthermore, total antioxidant capacity increased from 1.37 to 1.46 times, due to increase in the activity of SOD, CAT, ascorbate peroxidase and glutathione reductase. However, browning and an increase in MDA content (slice > strip > piece) also occurred as a result of cutting, that is, an increase in lipoxygenase, PPO and POD activity. It appears that cutting into pieces contributes to less FCP browning than cutting into strips and slices.

11.2. Aroma Compounds

In addition, aroma compounds are very important chemical components of potatoes, which can be severely affected by FCP production and storage. Cutting damages the potato cells and, as mentioned earlier, causes many biochemical reactions and microorganisms' growth for which a medium such as FCP is particularly suitable. Through their metabolism, they change the composition of the potato, including qualitative and quantitative changes in aroma substances (volatiles), which can greatly affect the sensory properties of FCP.

In addition to sugars and phenolics, Xu et al. (2022) [99] showed that the original odor and volatile components were effectively preserved with ascorbic acid and VP during storage. The authors identified 27 volatile compounds, including 22 lipid degradation products, three sugar degradation/Maillard reaction products, and two terpenoid compounds. Decanal*, hexanal*, (E,E)-2,4-decadienal, (E,E)-2,4-nonadienal, and 1-octen-3-one (lipid degradation products) that were the predominant volatiles(*) in the raw FCP and remained during storage. However, the development of aldehydes in FCP was inhibited, due to degradation of fatty acids, which could be responsible for the off-flavor produced during storage.

Li et al. (2022) [125] conducted a very comprehensive study on the potential relationship between the bacterial community and quality attributes, visual quality, and organic acids, as well as flavor and volatile compounds of vacuum-packaged peeled potatoes during 12 days of storage at 10 °C. They also performed a correlation analysis between the bacterial community and volatiles. A total of 37 volatiles, including alcohols >aldehydes> hydrocarbons as predominant categories, as well as ketones, furans, and esters, were detected using GC-MS. Their total content increased from 2164.85 to 10,658.68 g/kg during 12 days of storage, with the greatest contribution of alcohols, aldehydes, and hydrocarbons. Like in the study by Cheng et al. (2022) [88], esters (17.92 µg/kg) were only detected in potatoes on day 0. According to the volatiles identified, it was possible to distinguish samples per day of storage, where the difference between days 0 and 12 was the largest. The results obtained by electric nose showed that for the first 4 days the potatoes maintained a fresh-like flavor. However, during further storage, the increasing presence of nitrogen oxides, furans, hydrocarbons, sulfides, pyrazine, alcohols, aldehydes, ketones, and organic sulfides was detected by the sensitiveness of certain sensors of the electric nose for related compounds, especially after 8 days. Such results indicated that the flavor deterioration occurred significantly after 8 days of storage

and that it could be distinguished by the e-nose. *Enterobacteriaceae*, *Erwinia*, *Lacrimispora*, *Lactococcus*, *Serratia*, *Pantoea*, *Clostridium*, *Flavobacterium*, and *Clostridia* were positively correlated with the biosynthesis of volatiles. The authors found 10 spoilage markers, and the first was ethanol, which could be produced by fermentation of carbohydrates by *Clostridium* strains [218]. Furthermore, the following compounds *p*-mentha-1,8-dien-7-ol, (E)-2-hexenal, heptanal, (Z)-2-octen-1-ol, (Z)-3,7-dimethyl-3,6-octadien-1-ol, 3-ethyl-4-methylpentan-1-ol, (E)-2-heptenal, 4-ethylcyclohexanol and methyl salicylate were also selected as spoilage markers. In addition, ethanol, hexanal, 1-octen-3-ol, 3-methyl-1-butanol, and 2-methyl-1-butanol can produce an unpleasant flavor, while ethanol and the last two are off-odor components. Ethanol, which was the most abundant spoilage marker, was significantly related to *Enterobacteriaceae*, *Erwinia*, *Lacrimispora,* and *Lactococcus*, while 3-methyl-1-butanol, and 2-methyl-1-butanol were positively correlated with *Lacrimispora*, *Lactococcus*, *Clostridia*, *Clostridium*, and *Flavobacterium*, but they could be derived by the proteolytic activity of *Lactococcus* and leucine catabolism. *Leuconostoc* and *Lactococcus* are responsible for the accumulation of lactic and acetic acids, consequently also influencing on flavor. In addition to microbial spoilage, physical damage is also responsible for the synthesis of volatiles as a result of contact between enzymes and non-volatile precursors (e.g., carbohydrate and amino acids) in cells. For example, numerous aldehydes and alcohols such as heptanal, 1-penten-3-one, 1-pentanol, 2,4-heptadienal, and 2-pentylfuran can be formed from an intrinsic lipid upon contact with enzymes in cut potatoes [219].

Furthermore, Cheng et al. (2022) [88] found that the combination of cactus polysaccharide solution and US treatment showed the best results in volatile profiles after 8 days of storage at 4 °C. The volatiles determined by the HS-GC-IMS taste analyzer were: alcohols (7): (E)-3-hexen-1-ol, 2-hexanol, 5-methyl-2-furanmethanol, 3-methyl-1-butanol, (Z)-3-nonen-1-ol, linalool, n-hexanol; aldehydes (13): (E)-2-octenal, (E)-hept-2-enal, heptanal, (E)-2-hexenal, (E)-2-pentenal, pentanal, 3-methylbutanal, octanal, furfural, butanal, propanal, E,E-2,4-nonadienal, 3-methylthiopropanal; ketones (7): 1-octen-3-one, cyclohexanone, 3-pentanone, acetone, 2-butanone, 6-methylhept-5-en-2-one, heptan-2-one; esters (7): 1-methoxy-2-propyl acetate, ethyl butyrate, methyl 3-methylbutanoate, acetic acid (these 4 esters were detected only in samples on day 0) ethyl ester, acetic acid, 4-hydroxynonanoic acid, lactone, ethyl cinnamate; hydrocarbons (2): ocimene, phellandrene; furans (2): 2-pentyl furan, 2,5-dimethylfuran; others (4): 2-ethyl-5-methylpyrazine, propylsulfide, propanoic acid, 2-propanol. In the study of Li et al. (2022) [125] esters were detected only on storage day 0. Although hydrocarbons and esters do not have an important impact on overall flavor, they can enhance or reduce the overall aroma of potatoes [220]. Different treatments showed different inhibitory effects on the contents of (E)-2-octenal, (E)-heptyl-2-enal, heptanal, (E)-2-hexenal, pentaldehyde, furfural, and propionaldehyde with the most inhibitory effect of combined treatment during storage. Furthermore, the content of 1-octen-3-one (with potentially negative flavor effects) progressively increased during storage, whereas the smallest increase occurred in combined treatment, which was also noticeable for aldehydes. The authors speculated that a lower increase in aldehydes contributes to preserving the potato flavor of FCP [125].

Luo et al. (2019) [106] found that vacuum impregnation combined with rosemary essential oil resulted in a decreased content of eucalyptol and camphor with storage time at all concentrations tested (4, 8 and 12%). After 14 days of storage, camphor, 1,3,8-*p*-menthatriene and linalool were no longer detected in any of the samples, while the amount of α-pinene increased in the first 7 days and then decreased but was still detectable; eucalyptol, camphor and 3-methyl-apopinene behaved similarly. On the last day of storage, the presence of ethanol was detected, probably due to the metabolism of endogenous cells and/or microorganisms.

12. Effect of Cooking Unprocessed Potatoes and FCP during Storage on Chemical Constituents and Sensory Properties

The purpose of this section, along with a brief overview of the influence of cooking on the chemical composition and sensorial properties of potatoes, is primarily to provide an overview of papers dealing with the influence of storage of FCP on its properties after cooking. More than 50% of marketed potatoes are industrially processed (frozen or minimally processed) and then fried, steamed, and/or microwaved, etc. for consumption. Processing and storage before cooking and cooking itself affect functional quality by reducing or increasing certain components of the potato [33,221]. In fact, the potato is a predominantly starchy food and is therefore considered a food with a high glycemic index. However, during cooking, starch changes its structure and becomes partially digestible or resistant, which can affect the glycemic index. Resistant starch consists mainly of amylose and is resistant to α-amylase and indigestible in the small intestine, but is fermented in the large intestine, similar to dietary fiber, and thus contributes to lowering the glycemic index. Its presence depends on many factors, including the cooking method. The preferred cooking method should be selected based on differences in starch content and overall composition of potato cultivars [222]. In addition, optimization of cooking conditions is required to achieve the desired textural and rheological properties, and chemical composition of cooked potatoes. Recently, Jayanti et al. (2019) [223] gave an overview on the influence of cooking methods on valuable nutritive and anti-nutritive components of potatoes, and along with phenolics they included vitamins, minerals, pigments and antioxidant properties, as well as glykoalkaloids and acrylamide. Although there are many scientific papers available on the influence of cooking on potato quality, there are not many published papers dealing with the influence of minimal processing and storage duration of FCP on the properties of cooked potato.

12.1. Phenolics

Potatoes, as an important source of bioactive compounds (BAC), are highly desirable in the diet, but their chemical composition changes during cooking, which depends on the cultivar, cooking style and conditions [224]. Conflicting results on the effects of cooking on total phenolics and chlorogenic acid content are found in the literature [225,226]. The variability of the effects of cooking on the content of BAC can be related to genotype and growing location, but also to the specificity of the targeted BAC and its binding in the matrix with fats, proteins, carbohydrates, or starch. Furthermore, it may be related to the physical processing before cooking, and to the style and conditions of cooking (varying the method of heat transfer, the time, or amount of water added, etc.) [225,227]. Some studies reported a decrease, no difference, or an increase in the content of chlorogenic acid and phenolics in cooked potatoes [228]. According to Xu et al. (2009) [229], the content of total phenolics and chlorogenic acid in all potato cultivars studied decreased after boiling, baking, and microwave cooking (from 30 to 42% compared with the raw tuber), and the effects of different cooking methods on the phenolic content of the potato were cultivar dependent. Blessington et al. (2010) [228] reported that baking, frying, and microwave cooking of potatoes significantly increased the content of total phenolics and chlorogenic acid because hydrophilic phenolics were poorly extracted from the potato matrix in the oil used for frying. Previous studies have shown that the stability of chlorogenic acid (the main phenolic compound in potatoes) in baked potatoes is strongly dependent on the baking conditions (temperature and time) [230], while chlorogenic acid in boiled potatoes decreases significantly due to its water solubility [33,230]. The decrease in chlorogenic acid during processing could be due to isomerization to neochlorogenic acid, although the cryptochlorogenic acid content remained stable during processing [231]. Catechin, quercetin and kaempferol glycosides are the most abundant flavonoids in raw potatoes, but different cooking methods considerably reduced the total flavonoids content and baking and microwave cooking resulted in a loss of approximately 50% [230]. Some studies support the assumption that potatoes contain relatively stable phenolics, which can be well

recovered by cooking processes. In short, cultivar, tuber maturity, cooking temperature and time, and the presence of water or moisture during cooking all have a strong influence on the loss of phenolics in potatoes [227]. Literature data indicate that a shorter cooking time and lower temperature during cooking can significantly increase or do not change the content of total phenolics [232]. Thakur et al. (2022) [233] compared the effect of potato boiling and microwave cooking on phenolics content and found that it decreased less with microwaving (10%) than with boiling (26%), whereas the concentration of some individual phenolics showed different changes. Therefore, boiling showed a decrease in chlorogenic acid (29%), caffeic acid (20%) and rutin (6%), while microwaving showed an increase in chlorogenic acid (3-fold), caffeic acid (3.4-fold), and rutin (1.7-fold).

Dite Hunjek et al. (2021) [33] studied the content of phenolics and sugars as a function of FCP storage time (1, 5, and 8 days at 10 °C) and subsequent boiling and frying. Total phenolics, as well as chlorogenic acid, the most abundant identified phenolic compound, were lost during cooking and losses were higher during boiling than during frying. Moreover, losses were lowest on day 0 and increased with increasing storage time. Compared to raw potatoes, boiled potatoes retained 75% of total phenolics on day 0 and fried potatoes retained 95%, while retention was 53 and 75% on days 5 and 45 and 67% on day 8. Regarding the content of total sugars, the retention of total sugars was 85% for boiled potatoes on day 0 and 72% for fried potatoes, while on day 5 it was 54 and 90%, respectively, and on day 8 it was 68 and 94%, respectively.

12.2. Carotenoids

The stability of carotenoids in foods varies greatly due to the physical form of the carotenoid [234]. The concentrations of lutein and zeaxanthin in the boiled tubers were not affected or were higher than in the raw tubers [235]. According to Blessington et al. (2010) [228] the lutein content in different potato cultivars was not affected by cooking, but the carotenoids content was lower in boiled potatoes than in baked potatoes, microwaved potatoes, and fried potatoes. The carotene content in steamed potatoes decreased by 33.34% and increased by 5.55% in sautéed potatoes [236]. In the study by Fang et al. (2022) [237], the lowest loss of total carotenoids was observed in potatoes after steaming, while frying and air frying caused the highest loss. As fat-soluble compounds, carotenoids are less susceptible to water loss during cooking, but are relatively unstable when treated with oil and heat during cooking [234]. The possible increase in carotenoids content in cooked sweet potatoes is due to the fact that β-carotene can be better extracted due to changes in the structure of the cell wall caused by cooking, and that carotenoids bound to certain proteins dissociate in water, increasing their content [238]. Thermal treatments also result in the isomerization of carotenoids [42]. Burmeister et al. (2011) [239] reported that heat treatment of potato cultivars with lutein and violaxanthin as major carotenoids and zeaxanthin at low concentrations converted all-*trans* carotenoids to isomeric 9-*cis* and 13-*cis* forms or degraded them.

The variability in carotenoids retention in sweet potatoes after cooking may be due to differential enzymatic oxidation during processing, but also due to influence of genotype, maturity, slice thickness of pieces, and cooking time [240].

12.3. Antioxidant Properties

In general, phenolics and carotenoids are the phytochemicals most associated with total antioxidant capacity. Although the potato is not very rich in these compounds and loses them during cooking, it still plays an important role as an antioxidant in the human diet due to its relatively high daily intake [226]. The changes in phytochemicals during cooking are usually accompanied by changes in antioxidant capacity. For example, Perla et al. (2013) [230] reported a decrease in free radical scavenging activity of 42.22, 50.4, and 63.77% in cooking, microwaving, and baking treatments, respectively, while Blessington et al. (2010) [228] reported a decrease of 42.72, 68.18, 63.86, and 9.31% in antioxidant capacity after baking, microwaving, boiling, and frying, respectively. As with phenolics,

antioxidant capacity can be reduced by cooking due to loss of water-soluble antioxidants. On the contrary, the increase may be a consequence of better extractability [223], but many chemical reactions occur during cooking, such as the Maillard reaction, which can lead to the formation of new antioxidants [226]. In addition to phenolics and carotenoids, the potato also contains vitamin C, a known antioxidant that is also degraded during cooking due to its heat sensitivity and water solubility. The cultivar, the location, the degree of ripeness, the harvest time, the storage conditions, the storage duration and the cooking method influence the stability of vitamin C [223].

12.4. Potato Antinutrients

12.4.1. Glycoalkaloids

Steroidal glycoalkaloids are another important class of BAC in potatoes, and the most important potato glycoalkaloids in terms of their contribution to the total glycoalkaloids content and their bioactivity are α-chaconine and α-solanine. Due to their toxicity, according to EC Recommendations 1 mg of total potato glycoalkaloids/kg body weight per day as the lowest observed adverse effect level (LOAEL) is the reference point for the risk characterization after acute exposure. The total glycoalkaloids content in commercial potato cultivars varies between 1.37 and 33.35 mg/100 g of fresh weight [241]. Glycoalkaloids are quite stable and cooking methods have limited effects on their content, so their concentrations in processed potatoes are mainly proportional to the concentrations in the raw materials used [242]. There are some reports that the steroidal glycoalkaloids content in cooked potatoes may decrease or remain the same when compared to uncooked samples. According to Mulinacci et al. (2008) [243] boiling the unpeeled potato had a very slight effect on the decrease in glycolkaloids. In the study by Lachman et al. (2013) [244], boiling peeled tubers was considered as the most favorable cooking method because the total glycoalkaloids content was reduced. Steam cooking did not have a significant effect on glycoalkaloids content [231], but frying significantly reduced glycoalkaloids content in fried peeled potatoes, for example, 82–86% [245] and even more (90%) [48]. According to the study by Nie et al. (2018) [246], peeling is crucial to reduce the glycoalkaloids content in potato products. Furthermore, immersion of the cut potato in, for example, acetic acid solution, was shown to be a useful strategy to reduce glycoalkaloids in French fries [247]. Furthermore, Tsikrika et al. (2021) [9] reported a significant decrease in glycoalkaloids with HPP treatment of cv. Maris Piper and Rooster.

12.4.2. Acrylamide

As mentioned above, the free amino acid asparagine and the reducing sugars are precursors of Maillard reactions that occur at low tissue water content at frying temperatures (above 120 °C) and lead to the formation of acrylamide, for example, in fried potatoes [248]. Acrylamide is a neurotoxic compound that is metabolized to glycidamide, among other compounds, which is considered genotoxic and carcinogenic [249]. Therefore, acrylamide is classified as a probable human carcinogen in Group 2A by the International Agency for Research on Cancer (IARC) [250], which is why a limit for acrylamide in potato products has been established in the EU Commission Regulation (2017/2158) [203] (750 µg/kg fresh weight) and the conditions before and after harvest (temperature and the atmosphere), and cooking conditions affect the final acrylamide content. Many published articles addressed the study and development of strategies to reduce acrylamide in potato products [251]. Haddarah et al. (2021) [252] found that dipping potato strips in borage, fennel and ginger extracts immediately before frying can reduce acrylamide content by 59.67, 67.99, and 73.36%, respectively, during deep frying and by 21.91, 66.29, and 29.15%, respectively, during air frying. Liu et al. (2020) [247] also found that immersion in an acetic acid solution for 8 h reduced the acrylamide content in French fries. On the contrary, there are not many articles investigating the effect of FCP storage time. In the study by Dite Hunjek et al. (2021) [33], it was shown that the acrylamide content in the fried samples was significantly affected by the cultivar (Birgit > Lady Claire) and increased with storage time of FCP. The

age of tubers also caused an increasing trend, but without statistical significance. Furthermore, the content of simple sugars and the acrylamide content in the fried samples increased with UV-C treatment of FCP, as reported by Pelaić et al. (2021) [191]. However, in both studies, the acrylamide content in all samples was below the maximum level approved by the EFSA (750 µg/kg fresh weight).

12.4.3. Polycyclic Aromatic Hydrocarbons (PAH)

Polycyclic aromatic hydrocarbons (PAH) are a large group of ubiquitous lipophilic toxic pollutants formed by incomplete pyrolysis of organic material. They consist of two or more fused aromatic rings and can be classified as "light" with two to three rings or as more stable and toxic, "heavy" PAH with four or more rings [253]. PAH can contaminate food through a variety of pathways, such as growing fruits and vegetables on contaminated soil. PAH can also enter food through preparation methods such as smoking, grilling, baking, and frying [254]. Due to their carcinogenic, mutagenic, and teratogenic properties, the levels of PAH in food must be monitored. In 2008, the EFSA established a PAH priority list, which included the well-known EU 15 + 1 PAH. Additionally, the EU has established strict limits for benzo[a]pyrene (BaP) and PAH4 (BaP, benzo[a]anthracene (BaA), benzo[b]fluoranthene (BbF), and chrysene (Chr)) in various types of food [255]. PAH4 and benzo[k]fluoranthene, dibenzo[a,h]anthracene, benzo[ghi]perylene, and indeno[1,2,3-cd]pyrene, known as PAH8, are currently recognized by most food safety researchers as reliable indicators of PAH contamination in food. As environmental and processing conditions can affect food contamination, the PAH content of fried potatoes can derive from the frying oil or the potatoes themselves as well as from the frying process. Differences in PAH concentrations found in fresh potatoes by different authors suggest that they depend on growing conditions, region, or variety [256–259]. Although Fismes et al. (2002) [260] determined higher levels of PAH in whole tubers than in peeled potatoes, which they explained by the higher lipid content in potato peels, Kulhánek et al. (2005) [261] believe that root vegetables are still a significant source of plant-derived PAH in the human diet, regardless of peeling. In a detailed study on PAH in fried FCP, Balbino et al. (2020) [262] found that they were below EU regulatory limits in all samples, indicating no immediate health risk. Although the content of most PAH species was influenced by the potato cultivar, anti-browning treatment did not affect the PAH levels. On the other hand, VP decreased the levels of naphthalene, fluorene, and pyrene. Since PAH levels did not change during the 8 day storage period considering this parameter, FCP can be safely used throughout the tested period. Similarly, Shariatifar et al. (2022) [263], in a comprehensive study addressing the influence of the cooking method of potatoes on the level of PAH, found that the level of PAH in all samples was below the established limits (the provisional maximum tolerable daily value is 10 ng/kg body weight per day).

12.5. Flavor and Sensory Properties

The flavor is an indispensable parameter for evaluating the quality of FCP and can be determined by instrumental or sensory methods. Flavor compounds develop in potato tubers when they are cut and heated [219]. Sugars, amino acids, RNA, and lipids are flavor precursors in potatoes. Cultivars, production conditions, and storage conditions, including temperature and duration, affect the content and type of these compounds, such as fatty acids and sugars, which increase and change composition during storage, as well as the enzymes responsible for the flavor compounds [219,264]. The flavor is mainly determined by taste (non-volatile compounds), aroma (volatile compounds), and texture (mouthfeel) [219]. Although color is not flavor component, it can affect taste perception, as does texture [219]. During cooking, aroma compounds that contribute to flavor as aldehydes, ketones, furan, methional, pyrazines, and other compounds are forming from flavor precursors mainly lipids, sugars, and amino acids. The components derived from lipids and sugars are the most abundant. By degradation of lipids, aldehydes and ketones are produced, which contribute to the fatty, fruity, and floral flavor notes [265].

Through Maillard reactions (among sugars and amino acids) the main flavor components are produced [264–266], including methional (by Strecker degradation of methionine) which is a characteristic compound of cooked potato flavor, and pyrazines which are characteristic compounds of baked potato flavor [266]. In addition to methional, boiled potatoes contain 2- and 3-methylbutanal (also a product of the Strecker degradation of isoleucine and leucine) characterized by fruity or 'malty' notes [265]. Furthermore, during cooking, RNA is hydrolyzed by enzymes liberating 5′ ribonucleotides which interact with amino acids, especially glutamate and aspartate giving products considered to be mainly responsible for umami taste. As an enhancement of flavor in cooked potatoes and carrier of umami taste, guanosine 5′-monophosphate is the most important ribonucleotide [267].

Unlike most flavor compounds, methoxypyrazines (for example, 2-isopropyl-3-methoxypyrazine), as the products of free amino acids, are present in raw tubers and are responsible for the slightly earthy flavor and its presence is dependent on the cultivar [266]. Peeling and cutting tubers can increase amount of methoxypyrazines, but also, they may be produced by soil bacteria (*Pseudomonas taetrolens*) and then absorbed by the tuber [268]. The odor threshold of these compounds is extremely low and these compounds have characteristic vegetable-like odors, including potato-like odors [219].

Furthermore, phenolics were positively correlated with the potato tuber bitterness, but not significantly, while glycoalkaloids had an effect on bitterness at levels greater than 14 mg/100 g, while levels lower than 7.3 mg/100 g had no effect [269]. Sinden et al. (1976) [269] noted that tubers containing 120 mg/100 g of chlorogenic acid may taste slightly sour. In addition, Vainionpää et al. (2000) [270] reported that organic acids such as citric, malic and chlorogenic had no pronounced effects on sweetness and flavor.

Oruna-Concha et al. (2001) [266] identified the following compounds as key potato aroma compounds on the skin and/or flesh of baked potatoes: dimethyl disulfide (onion-like, cooked cabbage), methional, 1-octen-3-ol (mushroom-like), (E)-2-nonenal, (E,E)-2,4-decadienal (oily, deep fried-like), phenylacetaldehyde (floral), 2-ethyl-3,5-dimethylpyrazine, 2-ethyl-3,6-dimethylpyrazine, and 2-isopropyl-3-methoxypyrazine (earthy, potato-like).

Duckhman et al. (2001) [264] identified volatiles in raw, boiled, baked, and French-fried potatoes of 11 cultivars and classified them into 5 categories in decreasing order: lipid derived (41; mostly not in raw), sugar degradation and/or Maillard reaction (not involving sulfur amino acids) derived (20; mostly not in raw, alkylpyrazines linked to the flavor of baked potatoes), sulfur amino acids (4; not present in raw), methoxypyrazines (2-isobutyl-3-methoxypyrazine present, 2-isopropyl-3-methoxypyrazine in raw and cooked) and terpenes (i. e., α-pinene, β-myrcene, D-limonene, 3-carene, Z-ocimene, E-ocimene, linalool, isophorone, β-cyclocitral, β-damascenone, α-copaene, geranyl acetone, α-aromadendrene and δ-guaiene, mostly in cooked). The first two categories made up mainly more than 90% of all identified volatiles. Additionally, 2- and 3-methylbutanal, volatile components of boiled and baked potatoes, contributed 75 ± 96% of the volatiles in this category. The author noted that of the compounds they monitored, the greatest flavor impact had 2-isopropyl-3-methyoxypyrazine, 2-isobutyl-3-methoxypyrazine, dimethyl trisulfide, decanal, and 3-methylbutanal, as well as methylpropanal, 2-methylbutanal, methional, and nonanal.

12.6. Influence of Storage Time of FCP

The influence of FCP storage time on flavor and sensory attributes of subsequently cooked potatoes has not been widely explored.

Thybo et al. (2006) [50] analyzed sensory impact and identified aroma compounds in pre-peeled, stored 5 days and boiled potatoes of six cultivars during 6 months of tuber storage. The results showed that pentanal, hexanal, heptanal, (E)-2-hexenal, 2-pentyl-furan, 1-pentanol, octanal, (E)-2-heptenal, 1-hexanol, E-2-octenal, 1-octen-3-ol, 2,4-heptadienal, (E,E)-2,4-heptadienal, E-2-nonenal, decanal, 2,4-nonadienal, dimethyl sulfoxide, (E,E)-2,4-octadienal, (E,E)-2,4-decadienal, butyl butyrate and phenol did not contribute to differentiation in aroma profiles of the investigated samples and most of them had no significant influence on the sensory attribute 'potato flavor'. The methional, linalool, *p*-cymene,

nonanal and decanal characterized aroma differences between potato cultivars and tuber storage time. The first three were found to be high intensity, while the last two were found to be low intensity in potatoes at the beginning of 6 months of storage. Methional is formed during the boiling of potatoes and has a boiled potato flavor and odor, while linalool has a floral odor. Nonanal and decanal characterized a high intensity of rancidness flavor, further decanal contributed with a "fatty" odor, and nonanal with a "rancid" odor. Also, the content of non-volatiles components such as dry matter, chlorogenic, caffeic and glutamic acid, glutamine, tyrosine, nitrate, and total nitrogen (total N) had a significant effect on the potato flavor or on off-flavor. As already mentioned, amino acids, sugars, and nucleotides are precursors for the formation of volatiles by heating. A high content of total N, nitrate, glutamine, glutamic acid, 2-ethyl-furan, (E)-2-hexenal, 2,4-heptadienal, (E,E)-2,4-heptadienal, dimethyl sulfoxide and (E,Z)-2,4-decadienal was negatively correlated with potato flavor and positively with rancidness. Furthermore, off-flavor was not correlated with potato flavor and rancidness, however it was mostly affected by non-volatile compounds (e.g., chlorogenic acid, total N, nitrate, glutamine, and glutamic acid) and less aroma compounds. The off-flavor/off-taste defined as the bitter and scratchy taste could be related to non-volatile phenolics or glycoalkaloids.

Recently, Xu et al. (2022) [99] investigated the influence of ascorbic acid treatment and VP of FCP, stored at 4 °C for 5 days and subsequently boiled, on odor, taste and volatiles using an electronic nose, an electronic tongue, and SPME/GC-MS. Treated FCP, unlike control samples, were found to have lower bitterness, higher umami taste and acidity below the perception threshold, indicating that this treatment preserved the good taste and quality of FCP during storage. In raw FCP a total of 27 volatile compounds were identified (22 lipid degradation products, three sugar degradation/Maillard reaction products and two terpenoid compounds), where 13 of them presented the primary source of the raw FCP aroma. In treated FCP, less changes occurred during storage compared to sample before storage. The lipid degradation products (decanal, hexanal, (E,E)-2,4-decadienal, (E,E)-2,4-nonadienal, and 1-octen-3-one) were the predominant volatile compounds in the raw FCP. The presence of decanal, hexanal, (E,E)-2,4-decadienal, (E,E)-2,4-nonadienal, and 1-octen-3-one increased during storage. In boiled FCP a total of 32 volatile compounds (25 lipid degradation products, five sugar degradation/Maillard reaction products, and two terpenoid compounds) were identified. The decanal and (E)-2-nonanal more influenced odor in boiled FCP then in raw FCP while (E,E)-2,4-decadienal acted inversely. Decanal, hexanal, (E,E)-2,4-nonadienal, (E)-2-nonanal and 1-octen-3-one gradually increased in boiled FCP during storage, but lower in treated samples. The contents of 3-methylbutanal (fruity) and phenylacetaldehyde (green, flower, sweet odor) were higher in the boiled FCP. Methional showed increasing odor activity values during storage independently of treatment. Generally, treatment with ascorbic acid and VP preserved FCP by reducing the potential for rancid off-flavor occurrence.

Dite Hunjek et al. (2019) [100] compared the sensory properties of raw and subsequently boiled FCP, pretreated with sodium chloride and sodium ascorbate and vacuum-packaged or packaged in a modified atmosphere during 10 days of storage at 3 and 10 °C. They found that there were no significant changes in the characteristic odor and off-odor of raw and boiled FCP as well as the characteristic taste and off-taste in the boiled samples during the first 4 days, including the results obtained at both temperatures. After the fourth day, some changes occurred, but the samples were acceptable until the eighth day, with slightly better results obtained by sodium ascorbate and VP. In general, boiled samples had higher characteristic odor scores and lower off-odor scores than raw FCP samples. In another study, Dite Hunjek et al. (2020) [54] investigated the effect of storing tubers for 9 months on the durability of FCP. After 1, 5 and 9 months of storage, the tubers were used for the production of FCP and the shelf life and sensory properties of raw and subsequently cooked (boiled, fried and baked) FCP samples were monitored for 8 days. The characteristic odor and off-odor of raw, boiled, fried and baked FCP were not affected by tuber age, while the storage of FCP decreased the characteristic odor and increased off-odor after

the fourth day. The characteristic taste of fried and baked FCP was not affected by tuber age, while FCP storage decreased the characteristic taste after the fourth day, but without occurrences of off-taste. However, in cooked FCP prepared from tubers stored for 9 months, off-flavor was slightly present, although the storage of FCP did not increase it further. The characteristic taste of boiled FCP was slightly lower when prepared from tubers stored for 9 months and after 4 days of storage, while off-taste showed an opposite trend.

Luo et al. (2019) [106] studied vacuum impregnation and rosemary essential oil for the enrichment and innovation of FCP. They investigated the presence of rosemary essential oil during FCP storage and also in subsequently fried samples by sensory tests and GC analysis. The flavor and odor, as well as volatiles of rosemary essential oil, were detected in all samples depending on the oil concentration during storage and after frying by both tests. In the samples to which rosemary oil was not added, only two components (2-methyl-propanal and pyrazine), which were also present in all other samples, were present. In all samples, their concentration was similar during storage and without significant changes. In samples impregnated with 4, 8 and 12% of rosemary essential oil, proportional concentration of camphor and eucalyptol were detected. During 14 days of storage, they decreased in all samples but were still present.

13. Conclusions

From the scientific literature presented in this review, it is clear that FCP are still in the focus of the scientific community, dealing with several directions of scientific research. One of the directions includes metabolic studies on the response of potato tissue to abiotic stress caused by various agents and/or treatments. It has already been concluded that physiological and metabolic research is necessary to optimize the process and maintain quality and safety. The activity of oxidative and antioxidant enzymes, phenolic content, and also gene expression were studied, all of which play a specific role in the response of tissue response to stress. Therefore, the selection of an appropriate cultivar has a significant impact on the quality and safety of FCP. In view of this, future trends in the selection of cultivars with the required traits and the data obtained on current cultivars will be useful for these processes. The study of the effects of various ABA and antimicrobials on the quality, chemical constituents, and stability of FCP is another direction in which phenolics have been analyzed and compared to other constituents, such as volatile compounds. Although the FCP is already on the market, there is still room for improvement. Sodium metabisulfite is commonly used as a browning inhibitor and antimicrobial agent, although it may have negative health effects. Despite the general increase in the demand for FCP, health conscious consumers are opting for products without chemical preservatives (e.g., sodium metabisulfite) and preferring those with natural compounds. Scientific results show that many other more desirable compounds can be considered as possible substitutes for sodium metabisulfite. Aromatic plant extracts (the third direction) have the potential to prevent browning and act as antimicrobials, and are of particular interest due to their health benefits and flavor, so their use can open up and develop new areas of FCP. Their use therefore represents a future trend for the development of new innovative naturally preserved and flavored products on the FCP market. Their selection should be based not only on sensory properties and efficacy, but also on accessibility and cost. The fourth direction includes studies on the possible use of emerging non-thermal technologies in the production of FCP. Based on the promising results obtained so far, it can be assumed that their use in the industrial production of FCP will be one of the future trends. All of this requires the introduction of appropriate legislation.

An area that has not been sufficiently studied is the impact of the production and shelf life of FCP on the potato components of the subsequently cooked FCP.

In general, it can be stated that all studies of the optimal cultivar, the simplest, most effective and natural anti-browning and antimicrobial treatment, packaging and non-thermal technologies have been carried out with the main objective of ensuring a longer shelf life

of FCP and more health-promoting innovative products whose production minimizes the negative impact on the environment.

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