Effect of UV-C irradiation and high hydrostatic pressure on shelf-life and quality of minimally processed potatoes (Solanum tuberosum L.)

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DOCTORAL THESIS

Supervisor:
Branka Levaj, Ph.D., Full Professor

Zagreb, 2023

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Prehrambeno-biotehnološki fakultet

Zdenka Pelaić

UTJECAJ UV-C ZRAČENJA I VISOKOGA HIDROSTATSKOGA TLAKA NA TRAJNOST I KVALITETU MINIMALNO PROCESIRANOGA KRUMPIRA (*Solanum tuberosum* L.)

DOKTORSKI RAD

Mentor:
prof. dr. sc. Branka Levaj

Zagreb, 2023.

Zdenka Pelaić

Effect of UV-C irradiation and high hydrostatic pressure on shelf-life and quality of minimally processed potatoes (*Solanum tuberosum* L.)

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Branka Levaj, Ph.D., Full Professor (University of Zagreb, Faculty of Food Technology and Biotechnology, Laboratory for Chemistry and Technology of Fruits and Vegetables)

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This is an article based doctoral thesis, known as Scandinavian model, which consists of already published scientific papers accompanied by a chapter with the critical review, which was written in accordance with Article 14 of the Doctoral Studies Regulations at the University of Zagreb (2016).

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Effect of UV-C irradiation and high hydrostatic pressure on shelf-life and quality of minimally processed potatoes (*Solanum tuberosum* L.)

Zdenka Pelaić, 381/PT

Short abstract: Treatment of fresh-cut potatoes (FCP) with UV-C radiation (2.70 kJ m^{-2}) and treatment with high hydrostatic pressure (400 MPa/3 min) reduced the total number of aerobic mesophilic bacteria and slowed their growth during storage of FCP, thus maintaining product quality and extending shelf life until the 15th day of storage. The effectiveness of the treatment depended on the treatment conditions applied. UV-C irradiation (2.70 kJ m^{-2}) and HHP treatment (400 MPa/3 min) mostly had minor effect on the physical properties, maintained sensory properties of raw FCP and subsequently thermally treated FCP. Compared to the control samples, the treated raw FCP had a lower content of chlorogenic acid and an increased content of reducing sugars. The treated and subsequently fried FCP had increased acrylamide content, but these changes did not affect the safety of the product, as the levels were under the limits according to the official regulation. Overall, the application of these treatments to FCP pretreated with a sodium ascorbate solution (2%) and vacuum packed has the potential to maintain the quality and safety of raw FCP during a 15-day storage at 6 °C.

Keywords: fresh-cut, UV-C, HHP, browning, aerobic bacteria, chlorogenic acid, reducing sugars, acrylamide, PAH, sensory properties

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Utjecaj UV-C zračenja i visokoga hidrostatskoga tlaka na trajnost i kakvoću minimalno procesiranoga krumpira (*Solanum tuberosum* L.)

Zdenka Pelaić, 381/PT

Sažetak: Tretiranje svježe rezanog (minimalno procesiranoga) krumpira (MPK) UV-C zračenjem 5 minuta (2,70 kJ m^{-2}) i tretiranje visokim hidrostatskim tlakom (400 MPa/3 min) smanjilo je ukupan broj aerobnih mezofilnih bakterija i usporilo njihov rast tijekom skladištenja MPK-a., čime se održava kvaliteta proizvoda i produljuje rok trajanja do 15-tog dana skladištenja. Učinkovitost tretmana ovisila je o primijenjenim uvjetima tretiranja. UV-C zračenje (2,70 kJ m^{-2}) i HHP tretman (400 MPa/3 min) uglavnom su imali manji učinak na fizikalna svojstva, zadržana su senzorska svojstva sirovog MPK-a i naknadno termički tretiranog MPK-a. U usporedbi s kontrolnim uzorcima, tretirani sirovi MPK je imao niži sadržaj klorogenske kiseline i povećani sadržaj reducirajućih šećera. Tretirani i naknadno prženi MPK imao je povećan sadržaj akrilamida, ali te promjene nisu utjecale na sigurnost proizvoda, jer su razine bile ispod granica prema službenoj regulativi. Primjena ovih tretmana na MPK, koji je prethodno tretiran s otopinom natrijeva askorbata (2%) i vakuumski upakiran, ima potencijal za održavanje kvalitete i sigurnosti sirovog MPK-a tijekom 15-dnevnog skladištenja na 6 °C.

Ključne riječi: svježe rezani, UV-C, VHT, posmeđivanje, aerobne mezofilne bakterije, klorogenska kiselina, reducirajući šećeri, akrilamid, PAH-ovi, senzorska svojstva

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Extended abstract

The aim of this study was to examine the effects of different UV-C doses and high hydrostatic pressure (HHP) conditions on the safety and quality of minimally processed (fresh-cut) potatoes (FCP), and on the sensory properties of raw and thermally treated FCP, while observing the changes during storage. The goal was to compare the effects of optimal UV-C and HHP treatment, as well as their combination, on the properties of FCP. In the first of the research, FCP was treated with a 2% sodium ascorbate solution (SA) and vacuum packaged (VP), treated with UV-C (0, 3, 5 and 10 min), and stored (23 days/6 °C). These samples were also used for the second part of the study. In the third part, FCP was treated with HHP (400 MPa/0, 3, 5 and 10 min) in vessels containing SA solution, VP and stored. In the fourth part, the samples were prepared as in the first part and treated: 5-UV-C, HHP (400 MPa/3 min) and combined: 5-UV-C/HHP (400 MPa/3 min). The 5- and 10-UV-C treatments effectively slowed the growth of aerobic mesophilic bacteria during storage and positively affected the color and odor of raw FCP, while the thermally treated had a more pronounced odor and taste. By the effect of UV-C the content of chlorogenic acid (CA) decreased, while 5-UV-C treatment increased the content of reducing sugars (RS) in raw FCP and acrylamide in fried FCP, which was below the suggested limit. The UV-C treated FCP maintained safety, quality and sensory properties for 15 days. Due to the similar antimicrobial effect of 5- and 10-UV-C treatments and to save energy, 5-UV-C was chosen for further investigations. A 10-min HHP treatment significantly reduced the bacteria count. The 5- and 10-min treated samples had lower sensory scores, and showed texture damage during frying. The 3-min treatment resulted in significantly slower bacterial growth during storage and lower sensory scores for the boiled and fried FCP compared to control. For further tests, a 3-min HHP was chosen but applied to the VP FCP. When comparing selected UV-C, HHP and UV-C/HHP treatment, the greatest reduction of bacteria and their slowest growth during storage was observed in UV-C/HHP treated samples. The greatest decrease in CA was observed in HHP treated samples. All treatments increased the content of RS, especially UV-C/HHP with a significant increase in acrylamide content in fried FCP. The PAH values were below the limits set by the EU. The application of 5-UV-C and HHP (400 MPa/3 min) to MPK pretreated with sodium ascorbate solution (2%) and vacuum packed has the potential to maintain the quality and safety of raw MPK during a 15-day storage at 6 °C.

Keywords: fresh-cut, UV-C, HHP, browning, aerobic bacteria, chlorogenic acid, reducing sugars, acrylamide, PAH, sensory properties

Proširenisažetak

Cilj ovog istraživanja bio je ispitati učinak različitih UV-C doza i uvjeta visokoga hidrostatskoga tlaka (VHT) na sigurnost i kvalitetu minimalno procesiranoga (svježe rezanoga) krumpira (MPK), te na senzorska svojstva sirovoga i termički obrađenoga, uz praćenje promjena tijekom skladištenja. Cilj je bio na temelju dobivenih rezultata usporediti utjecaj optimalnoga UV-C i VHT tretmana, kao i njihove kombinacije na svojstva MPK-a. U prvom dijelu istraživanja MPK je tretiran s 2 %-tnom otopinom natrijeva askorbata i vakuumski upakiran (VP), tretiran UV-C-om (0, 3, 5 i 10 min) te skladišten (23 dana/6 °C). Ti su uzorci korišteni i za drugi dio istraživanja. U trećem dijelu MPK su tretirani VHT-om (400 MPa/0, 3, 5 i 10 min) u posudama s otopinom natrijevog askorbata te VP i skladišteni. U četvrtom dijelu svi su uzorci pripremljeni kao u prvom i tretirani: 5-UV-C, VHT (400 MPa/3 min) i kombinacijom 5-UV-C/VHT (400 MPa/3 min) te skladišteni. 5- i 10-UV-C tretmani efikasno su usporili rast ukupnog broja aerobnih mezofilnih bakterija tijekom skladištenja, pozitivno utjecali na boju i miris sirovog MPK-a, dok su termički obrađeni imali izraženiji miris i okus. Djelovanjem UV-C-a smanjio se sadržaj klorogenske kiseline (KK) u sirovom MPK-u, dok se djelovanjem 5-UV-C-a povećao sadržaj reducirajućih šećera (RS) u sirovom i sadržaj akrilamida u prženom MPK-u, ali je on bio ispod predloženog limita. MPK tretiran UV-C-om zadržao je sigurnost, kvalitetu i senzorska svojstva 15 dana. Zbog sličnog antimikrobnoga učinka 5- i 10-UV-C tretmana te radi uštede energije, 5-UV-C odabran je za daljnje istraživanje. Tretman 10-min VHT značajno je smanjio broj bakterija. Uzorci tretirani VHT-om 5 i 10 min bili su senzorski slabije ocijenjeni te su pokazali oštećenja teksture tijekom prženja. Tretman 3-min VHT rezultirao je sporijim rastom bakterija tijekom skladištenja i lošijim senzorskim ocjenama kuhanog i prženog MPK-a u odnosu na kontrolne uzorke. Za daljnje ispitivanje odabran je 3-min VHT, ali primjenjen na VP MPK. Uspoređujući odabrani UV-C, VHT i kombinirani UV-C/VHT tretman, najveće smanjenje broja bakterija i njihov najsporiji rast tijekom skladištenja uočen je u uzorcima tretiranim UV-C/VHT. Utjecajem UV-C/VHT značajno se povećao sadržaja akrilamida u prženom MPK-u. Vrijednosti PAH-ova bile su ispod granica koje je postavila EU. Primjena 5-UV-C i HHP (400 MPa/3 min) tretmana na MPK, koji je prethodno tretiran s otopinom natrijeva askorbata (2%) i vakuumski upakiran, ima potencijal za održavanje kvalitete i sigurnosti sirovog MPK-a tijekom 15-dnevnog skladištenja na 6 °C.

Ključne riječi: svježe rezani, UV-C, VHT, posmeđivanje, aerobne mezofilne bakterije, klorogenska kiselina, reducirajući šećeri, akrilamid, PAH-ovi, senzorska svojstva

Od srca zahvaljujem svojoj mentorici, prof. dr. sc. Branki Levaj, koja mi je pružila priliku da budem dio njenog tima, vjerovala u mene i vodila me kroz studij. Draga Branka, hvala na nesebičnoj, velikoj stručnoj pomoći i podršci tijekom doktorskog studija i hvala na razumijevanju u najtežim trenucima mog života.

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Information about the supervisor: Ph.D. Branka Levaj, Full Professor

BRANKA LEVAJ has been Interim dean at the University of Zagreb, Faculty of Food Technology and Biotechnology since 2023, where she has been working since 1982. In 2011 she was appointed full professor and in 2016 full professor in a permanent position. Since 2003, she has been the Head of the Laboratory of Chemistry and Technology of Fruits and Vegetables. Her professional interests include the chemistry and technology of fruits and vegetables and research into changes during processing and storage. As a professor of undergraduate, graduate and postgraduate courses, she is the coordinator of 5 courses and collaborator of 7 courses. She has supervised more than 120 undergraduate and graduate theses, 2 master theses and 4 doctoral theses. She was a collaborator in 2 international scientific projects, leader or collaborator in more than 10 scientific or professional national projects, and leader in 1 bilateral project. Prof. Ph.D. Branka Levaj is actively involved in scientific research and has published more than 80 scientific papers indexed in WoS and other databases, a number of papers in the Proceedings of the international and national conferences and meetings, and several professional - popular papers. She has reviewed more than 100 manuscripts for scientific journals. She received awards for her work, including „Acknowledgment of longstanding cooperation and outstanding contribution to the promotion of higher education, science and profession" regarding the 50th anniversary of studies of Food Technology, Biotechnology and Nutrition (2006) and special recognition at the International Exhibition of Innovations, New Ideas, Products and Technologies, ARCA in Zagreb (2005). Furthermore, prof. Ph.D. Branka Levaj was Vice Dean for education, the Head of master study program Food Engineering, ECTS coordinator and President of the quality management committee as well as member of Committee for biotechnical science of Agency for Science and Higher Education and now she is interim of dean. She is a member of the Croatian Society of Food Technologists, Biotechnologists and Nutritionists and a member of the editorial board of the scientific journal Food Technology and Biotechnology. She was a member of the organizing committee of several scientific meetings.

Authors publications included in the doctoral dissertation:

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List of abbreviations

AA – ascorbic acid

ABA – anti-browning agents

DM – dry matter

DW – dry weight

EFSA – European Food Safety Agency

EU – European Union

FC – fresh-cut

FCP – fresh-cut potatoes

FW – fresh weight

HHP – high hydrostatic pressure

HPLC − high performance liquid chromatography

IFPA − International Fresh Cut Product Association

MAP − modified atmosphere packaging

MP − minimal processing

PA − polyamide

PAH – polycyclic aromatic hydrocarbons

PAL – phenylalanine lyase

PCA – Principal Component Analysis

PE – polyethylene

POD – peroxidase

PP – polypropylene

PPO – polyphenol oxidase

RS – reducing sugars

SA – sodium ascorbate

TAMBC – total aerobic mesophilic bacteria

TS – total solids

TSS – total soluble solids

UPLC MS2 – ultra-performance liquid chromatography - tandem mass spectrometry

UV-C – ultraviolet-C

VP – vacuum packaging

General introduction

Potato (*Solanum tuberosum*) is of global importance for world food security and nutrition (Wijesinha-Bettoni and Mouillé, 2019). In 2021 it was the fifth largest crop in the world and the global potatoes production was 376 million t (FAOSTAT, 2022). Of the 55 million t of potatoes produced in Europe in 2020, Croatia accounted for 0.4% (EUROSTAT, 2021). Potato tubers can be processed in various ways, therefore potato products such as frozen, dehydrated or minimally processed can be found on the market. The demand for such food, which can be consumed immediately or require minimal processing before consumption, is increasing. Minimally processed or fresh-cut potatoes (FCP) are a relatively new branch of potato processing, but their production is increasing in the market, which is why the scientific community has become more interested in this topic in recent years *(Publication No. 5)*. Of the almost 200 articles (WoS) published in the last 30 years, around 70 were published in 2020-2023 *(Publication No. 5)*.

Minimal processing, which includes mechanical operations such as peeling and/or cutting disrupts the cell structure, leads to decompartmentalization of enzymes and substrates, increased metabolic processes and increased growth of microorganisms. Consequently, numerous changes such as microbial spoilage, browning, softening or alteration of sensory properties can occur during storage in the refrigerator and ultimately shorten the shelf-life of FCP products. The aforementioned changes can be reduced by choosing optimal processing methods and storage conditions. This may include the use of chemicals such as disinfectants and/or anti-browning agents (ABA), appropriate packaging materials and conditions, appropriate storage temperature, etc. In order to reduce the use of chemicals (disinfectants and/or ABA) due to the increasing demand for healthy, organic, and safe food, the application of non-thermal technologies in the production of fresh-cut fruits and vegetables has been explored more intensively in recent years. These technologies include ultraviolet-C (UV-C) irradiation and high hydrostatic pressure (HHP), whose germicidal effects on fruits and vegetables are already known (Li et al., 2019; Manzocco et al., 2011; Tsikrika et al., 2021).

The effectiveness of UV-C irradiation is based on damaging the DNA of microorganisms, thus preventing their replication (Bintsis et al., 2000). However, the effectiveness depends, among other things, on the intensity applied and the duration of irradiation. Given the limited quantity of research that have been conducted on the effects of UV-C irradiation on FCP (Čošić et al., 2021; Teoh et al., 2016; Xie et al., 2017), it is difficult to draw more precise conclusions on the effectiveness of UV-C irradiation in preserving the physical, chemical and sensory properties of

FCP. However, previous results showed an increase in acrylamide content in fried potatoes produced from irradiated potato tubers, as well as increased total phenolics content and decreased enzyme activity in raw irradiated FCP (Čošić et al., 2021; Teoh et al., 2016; Sobol et al., 2020).

In terms of antimicrobial activity, HHP cause protein denaturation and ribosome disintegration, affecting cellular structural arrangement and metabolic pathways (Aganovic et al., 2021; Niven et al., 1999). There are a variety of factors that influence efficacy, such as the pressure applied, the holding time, the temperature, the characteristics of the target microorganism, etc. (Alvarez-Ordóñez et al., 2022). There is limited research on the effects of HHP on the characteristics of FCP. Different effects on the enzyme polyphenol oxidase (PPO), a reduction in brightness (L^*), a reduced chlorogenic acid content in raw, minimal processed potatoes or nonsignificant effect on acrylamide content in fried potatoes have been found (Eshtiaghi and Knorr, 1993; Dourado et al., 2020; Procaccini et al., 2022; Tsikrika et al., 2021).

Therefore, it is important to examine and adjust the conditions of these technologies in relation to the characteristics of the raw material used, in order to create a high quality and safe product with extended shelf-life. To author's knowledge, the influence of UV-C and HHP on the sensory properties of FCP has not yet been investigated.

Storage of FCP in the refrigerator can change its properties (physical properties, chemical composition, sensory properties, etc.), depending on the conditions prevailing there. Potatoes contain about 80% water and 20% dry matter (DM) of which up to 70-80% (ω/ω) is starch, but also a substantial array of other nutritional constituents is present, including proteins, amino acids, minerals, vitamins, reducing sugars and phenolic compounds (Akyol et al., 2016; Miller et al., 2022). Phenolics are bioactive components produced by plants in response to biotic or abiotic stress. They not only influence the browning processes, but also act as antioxidants and have numerous beneficial effects on health (Tian et al., 2016a). Their content in potatoes depends, among other things, on the variety, the processes and treatments used during growth and harvest and storage conditions (Akyol et al., 2016). The most abundant sugars in potatoes are fructose, glucose and sucrose. Reducing sugars content in tubers is important as they are involved in the formation of acrylamide together with amino acids through Maillard reactions, but also play a role in the formation of flavors in fried potatoes (Jansky, 2010). Acrylamide is a potentially carcinogenic compound, the amount of which in potato products is regulated by the European Food Safety Authority (EFSA) (EFSA, 2015). In addition, environmental contaminants, polycyclic

aromatic hydrocarbons (PAH), are present in raw potatoes and frying oil or may be generated during the frying process (Abou-Arab et al., 2014; Samsøe-Petersen et al., 2002; Wennrich et al., 2002) and may also affect the safety of FCP. They are genotoxic and mutagenic contaminants, which is mainly attributed to the heavy fraction of PAH.

FCP is a product intended for cooking. The properties of the raw FCP ultimately affect the quality of the thermally treated FCP, so it is important to ensure the quality of the raw material through appropriate methods and preparation.

The aim of this study was to examine the effects of different doses of UV-C irradiation, different HHP treatment conditions, and storage time on the number of aerobic mesophilic bacteria, on the physical and chemical quality and sensory properties of raw FCP and thus on the shelf-life, as well as on the sensory properties of thermally treated (boiled and fried) FCP. This PhD thesis is presented in the form of published articles, accompanied by a theoretical section, a comprehensive discussion and concluding remarks.

Chapter 1

Theoretical background

- Potato (*Solanum tuberosum*)
- FCP, minimal processing, effect of minimal processing on the properties of FCP during storage and methods to extend their shelf-life
- Effect of UV-C irradiation and high hydrostatic pressure on the properties of FCP
- Effect of cooking on physical, chemical and sensory properties of FCP
- Hypothesis, research objectives, and expected scientific contributions

1. Potato (*Solanum tuberosum*)

The potato (*Solanum tuberosum* L.) belongs to the Solanaceae family, the genus *Solanum*, which is one of the largest genera with about 1500 to 2000 species (PBI Solanum Project, 2014). It is a worldwide crop that originated in South America, in the Andes in southern Peru, where it was domesticated about 10 000 years ago (Ovchinnikova et al., 2011). From America, potatoes were brought to Europe by the Spanish in the late 16th century. As a result of the long and widespread cultivation, there are about 5000 potato cultivars (Datiles and Acevedo-Rodríguez, 2014). They are distinguished in the morphological and qualitative properties of the tubers or in culinary characteristic (Datiles and Acevedo-Rodríguez, 2014). Modern potato cultivars are produced by intensive breeding from the germplasm of landrace of *Solanum tuberosum* varieties and 15 wild species of the *Petota* section (Ovchinnikova et al., 2011). Potatoes can be propagated from botanical seed (generative propagation), but most often vegetative from small tubers (whole or cut).

Potato plants are built from a green stem and the leaves, and bears five-petalled flowers, which after flowering develop into pods containing up to 300 seeds (Singh and Kaur, 2009). The underground part of the stem (stolons) develops horizontally, at the end of which tubers are formed (Figure 1), the number of which depends on various factors.

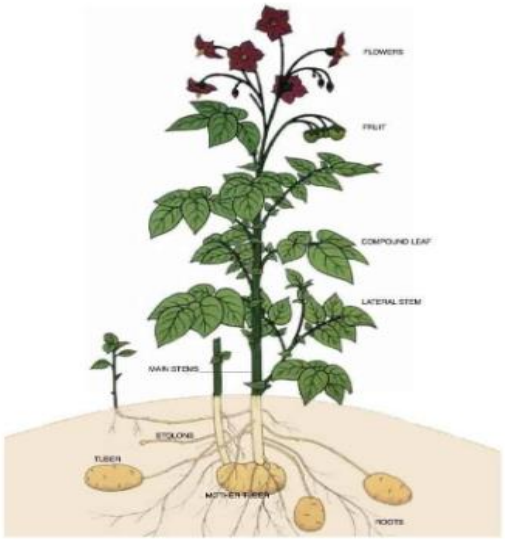

Figure 1. Above-ground and underground parts of the potato plant (Anonymous, 2023)

The potato tuber is a starch storage organ of the plant and consists of periderm (skin), cortex, vascular ring, outer medulla and pith (Troncoso et al., 2009). Potato cells contain starch granules whose size and shape depend on the location in tuber (Troncoso et al., 2009). The characteristics of the tubers differ among varieties in terms of skin color, shape and size, yield, quantity and uniformity of tubers (Datiles and Acevedo-Rodríguez, 2014), but also in terms of biochemical characteristics, growth physiology, resilience against microorganisms and various diseases. After the leaves and stem of the plant dry out, the tubers stop growing and a solid cover is formed on the mature tubers. Depending on the degree of maturity (the period from planting to harvesting) potato cultivars can be classified into several groups, from very early (65-70 days) to very late (more than 130 days) (Camire et al., 2009). After harvest, potato tubers go into dormancy, which is physiological state of the tuber in which they do not sprout. The length of dormancy gives an indication of how long the potato should be stored. By interrupting dormancy phase, buds ('eyes'), which are arranged in spiral on the surface of the tuber, form sprouts that can grow into new plants under favorable conditions. In addition, sprouting and stress influence the quality of the tubers by reducing the content of starch.

Following the harvest, the tubers are usually stored at a temperature of 12-16 °C and in conditions of high relative humidity (90-95%) for two weeks (Pinhero et al., 2009), which allows recovery of damaged parts (curing treatment). During this time, the sensory properties are improving, the content of phenolic compounds, such as chlorogenic acids, and the activity of PPO increase, while activity of phenylalanine ammonia lyase (PAL) decrease (Wang et al., 2015). After curing period, the temperature in the warehouse is gradually lowered until the optimal conditions for an extended storage in the dormant phase are achieved. The storage temperature of potato tubers depends on intendent use of the potato. Industrial potatoes are usually stored at 7-10 °C, and table potatoes at 5-7 °C (3 months) or at 3-4 °C (up to six months) (Anonymous 1, 2023).

1.1. Chemical composition of potato tubers

The chemical composition of potato tubers is influenced by various factors such as variety, soil and climatic conditions, storage conditions, age of the potato and processing methods. Raw potatoes (with skin) contain approximatively 80% water and 20% dry matter (DM) containing 65-80% starch. Included in the total mass of tubers are about 17.5% carbohydrates, 2.1% proteins,

2.1% total dietary fibers, reducing sugars (0.57 %), minerals (most abundant K, P, Mg and Ca), vitamins (most abundant vitamin C, 19.7 mg 100 g^{-1}), β-carotene, amino acids and other nutritional components (USDA, 2019). Based on starch content, potatoes can be divided into mealy potatoes (20-22% starch) which are suitable for baking and frying and waxy potatoes (16-18% starch) which are better suited for boiling. Mealy potatoes contain starch with a higher proportion of amylose, which make them suitable for making mashed potatoes in addition to baking and frying, while waxy potatoes contain a higher content of amylopectin which ensures that the potatoes retain their shape after boiling (Dresser, 2007). The soluble solids of potato tubers consist of sugars, acids, vitamins, minerals and other soluble substances (Khorramifar et al., 2022). The DM and sugar content of potato tubers depends on cultivar, but also on numerous pre-harvest factors, such as maturity, climatic and soil conditions, as well as mechanical stress during harvest and storage conditions (Kumar, 2004, Vreugdenhil, 2007; Cabezas-Serrano et al., 2009). Therefore, to keep the sugar levels low, any stress that could lead to sugar accumulation should be avoided.

Predominant sugars found in potatoes include reducing sugars (RS) glucose and fructose (0.15–1.5%), as well as sucrose (0.4–6.6%) (Storey and Davies, 1992), but their content depends on factors such as cultivars or storage conditions. RS and amino acids are involved in formation of dark pigments through Maillard reactions, but also in formation of taste (as forming bitter taste) of fried potatoes. In addition, RS and asparagine are substrates for the formation of acrylamide through Maillard reactions, during frying at temperatures exceeding 120 °C. Acrylamide is an organic compound, neurotoxic to humans and probably cancerogenic, classified in Group 2A by the International Agency for Research on Cancer (EFSA, 2015). Once acrylamide is dispersed across organs, it is metabolized to the glycidamide, among other substances (EFSA, 2015). The formation of glycidamide is considered to be the basis for the genotoxic and carcinogenic properties of acrylamide (EFSA, 2015). The upper limit for acrylamide in potato products is 750 µg kg^{-1}, according to the EU Commission Regulation (2017/2158) (EU, 2017). Therefore, the suggested content of RS in raw potatoes intended for the production of chips is 0.2-0.3% and 0.3-0.5% for French fries (Vreugdenhil, 2007). To avoid the sweet taste of cooked potatoes, the sucrose content in raw table potatoes should be below 1% (Vreugdenhil, 2007). Of the 19 amino acids present in potatoes, 10 are essential. About 49% of the total amino acids are present in free form, with asparagine and glutamine amides accounting for the largest proportion (34–90%) (Pęksa et al., 2021). Specifically, the content of asparagine in the sixteen potato cultivars was found to vary

between 8.9 and 34.5 g kg^{-1} DW (Zhu et al., 2010), but it depends, among others things, on the cultivar type and storage time (Pęksa et al., 2021).

PAH are toxic chemicals, that are absorbed into food as contaminants originating from the surroundings (soil, air and water), but can also be generated in food as through incomplete combustion of organic material during thermal processing (Bansal and Kim, 2015). Raw potatoes contain PAH in small quantities, but they can additionally be formed during frying in oil. The structure of PAH contains 2 or more aromatic rings, which is why they are divided into light fractions (2-4 rings) and heavy fractions (more than 4 rings) (Singh et al., 2016). The number of rings in PAH correlates positively to toxicity level; light PAH fractions exhibit toxicity, while heavier PAH are associated with genotoxicity and mutagenicity (Hanedar et al., 2014, Singh et al., 2016). The highest permissible PAH concentrations in oils and fats intended for direct human consumption or use as ingredients are: 2 µg kg^{-1} for benzo(a)pyrene and 10 µg kg^{-1} for the sum of benzo(a)pyrene, benzo(a)anthracene, benzo(b)fluoranthene and chrysene (EU, 2011a). According to Balbino et al. (2020), the content of benzo(a)pyrene in FCP fried samples was 0.62 µg kg^{-1} and of PAH4 was 1.36 µg kg^{-1}, which is under the levels specified in the EU Regulation (EU, 2011a).

Phenolics represent a significant group of compounds in potatoes, primarily due to their antioxidant properties, as they can act as hydrogen or electron donors thus preventing the formation of free radicals. In addition, phenolics have a significant role in the enzymatic reactions of browning processes, which can lead to deterioration in appearance and quality of the FCP products. They are mainly found in peel and outer flesh of the tubers, but considerable amounts are also present in the inner flesh. The most represented phenolic component in potatoes (skin and flesh) is chlorogenic acid, whose content in the inner flesh of sixteen potato varieties was found to be 2.1–188 µg g^{-1} DW (Deußer et al., 2012), and accounts for up to 90% of the total phenolic content of potato tubers (Friedman, 1996). It exerts various positive health impacts, including anti-inflammatory effects, cardiovascular diseases and diabetes prevention and additionally, it can increase insulin sensitivity and reduce glucose absorption in the intestine (Akyol et al., 2016; Manach et al., 2004; Plazas et al., 2014; Andre et al., 2014). In addition, potato contains chlorogenic acid isomers and other phenolic acids such as caffeic, ferulic or *p*-coumaric. Certain flavonoids in potato are also included: (+)-catechin (which is the most abundant with 0-1.5 mg 100 g^{-1} dry extract), kaempferol-3-*O*-rutinoside, quercetin-3-*O*-rutinoside and quercetin-3-*O*-sophoroside (Akyol et al., 2016; Mäder et al., 2009). Phenolics can be synthesized by plants in

response to biotic and abiotic stresses through biosynthesis processes that include the shikimate, pentose phosphate and phenylpropanoid pathways. They contribute to healing by lignification of damaged areas (Akyol et al., 2016). However, the phenolics content depends on cultivar type, degree of maturity, agrotechnical practices, climatic conditions, treatment applied and many other factors.

In smaller amounts, the tuber also contains essential lipids (0.15–0.5% of fresh weight - FW), such as linoleic, palmitic and linolenic acid. It also contains glycolipids, phospholipids and sterols as well as carotenoids. Carotenoids contribute to the yellow color of potato tubers, especially the group of xanthophylls (Vreugdenhil, 2007). Carotenoids in potatoes include lutein, zeaxanthin, violaxanthin and neoxanthin, while β-carotene is present in trace amounts (Haynes et al., 2011). In yellow potatoes, the total carotenoid content ranges from 5.57 to 20.20 mg kg^{-1} FW (Tatarowska et al., 2019).

Glycoalkaloids are natural compounds of the Solanaceae plants family. They are classified as a health concern (toxic and leading to poisoning) for infants and toddlers, and only for adults who are high consumers (EFSA, 2020). However, they are involved in the plant's defense against fungi and insects. Glycoalkaloids (such as α-chaconine and α-solanine) are present in tubers in relatively small amounts, but their concentration in peel is 3- to 10-fold higher than in flesh (EFSA CONTAM Panel, 2020). The content of glycoalkaloids should be below 20 mg 100 g^{-1} of FW, or even less than 10 mg 100 g^{-1} FW of the potato, as they are responsible for the sour or bitter taste (Rytel et al., 2015). Green and immature tubers contain an increased content of glycoalkaloids. Their content can be kept low by storing the tubers in a dark and cool place, as they are produced in the tubers under the light. Peeling can reduce their content, as can boiling and especially frying (up to 90%) (EFSA, 2020).

2. FCP

The processing of fruits and vegetables to produce fresh-cut fruits and vegetables involves relatively simple operations such as washing, peeling, cutting, dewatering and packaging. The main objective is to produce a fresh, safe and nutritionally valuable product. FCP are very perishable products. This is because minimal processing creates conditions that favor the development of microorganisms, followed by other undesirable changes such as possible loss of

water, the development of an unpleasant odor and softening and browning of the tissue. In general, they lose their quality and safety, which limits their shelf-life. In addition, the quality of FCP depends on some other factors, such as the cultivar used, the growing and harvesting conditions and the degree of maturity of the tubers. The good quality of FCP is reflected in its firm texture, slightly moist and bright appearance without signs of darkening and in the flesh color typical of the variety (Tudela and Gil, 2020). Due to the above-mentioned undesirable changes that may occur by processing and during storage, peeled and packaged potatoes have a relatively short shelf-life of about 5–7 days (at 4–5 °C) (Ierna et al., 2016). Over the years, many studies have focused on investigating the optimal conditions for minimal processing of potatoes in order to preserve their quality and shelf-life.

2.1. Effect of minimal processing on the properties of FCP during storage

Minimal processing of potatoes starts with washing the tubers to remove dirt and pesticide residues and to avoid cross-contamination that can be caused by further processing. For this purpose, it is advised to use 5-10 L of cold water (below 5 °C) per kg of potatoes (Rocculi et al., 2009). In addition, disinfectants such as chlorine agents or organic acids and hydrogen peroxide can be used in the washing water (Dite Hunjek, 2021). After washing, the tubers are peeled, which can be done mechanically, chemically or with the help of high pressure steam peelers (Rocculi et al., 2009). Cutting of peeled tubers is done with stainless steel or carbon blades, and then the peeled or cut potatoes are additionally washed to remove of microorganisms, released cellular liquid and enzymes, or anti-browning treatment is done to reduce the browning process. However, excess liquid should be removed from peeled or cut potatoes before packaging to reduce microbial activity.

Minimal processing steps are stressors that trigger physical and physiological processes in the tissues of fresh-cut fruits and vegetables (Figure 2). In response to wounding, respiration rate increases (about 3-5 times) (Rocculi et al., 2009) and oxidative browning reactions are triggered, among others. In addition, the surface of the cuts provides a good basis for increased microbial activity. All this leads to a loss of tissue quality and safety. Appropriate preparation of fresh-cut material using disinfectants and ABA or the use of innovative technologies, as well as appropriate packaging and storage, can mitigate these changes and extend the product's shelf-life. Storage

temperature is the most important factor affecting the properties of FCP. At lower temperatures, the respiration rate decreases and the degradation processes of the product slow down.

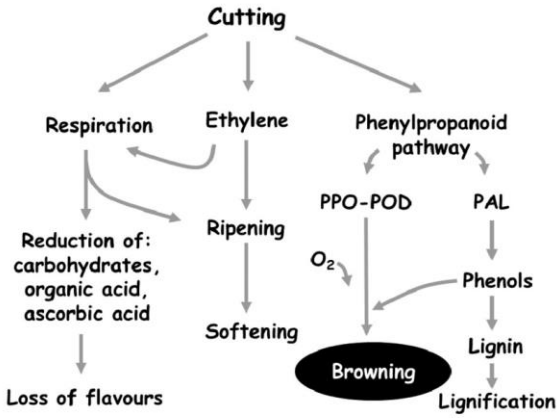

Figure 2. Interactions between several cutting-induced effects on the physical and physiological processes in the tissues of fresh-cut products (Landi et al., 2015).

2.1.1. Effects on enzymatic browning processes

The color of FCP must be characteristic of the variety from which it was derived, with no signs of darkening (Tudela and Gil, 2020). However, during processing, cell integrity is damaged and enzymatic oxidation reactions take place, resulting in browning of the tissue. Enzymatic browning not only has a negative effect on the appearance, but also on flavor and overall quality of the potato. The enzymes responsible for enzymatic browning of potatoes are primarily PPO, but also peroxidase (POD), which are naturally present in potatoes. When potatoes are cut, the PPO enzymes, which are localized in the cytoplasm of the potato cells, are released from the damaged cells and activated on contact with air (oxygen). The PPO enzyme catalyzes the oxidation of phenolic compounds to quinones: the ortho-hydroxylation of monophenols to *o*-diphenols and the oxidation of diphenols to *o*-quinones. This reaction is reversible. The quinones formed are highly reactive compounds that are involved in further non-enzymatic reactions, that lead to the formation of dark (brown) melanin pigments. In addition, the wound-induced enzyme PAL also plays an important role in these processes, as it is a key enzyme in the phenylpropanoid pathway and thus involved in the biosynthesis of the polyphenol compounds. Considering the main factors involved in complex browning reactions, browning can be inhibited by various methods: inhibition of the enzymes that catalyzing the reactions, removal of the enzyme substrates (phenolics or oxygen) or

interaction with intermediates (Bobo-Garcia et al., 2020; *Publication No. 5*). The rate and extent of enzymatic browning of FCP can be influenced by temperature, pH, moisture content and variety. Temperature control during processing, storage and transport of FCP is critical for reducing enzymatic browning, as temperature affects the activities of PAL, PPO and POD. Vitti et al. (2011) stored FCP at 5 and 15 °C for 9 and 5 days, respectively, and observed an increase in enzymatic activity in all the cultivars stored at 15 °C. In addition, the PPO enzyme is more active at neutral to slightly acidic pH values, and as Li et al. (2018) found, the optimal PPO activity is at pH 6.5. Therefore, acidification of FCP may affect the activity of PPO and consequently reduce enzymatic browning. The browning process also depends on the variety used, i.e., its phenolics content. Cabezas-Serrano et al. (2009) reported that of the five FCP cultivars studied, 'Marabel' showed less browning incidence and color changes, and was characterized by low phenolics content and lower PPO activity as well as high sugar content. According to Qiao et al. (2022), the cultivar most susceptible to post-cut browning exhibited increased PPO and POD mRNA accumulation but lower CAT mRNA accumulation. The study found that reactive oxygen species and respiration contribute to post-cut browning, while lipid and amino acid metabolism were critical for these processes. In contrast, the browning-resistant cultivar showed elevated levels of metabolites such as jasmonic acid, glutamate and gibberellin.

Browning processes can be mitigated by methods such as: treatment with ABA, thermal processing to inactivate enzymes, use of appropriate packaging, or by applying some innovative technologies. Due to their synergistic effect, some of these methods can also be combined. Treatment with ABA is usually applied to FCP after cutting, after which excess water should be removed to prevent microbial spoilage of FCP after packaging (Rocculi et al., 2009). The effectiveness of inhibiting enzymatic browning reactions through the action of ABA is based on the reduction of quinones to phenolics, lowering of pH (depending on the enzyme) or chelation (binding of metal ions of the enzyme) (Bobo-Garcia et al., 2020). Organic acids (such as citric acid and ascorbic acid) used as ABA can also have a positive effect on sensory, physical and nutritional properties of FCP (Ierna et al., 2016). Furthermore, sodium ascorbate (SA) solution (2%) proved to be effective in preventing browning of vacuum-packaged (VP) FCP (Dite Hunjek et al., 2020a). SA (E 301) is approved in the EU as a food additive under EC Regulation No. 1333/2008 (EC, 2008) and Regulation (EU) No. 1129/2011 (EU, 2011b). The use of this additive is labelled as

"*quantum satis*", including pre-packaged unprocessed and peeled potatoes intended for further processing before consumption, including heat treatment.

The choice of packaging material can significantly influence the oxygen availability, and thus can slow down enzymatic browning of FCP during storage. Products can be packaged in bags or trays, which are mostly made of polymeric materials such as polyethylene (PE), polypropylene (PP) and polyamide (PA) *(Publication No. 5)*. Modified atmosphere packaging (MAP) is a technique that change composition of the atmosphere surrounding the product by replacing the air with a mixture of gases (nitrogen, carbon dioxide and oxygen) in controlled proportions. VP method removes the air from the packaging and hermetically seals products inside the bag. The removal of oxygen slows down the oxidative reactions responsible for browning, but also the deterioration of the texture and taste of FCP and the growth of aerobic spoilage microorganisms (bacteria and molds). Dite Hunjek et al. (2020a) observed that the browning process during storage (8 days/10 °C) was slower on VP FCP than on the MAP ones. Similar results were obtained by Xu et al. (2022) for VP FCP stored at 4 ± 0.5 °C for 5 days and by Rocha et al. (2003) for VP peeled potatoes during storage at 4-6 °C for 7 days. Browning of FCP can be assessed by sensory analysis or by determining the color using instrumental methods, e.g., the Lab color space, which uses the dimension L^* for brightness (from 0-black to 100-white) and the dimensions a^* and b^* for the analysis of opposite colors, red (+) – green (-) and blue (-) – yellow (+), respectively. Increased values of a^* and b^* and a decrease in L^* values may indicate increased enzymatic browning.

2.1.2. Effects on the chemical and physical properties of FCP

Phenolics are a substrate for enzymatic browning reactions, so changes in their composition can affect the color of FCP. Cutting induces PAL activity and increases phenolics content, which can be affected by cutting style, among other factors. According to Hu et al. (2021), an increase in phenolics content of 40.48% (pieces), 74.88% (strips) and 108.86% (slices) was observed. Wang et al. (2023) studied the physiological changes in FCP during 24 h after cutting, and created a hypothetical model based on the results: upon cutting, the tissues generate reactive oxygen species and plant hormones and genes responsible for the synthesis of secondary metabolites, such as phenolics, are activated. In addition, genes associated with enzymatic browning (PPO, POD, CAT, etc.) are triggered. During storage, PAL activity in FCP was found to slow down after 4 days of

storage (during 12 storage days) (Liu et al., 2019). Cantos et al. (2002) found an increase in the chlorogenic acid content in FCP during 6 days of storage at 4 °C. Delayed formation of chlorogenic acid was found in FCP pretreated with ascorbic acid and calcium ascorbate (Zhao et al., 2022). In contrast, Tsouvaltzis et al. (2017) did not report a significant change in phenolics in FCP during storage (5 °C/6 days). Similarly, Dite Hunjek et al. (2021), found that the content of phenolics (mainly chlorogenic acid) and sugars in FCP did not change significantly during storage (10 °C/8 days) of VP FCP, which was pre-treated with SA solution. Furthermore, the content of RS is important because they, together with asparagine, can form acrylamide in fried potatoes. Xu et al. (2022) found an increased content of RS, sucrose and starch and decreased phenolics content during storage (4 °C/5 days) of VP FCP, which was pre-treated with ascorbic acid. Also, it was found that the content of asparagine may decrease during long-term storage (Pęksa et al., 2021).

FCP should exhibit firmness, a slight moisture surface, and should not show any signs of drying (Tudela and Gil, 2020). The texture of potato tissue, which is directly related to DM content, can be influenced by various factors such as cultivar, processing methods and storage conditions. Due to wounding, cells walls may strengthen, as a result of additional secretion of lignin or suberin, which, followed by dehydration can lead to an undesirable white surface (Rocculi et al., 2009). However, the loss of water subsequently leads to disintegration of the cell wall and leakage of cell liquids, resulting in softening of the tissue (Rocculi et al., 2009). Furthermore, the activity of enzymes, such as pectin methylesterase, can alter the texture of FCP during processing and storage. The use of various FCP processing methods such as blanching, slicing and packaging can affect the moisture content and texture of the final product. VP reduces moisture loss from the product, prevents dehydration and maintains the desired texture. According to Amaral et al. (2018), the DM content of VP FCP (pre-treated with citric acid) was not significantly changed during storage at 3±1 ºC for 17 days. Zhou et al. (2021) observed delayed weight loss, inhibited hardening (delayed lignin formation) and maintained texture during storage (20 °C/4 days) of VP FCP (pre-treated with ascorbic acid). Beltrán et al. (2005) reported that the texture of VP FCP was better preserved during storage (14 days/4 °C) than that of MAP samples. According to Dite Hunjek (2021), treatment with ABA had little effect on total solids and the texture of FCP during storage, while VP performed slightly better texture compared to MAP. However, during longer storage, the firmness may significantly deteriorate. Beside instrumentally, firmness can also be assessed subjectively, by sensory evaluation conducted by trained panelists. These assessments provide

valuable insight into the perceived texture of FCP, as sensory evaluations are key to capturing the overall texture experience of FCP.

The pH of potatoes varies depending on factors such as cultivar, growing conditions and processing methods. In general, FCP are products with a large cut surface that is slightly moist and usually have a pH of 5.8-6, which is a good basis for microbial growth (Ahvenainen, 1996). Lower pH, i.e., a more acidic environment, can prevent the growth of microorganisms that cause spoilage, which can be achieved, for example, by using organic acids. However, Dite Hunjek (2021) found no significant effect of ABA (ascorbic acid and SA) on the pH of VP FCP. In addition, the pH of VP peeled potatoes was found to decrease during storage, which could be a consequence of the increased content of lactic and acetic acids, whose production under anaerobic conditions could be connected to the microbial population and metabolic processes, probably *Leuconostoc* and *Lactococcus* (Li et al., 2022). Ultimately, it is necessary to maintain an optimal pH value, as extreme pH values can have a negative effect on the texture.

The aroma compounds of FCP are impacted by both production and storage. Mechanical processes damage the cells, leading to the initiation of various biochemical reactions and increased microbial growth. This leads to changes in the composition and quantity of volatile compounds, which intensify during storage. During 12 days storage of potatoes, compounds such as nitrogen oxides, furans, hydrocarbons, sulfides, pyrazine, alcohols, aldehydes, ketones and organic sulfides increased after 4th day (Cheng et al., 2022), which may indicate deterioration of flavor. A relation between volatile compounds and microorganisms was investigated by Li et al. (2022). In addition to the deterioration of flavor quality of peeled VP potatoes after 8 days of storage, they detected 37 volatile organic compounds, of which alcohols, aldehydes, and hydrocarbons were the most prevalent, and also found a positive correlation between the biosynthesis of volatile organic compounds with *Enterobacteriaceae*, *Erwinia*, *Lacrimispora*, *Lactococcus*, *Serratia*, *Pantoea*, *Clostridium*, *Flavobacterium* and *Clostridia* (Li et al., 2022). Furthermore, Xu et al. (2022) found that decanal and hexanal, compounds derived from lipid degradation, were the predominant volatile in the raw VP FCP (pre-treated with ascorbic acid) during storage. However, this treatment of FCP inhibited the formation of aldehydes, thus suppressing the development of rancid off-flavor, and odor and taste were maintained during storage (detected by electronic tongue and GC-MS). The preservation of the sensory properties of VP FCP (with or without ABA) during storage has been noted by Zhou et al. (2021), Dite Hunjek et al. (2020a) and Beltrán et al. (2005), among

others. In an oxygen-reduced atmosphere, the oxidation of lipids and thus the formation of off-flavors and rancidity can be prevented.

2.1.3. Effects on the microflora of FCP

Potato tubers are exposed to various soil-borne microorganisms which, as a result of injury, can cause the development of potato diseases. As reported in *Publication No. 5*, several authors found human pathogens such as *Listeria monocytogenes*, *Escherichia coli* O157:H7, *Clostridium botulinum* and *Clostridium difficile* on raw potatoes or potato fields. However, contamination with pathogenic microorganisms is primarily a result of cross-contamination during processing. Fresh-cut vegetables, including FCP, are highly susceptible to colonization by microorganisms (bacteria, yeasts and molds) due to their pH (5.8-6), high humidity (Ahvenainen, 1996) and substantial surface area exposed to cross-contamination. Microorganisms from the soil can be transferred to FCP during processing through water, hands and equipment. The natural microflora of water-washed FCP was found to consist of aerobic mesophilic and psychotropic bacteria, anaerobic bacteria, yeasts and coliforms, and lactic acid bacteria (Beltrán et al., 2005). Kong et al. (2020) found the dominant bacteria during 14 days storage at 4 °C of FCP were mainly *Pseudomonas*, *Pantoea*, *Erwinia*, *Bucher Buchnera*, while Lund et al. (1968) found *Enterobacter Hafnia* sp. and *Erwinia herbicola* to be the predominant microflora after storage of packaged peeled, cut and sulfite-treated FCP. Li et al. (2022) found change in dominant bacteria in VP peeled potatoes during 12 days of storage, from *Ralstonia*, *Pseudomonas*, *Pantoea* and *Comamonas* to *Clostridia*, *Clostridium*, *Lacrimispora*, *Lactococcus* and *Leuconostoc*. The growth of microorganisms on FCP is influenced by various internal and external factors, such as temperature, pH and water activity. Proper packaging and refrigeration (below 5 °C) are effective methods to slow down the growth of microbes and extend the shelf-life of FCP. However, storing FCP at lower temperatures does not eliminate the risk of psychrophilic pathogenic bacteria, including *Listeria monocytogenes*, *Yersinia enterocolitica*, *Salmonella* spp., and *Aeromonas hydrophila*, which may still endure (Ahvenainen, 1996). A slightly acidic (near neutral) pH and higher levels of water activity are optimal for the growth of most microorganisms, so acidification or a reduction in water activity through techniques such as VP or MAP can inhibit microbial growth. In addition, the permeability of packaging is an important factor (Gorris and Peppelenbos, 1992), because if anaerobic

conditions are created, microorganisms such as *Clostridium botulinum*, *Listeria monocytogenes*, *Bacillus cereus*, *Salmonella typhimurium*, and *Staphylococcus aureus* can proliferate (Rocculi et al., 2009), and off-odors and spoilage can occur. The introduction of strict standards and controls (cultivation, handling, transport, food processing lines and facilities) such as Good Manufacturing Practices, Hazard Analysis and Risk-Based Preventive Control, guidelines, and other various measures are required to reduce foodborne disease transmission *(Publication No. 5)*.

In addition, innovative technologies such as UV-C irradiation and HHP are being explored to develop appropriate processing methods to maintain the safety and quality of fresh-cut products and have emerged as one of the possible preservation methods in the production of FCP. More on this topic is discussed in the following chapters.

3. Effect of UV-C irradiation and HHP on the properties of FCP

The effect of technologies such as UV-C and high hydrostatic pressure (HHP) on fresh-cut fruits and vegetables is being investigated to devise suitable methods for the production of safe and high-quality products. As previous research has shown, the application of these technologies, in addition to their germicidal effect, can also enable the preservation of the nutritional and sensory properties of fruits and vegetables (Jaeger et al., 2010; Koutchma, 2008; Manzocco et al., 2011; Santhirasegaram et al., 2015; Tsikrika et al., 2021; Wu et al., 2021). Food that have undergone UV-C irradiation may be considered as novel food in the EU, a classification that encompasses, among other criteria, food products produced using processes that were not present in Europe before 1997 (Koutchma, 2018; EU, 2015). Before such foods are placed on the market in the EU, they must undergo a safety assessment to ensure human health (EU, 2011c; EU, 2015). If UV-C irradiation proves effective and tests are carried out on an industrial scale, it could be part of the production process of FCP, with the aim of extending the shelf-life and reducing waste. However, for the successful adoption of UV-C treatment in the FCP industry crucial are consumer acceptance and regulatory compliance. HHP is a non-thermal food processing technology that is becoming increasingly important in the food industry. Compared to other standard processes like pasteurization, HHP food processing does not raise additional food safety issues, either microbial or chemical, and it is not specifically regulated in the EU (Alvarez-Ordóñez et al., 2022). It has been put into production and applied to, among other products, prepackaged juices, sauces and

dips. However, compliance with food safety demands, including implementation of good hygiene practices, procedures based on Hazard Analysis and Critical Control Point principles, and the fulfillment of traceability and labeling obligations, is essential (Alvarez-Ordóñez et al., 2022). This technology is relatively expensive due to the high initial investments in equipment. Nevertheless, the costs of HHP-processed products have improved in recent years (De la Peña-Armada et al., 2021). These technologies are also being investigated and combined with other preservation methods, including VP and MAP, ABA, etc., for fresh-cut fruits and vegetables.

3.1. Effect of UV-C irradiation on the properties of FCP

Non-thermal, non-ionizing and environmentally friendly UV-C irradiation has emerged as a promising technology for extending the shelf-life and preserving the quality of FCP. Short-wave ultraviolet light (200-280 nm) is used for disinfection, the optimal wavelength being 254 nm. The antimicrobial effect of UV irradiation relies on the induction of structural alterations in the DNA of microorganisms, due to cross-linking between pyrimidine bases (thymine and cytosine) (Livneh et al., 1993; Visser et al., 2002). The formation of dimers in DNA and RNA disrupts cellular functions by interfering with normal transcription and replication of nucleic acids, eventually leading to cell death (Alexandre et al., 2012; Bintsis et al., 2000). The efficiency of the application of this radiation depends among other things, on the irradiation intensity applied and the exposure time (Alexandre et al., 2012). The irradiation dose (kJ m^{-2}) takes in accounts both, the radiation intensity and the exposure time. It is important to use an adequate dose to achieve the purpose of the irradiation and to maintain the quality of the food. In addition, the effectiveness of irradiation depends on the initial microbial load, the topography of product surface and the packaging material used (if the packaged product is treated). Namely, surface topography of fresh-cut product may lead to local shading of the microorganisms and thus reduce the effect of UV-C irradiation (Allende et al., 2006). In addition, the choice of packaging material also may affect the effect of UV-C irradiation, as the UV-C transmittance of polymeric films is contingent upon their properties, including thickness, composition, degree of crystallinity, and the number of layers in the film (Tarek et al. 2016). Therefore, some polymer materials may have low permeability to UV-C irradiation, such as PET/PE (thickness of 52 µm) with 0% permeability, while PA/PE (40 µm) has 80% (Manzocco and Nicoli, 2015). UV-C treatment is superficial and therefore is an adequate

disinfection method for fresh-cut fruits and vegetables, as the surface of fresh-cut products, such as FCP, is the primary site of contamination by microorganisms.

Numerous studies have been conducted out on the effect of UV-C on fresh-cut fruits and vegetables, and reported reduced number and/or slower growth microorganisms during storage (Artés-Hernández et al., 2010; Li et al., 2019; Manzocco et al., 2011). Nevertheless, the size of the cuts (slices, cubes, cylinders) can influence the UV-C efficacy. Artés-Hernández et al. (2021) irradiated (0, 2.4, 4.8 and 7.2 kJ m^{-2}) cylinders of fresh-cut watermelon of different sizes (2.7 cm Ø; 1, 2, 4 or 8 cm length) and concluded that the microbial quality of the irradiated samples could be better preserved during storage if the samples had a high percentage of volume/cut area. According to their results, the total phenolic content in irradiated samples decreased, especially in 1 cm long cylinders, and more so the higher the UV-C dose was, although the decrease was less pronounced with increasing cut size. On the contrary, increased total and/or individual phenolics content and other bioactive compounds were also found during or at the end of storage of fresh-cut fruits and/or vegetables (Alegria et al., 2012; Moreno et al., 2017; Surjadinata et al., 2017). As a result of UV-C irradiation (abiotic stress), a plant cell defense system against oxidative damage is triggered, leading to an increase in the activity of enzymes involved in the synthesis of phenolic compounds. However, Wang et al. (2019) observed that UV-C treatment of 5 and 10 min (75 W) decreased the activity of oxidative enzymes (PPO, PAL and POD), and significantly reduced the degree of browning of fresh-cut lotus roots during storage, while longer treatments (20 and 40 min) had lesser effect on browning and increased the activity of PPO and PAL. Moreno et al. (2017) irradiated (12.5 kJ m^{-2}) carambola slices that maintaned fresh appearance for 21 days, while control samples showed spoilage and severe browning. According to the authors, the reduced browning in samples treated with UV-C was not due to a reduction in PAL and/or POD, but rather to inhibition of PPO and enhanced preservation of tissue structure. The effect of UV-C irradiation was also shown in increased firmness, improved flavor or preserved color in treated fruits and vegetables (Artés-Hernández et al., 2010; Barka et al., 2000; Yuan et al., 2022). Ortiz et a. (2022) found the dose of 4 kJ m^{-2} and the intensity of 36 W m^{-2} showed the greatest extension of shelf-life of fresh-cut strawberry, and the samples treated with UV-C also achieved better results in sensory consumer tests. However, some alteration due to UV-C irradiation have been observed in several studies, such as increase in the browning due to prolongation of the exposure time and induced browning through the storage of fresh-cut pineapples (Pan and Zu, 2012), as well as

breakages of cellular membranes under the influence of UV-C (Gómez et al., 2010). In addition, an increased respiration rate was found under the influence of UV-C, as reported in review by Rico et al. (2007), and decreased antioxidant capacity during storage, when higher UV-C doses were applied (Artés-Hernández et al., 2009).

The effect of UV-C irradiation on FCP is poorly studied, with only a few studies from recent years. Teoh et al. (2016) irradiated (2.28, 6.84, 11.41 and 13.68 kJ m^{-2}) potato slices previously treated with ascorbic acid and calcium chloride solution (AACCl) with UV-C, packaged in permeable plastic boxes after irradiation and stored them (at dark for 10 days/4 °C). All UV-C treatments decreased enzyme activity, yet activity of PPO, POD and PAL was lowest during storage when treated with AACCl + 6.84 kJ m^{-2}. Since enzymes such as PPO and POD catalyze oxidative browning reactions, inactivation of these enzymes by UV-C radiation can alleviate this process. Xie et al. (2017) treated potato slices with sodium acid sulfate, UV-C (3 min), and their combination, and stored them in PE bags (25 days/4 °C). According to the authors mentioned above, no significant effect of UV-C irradiation on PPO activity was observed during the early period of storage, but compared to the control, lower PPO activity was found after half of the storage time. Furthermore, UV-C alone did not lead to an extension of product shelf-life. Čošić et al. (2021) studied the effect of UV-C on whole potato tubers (0–10.08 kJ m^{-2}) and FCP (0–2.70 kJ m^{-2}) immediately after treatment, noting that no ABA or packaging was used. They observed a reduction in total aerobic mesophilic bacteria (TAMBC), but despite similar initial bacterial load, a significantly higher dose was required for potato tubers (5.40 kJ m^{-2}) than for potato slices (1.08 kJ m^{-2}) to achieve a corresponding log reduction (1-1.5 log CFU g^{-1}). This effect may be attributed to the surface topography. According to the same authors, an increase in the content of chlorogenic acid was observed, especially in the tubers, but they found that the content decreased with increasing dose of irradiation.

As mentioned in the introduction, the effectiveness of irradiation depends on variety of factors and it is extremely important to optimize the methods of minimal processing and irradiation and to choose appropriate packaging and storage, to ensure the safety and quality of FCP.

3.2. Effect of HHP on the properties of FCP

HHP is a non-thermal method that can be used to inactivate pathogens, spoilage microorganisms and enzymes while maintaining quality and extending the shelf-life of food. It is mainly applied to pre-packaged juices, sauces, dips, fishery and meat products and ready-to-eat meals (Alvarez-Ordóñez et al., 2022). It is also used, among other things, for freezing, cold gelatinization of starch, unfolding proteins or stimulating the growth of microbes (under mild conditions) to improve and shorten fermentation processes (Alvarez-Ordóñez et al., 2022). HHP treatment uses isocratic pressures (usually 400-600 MPa) and common holding times of 1.5 to 6 min at temperatures below 45 °C. Food products can be treated usually VP (Alvarez-Ordóñez et al., 2022) or packaged in liquid in a flexible container. In a pressure vessel, the packaged food is placed in a liquid medium, often water, which serves as the pressurizing medium. HHP acts homogeneously, i.e. immediately and uniformly on and through the product, regardless of its size, shape or composition (Gopal et al., 2017), preventing food from being crushed during treatment (Aganovic et al., 2021). Once the appropriate pressure is reached, it is maintained without further energy input, and during the pressure the temperature of the product increases by about 3 °C/100 MPa due to the heat of compression (Gopal et al., 2017). Cycle time is the total time required for pressurization, holding and depressurization. The effectiveness of HHP depends on the pressure and processing time used, as well as the pH, water activity, type of microorganism, taxonomic unit, or type of enzymes present (Alvarez-Ordóñez et al., 2022; Guerrero-Beltrán et al., 2005). HHP affects metabolic processes and the structural organization of the cell, leads to the denaturation of proteins and the disintegration of ribosome, which eventually leads to the cellular death (Aganovic et al., 2021; Niven et al., 1999). The secondary, tertiary, and quaternary structures are affected by HHP; however, covalent bonds remain intact. This allows desirable components, such as vitamins and flavor, to remain largely unaltered (Rastogi et al. 2007), while e.g. proteins, for example, can be denatured.

Some of the research of the effect of HHP on fresh-cut fruits and vegetables are given below. Zhou et al. (2014) investigated the effect of HHP (350-550 MPa/0.5-30 min) on microbial activity and quality of fresh-cut pumpkin stored at 4 °C for up to 60 days and reported that the 550 MPa/10 min treatment was suitable for significant inactivation of microorganisms. Although this treatment decreased vitamin C and RS content, color parameters, hardness and antioxidant activity, it proved to be the best method for maintaining the antioxidant capacity, bioactive compounds content, and sensory properties of pumpkin. Furthermore, this treatment had no significant effect

on TSS, pH, drip loss, sucrose, and total phenolics. The texture of fresh-cut products is an important factor, and considering that HHP can affect it, studies have been mainly conducted on this topic. Hu et al. (2020) investigated changes in texture and microstructure of cells of fresh-cut pumpkin treated with HHP (100–600 MPa/2 min). According to the authors, HHP caused changes in pectin characteristics, membrane integrity, and tissue morphology, but provided better preservation of color, hardness, relative electrical conductivity, and degree of pectin esterification, compared to thermal treatment. Zong and An (2009) reported inhibited polygalacturonase activity, reduced hydrolysis of non-water-soluble pectin and preserved firmness of fresh-cut jujube fruit, which were treated with HHP (600 MPa/10 min) and stored (9 days/4 °C). Trejo Araya et al. (2007) treated fresh-cut carrot cylinders of cortex material with HHP (100-550 MPa/2, 10 and 30 min), and reported significant hardness loss, even for 50% when 300 MPa was applied, but higher pressures did not result in greater texture loss. Furthermore, they found a linear correlation between tissue hardness and the degree of cell wall breakage during cutting. Consequently, the texture changes were primarily linked to the loss of turgidity caused by the HHP applied. In addition, it was found that changes in pectin methylesterase and degree of methylation did not significantly contribute to alterations in texture. Fresh-cut cubes of the Hachiya persimmon were treated with HHP (200–400 MPa/3 min, 25 °C) and stored for 28 days at 4 °C. (Vázquez-Gutiérrez et al., 2016). The authors observed diffusion of soluble compounds released due to cell wall and membrane damage, leakage of electrolyte, alterations in texture, total soluble solids, pH, and color. These changes were dependent on the applied pressure of the HHP. However, it appears that an HHP of 200 MPa enhances carotenoid extractability and tannin polymerization. Similarly, application of HHP (600 MPa/10 min) to packaged fresh-cut melon improved β-carotene content, but reduced vitamin C content, which was cultivar dependent (Wolbang et al., 2008). Queiroz et al. (2010) investigated the effect of HHP (250 and 400 MPa/5 min) on fresh-cut cashew apples, stored for 24 h at 2 or 27 ℃ and reported a decrease of ascorbic acid, soluble polyphenols and antioxidant capacity, and altered phenolic acids profile during storage, due to the effect of HHP. In addition, HHP treatments caused a significant color difference and HHP of 250 MPa enhanced PPO activity, so HHP of 400 MPa and storage at 2 ℃ was found to be the most effective method.

There are few studies on the effect of HHP on potato tubers or FCP, mostly in recent years. Tsikrika et al. (2021) applied HHP (600 MPa/3 min/10.6 °C) to VP potato tubers cv. Maris Piper and cv. Rooster, which were then stored at 4 ℃ for 14 days. They found a complete inactivation

of Enterobacteriaceae and a significant initial reduction in aerobic plate count. However, at the end of the storage, HHP and control samples had similar aerobic counts. According to the authors, a significant decrease in content of glycoalkaloids was observed. In addition, decreased content of chlorogenic acid was observed due to the effect of HHP, but the total phenolics content remained unchanged. The results of study by Tsikrika et al. (2019) showed that the total phenolics content increased under the same conditions (600 MPa/3 min). In addition, chlorogenic acid content was significantly decreased, followed by an increase in caffeic acid content (as its constituent) and *p*-coumaric acid content. HHP can damage tuber and cell structure, and therefore affect the firmness of treated samples (Oliveira et al., 2015; Procaccini et al., 2022). According to Dourado et al. (2020), who applied HHP (0.1, 100, 200 and 400 MPa /5 min) to potato sticks immersed in water or asparaginase solution, applied HHP of 100 MPa did not significantly affect the firmness of the potato sticks. However, the application of HHP of 200 and 400 MPa resulted in a decrease in firmness. Procaccini et al. (2022) treated FCP with 200 MPa/2, 6, 10 min and 400 MPa/1, 2 and 6 min, among other treatments, and reported reduced microbial load compared to the control, but also increased PPO activity, which was more pronounced with longer treatment time, and negative effects in terms of enzymatic browning (lowest L^* values) and hardness. Tsikrika et al. (2021) reported similar results for the L^* value changes during storage. Lower L^* values indicate browning of the tissue. As a result of the applied pressure for a longer time, the release of membrane-bound enzymes is possible, as well as their better interaction with the substrates (Oliveira et al., 2015), resulting in more pronounced browning. Complete inactivation of PPO with HHP (400 MPa/15 min/20 °C) was achieved, using dilute citric acid solution (0.5 or 1.0%) as immersion medium (Eshtiaghi and Knorr, 1993). During frying, the potentially carcinogenic acrylamide is formed. RS are precursors in its formation, so changes in sugar content can affect acrylamide levels. Dourado et al. (2020) found no significant effect of HHP applied on raw potatoes, on the acrylamide content in subsequently fried potatoes. However, the combined treatment asparaginase + HPP resulted in a significantly lower acrylamide content. The oil content of fried potatoes can be influenced by HHP. HHP treatment (400 and 600 MPa/15 min/20 to 60 °C) resulted in a reduction in the oil content and oil absorption of potato slices after frying compared to untreated or water-blanched samples (Kuldiloke and Eshtiaghi, 2008). On contrary, HHP treatment (200 – 800 MPa/5 min/25 °C/VP) resulted in increased surface and structural oil content compared to control samples (Al-Khusaibi and Niranjan, 2012). Finally, the sensory

properties of HHP-treated and subsequently thermally treated potatoes still need to be explored. Due to the multitude of factors that influence the outcome of HHP treatment, it is crucial to tailor the overall treatment conditions to a specific product to ensure the production of a safe and high-quality food with an acceptable shelf-life.

4. Effect of cooking on the properties of FCP

The potato is a food that is not consumed raw, but must undergo heat treatment (cooking). However, cooking has an effect on various properties of the potato. Due to the gelatinization and the change in structure, the starch becomes partially digestible and the tissue becomes softer. In addition, cooking leads to significant changes in chemical compositions and affects the bioavailability of bioactive compounds (Yang et al., 2016). Some aroma compounds are formed, which produce desirable taste and odor. Furthermore, cooking destroys microorganisms and reduce glycoalkaloids content (EFSA, 2020). However, heat treatment creates conditions for the formation of harmful components such as acrylamide or PAH. While PAH can also be found in raw potatoes (Abou-Arab et al., 2014), acrylamide is produced by heat treatment at high temperatures. Therefore, the choice of cooking method should consider the general overall characteristics of the potato cultivars, as well as the desired properties of the cooked products.

Thermal processing leads to changes in the content of nutrients and bioactive compounds. Fang et al. (2022) reported negative effects of cooking potatoes on vitamin C content, as did Tian et al. (2016b), which is to be expected since vitamin C is water-soluble and unstable when exposed to air, light, and heat. However, the rate of reduction was dependent on the cooking method. The mineral content is reduced by cooking; a decrease in the content of K, P, Mg, S, Zn, Mn and Fe was found by boiling (Bethke and Jansky, 2008), while a higher content of minerals such as Zn, Mg, Na and Ca was retained after frying, compared to boiling (Ikanone and Oyekan, 2014). An increased content of proteins, amino acids, and fibers was found in fried potatoes (Murniece et al., 2011). Through the process of frying, the protein content is elevated as a result of water evaporation and the increase in DM. Furthermore, the content of carotenoids, glycoalkaloids and nitrates decrease during thermal treatment (Fang et al., 2022; Rytel et al., 2015).

Cooking also affects the phenolic content, but the results of previous research vary. Faller and Fialho (2009) found an increase in phenolics content by 81.4 % during boiling. This may be

due to damaged cell walls and/or the release of phenolics through the breakdown of bonds with dietary fiber. This facilitates the enhanced extraction of phenolics from the cells. In contrast, Lemos et al. (2015) found a decrease of phenolics in baked, boiled, microwaved and steamed potatoes. Fang et al. (2022) also found reduced content of total phenolics and phenolic acids caused by all cooking methods, but this was more pronounced by frying, air-drying and roasting than that of steaming or microwave cooking, regardless of potato varieties Similar effects of cooking on total phenolics content were found by Perla et al. (2012), and on total flavonoids and caffeic acid derivates by Tudela et al. (2002), for different cooking methods. As phenolics are water-soluble and may degrade at higher temperatures or participate in Maillard's reactions, their content may decrease. Different results may be due to the different cooking methods, temperatures and cooking time, but also to the characteristics of cultivar used or pretreatment applied.

Frying produce the potentially carcinogenic acrylamide, the limit of which in potato products is 750 µg kg^{-1} according to the EU Commission Regulation (2017/2158) (EU, 2017). There are several ways prior FCP processing to reduce acrylamide content such as using cultivars with lower content of RS and asparagine, using undamaged tubers, storing at temperatures higher than 6 °C, controlling relative humidity and using of sprout inhibitors (EU, 2017). Various treatments of potatoes were found to influence the acrylamide content, e.g., peeling, blanching of FCP to remove some of the RS from the surface, treatment with enzyme asparaginase, immersion in sodium chloride solution, treatment with extracts of natural antioxidants as well as with amino acids. In addition, harmful PAH may be found in fried potatoes. Although they are present in small quantities in raw potatoes, their content in fried potatoes can be influenced by the frying conditions and properties of the frying oil used.

The desired texture of cooked FCP depends primarily on the starch content of the potato. Starch is found inside the cells of potato tubers in the form of starch grains, which differ in size and shape. Mealy potatoes contain a high starch content and larger and more irregularly shaped cells then waxy potatoes (McComber et al., 1994). The cells of mealy cooked potatoes retain gelatinized starch and the cell shapes are better preserved after mashing than those of the waxy potatoes (McComber et al., 1994). The gelatinization of the starch during cooking can also cause the cells to expand and burst, absorbing water and contributing to the waxy texture of the potato. Therefore, mealy potatoes are suitable for baking and frying and waxy potatoes for boiling. In addition to starch, the change in texture of cooked potatoes is also affected by non-enzymatic and

enzymatic changes in pectin, where the enzymatic degradation of cell wall pectin is catalyzed by pectinase enzymes (such as pectinmethylesterase) resulting in short demethylation of pectin chains and drastic texture variations (García-Segovia et al., 2008). Ideal temperature range for pectinmethylesterase activity is between 50 and 80 °C (García-Segovia et al., 2008).

The flavor of the potato can be described by taste, aroma and texture. The earthy flavor (characteristic potato-like odor) of raw potatoes can be attributed to methoxypyrazines, such as 2-isopropyl-3-methoxypyrazine, which are cultivar-dependent, and have extremely low threshold (Duckham et al., 2002; Jansky, 2010; Oruna-Concha et al., 2001). However, numerous compounds have been identified that influence potato flavor. In addition, the development of flavor compounds is induced by cutting and heating (Dresow and Böhm, 2009). During cooking of potatoes, reactions such as the degradation of lipids, Maillard's reactions between sugars and amino acids, and Strecker degradation of methionine take place, leading to the formation of flavor compounds (Duckham et al., 2002; Oruna-Concha et al., 2001). However, there are many factors that influence the development of flavor compounds such as cultivar, processing and storage conditions. The taste of boiled potatoes is influenced, among others, by non-volatile substances such as 5´-ribonucleotides (inosine 5´- monophosphate and guanosine monophosphate). These compounds improve the flavor and mouthfeel and are responsible for the umami taste. Methional is a distinctive compound in the aroma of cooked potatoes (formed by the Strecker degradation of methionine), while aldehydes and ketones (produced by degradation of lipids) contribute to fatty, fruity and floral flavors (Duckham et al., 2002). In addition, Bough et al. (2020) identified several potential biomarkers (aldehydes, ketones and alcohols) responsible for desirable flavor attributes such as buttery and sweet attributes and the characteristic potato flavor. Sugars impart sweetness of potato, and, along with amino acids, are responsible for developing the flavor of fried potatoes in non-enzymatic Maillard reactions, and participate in the formation of a dark brown color.

5. Hypothesis, research objectives, and expected scientific contributions

Research hypotheses are:

(i) UV-C irradiation and HHP treatments reduce the TAMBC and slow down their growth during storage of FCP, thus maintaining product quality and extending shelf-life. The effectiveness depends on the UV-C and HHP treatment conditions;

(ii) UV-C and HHP treatments and storage affect sugars and phenolics content in raw FCP and the acrylamide content in fried FCP, on which the safety of the product will also depend;

(iii) storage time affect microbiological, physical and chemical and sensory properties of raw FCP and increase acrylamide content in fried potatoes.

In order to confirm or reject the established hypotheses, the following objectives are defined:

(i) to examine the effects of different UV-C irradiation and HHP treatment conditions on the quality and shelf-life of FCP, based on their effects on microbiological stability, resistance to browning, texture and sensory properties before and after thermal treatment;

(ii) to examine the effects of UV-C irradiation, HHP treatment and storage times on sugar and phenolic content in raw FCP and on acrylamide in subsequently fried FCP;

(iii) to gain knowledge which of examined treatments could be applied to FCP in order to maintain the desired quality and safety and ultimately extend shelf-life.

This research is divided into four parts that are systematically linked:
In the first part of the research, the effect of different UV-C irradiation doses and storage time on the microbiological safety, quality and sensory properties of the raw FCP as well as on the sensory properties of the subsequently thermally treated samples were examined (*Publication No.1*).
In the second part of the research, the effect of different doses of UV-C irradiation and the storage time of FCP on the chemical composition was examined. The changes in the content of phenolics,

glucose, fructose and sucrose in raw and subsequently thermally treated FCP and in the acrylamide content in subsequently fried potatoes were examined *(Publication No. 2).*

In the third part, the effect of HHP treatment at different treatment times and the effect of the storage time of FCP on the microbiological safety, quality and sensory properties of raw FCP, and on the sensory properties of subsequently thermally treated samples was examined *(Publication No. 3).*

In the fourth part of the research, the effect of UV-C irradiation, HHP, combined treatment (UV-C/HHP) and storage time on the quality, chemical composition and sensory properties of raw FCP, on the sensory properties of subsequently thermally treated FCP and on the content of acrylamide and PAH in subsequently fried samples was examined *(Publication No. 4).*

In a view of the complexity of the topic, a very extensive literature search was necessary, which led to the publication of a review paper *(Publication No. 5).*

Within the scope of this dissertation the following issues were examined:

1) The effect of UV-C irradiation doses of 0, 1.62, 2.70 and 5.40 kJ m^{-2} on the microbiological safety, quality and sensory properties of raw FCP stored at 6 °C for up to 23 days, as well as on the sensory properties of subsequently boiled (in water at 100 °C, 15 min) and fried (in sunflower oil at 180 °C, 5 min). FCP was produced from potato tubers (*Solanum tuberosum* L.) of cv. Birgit, treated with SA (2%) for 3 min, VP and treated with UV-C *(Publication No. 1).*
2) The effect of UV-C irradiation doses of 0, 1.62, 2.70 and 5.40 kJ m^{-2} on the chemical composition (phenolics, glucose, fructose and sucrose content) of raw, boiled and fried FCP and on the acrylamide content in the subsequently fried FCP. The FCP prepared in the first part of the study was used for this investigation *(Publication No. 2).*
3) The effect of HHP treatments (400 MPa/0, 3, 5 and 10 min) on the microbial safety, texture, color and sensory properties of raw FCP stored at 6 °C for 15 days. FCP is prepared from tubers of cv. Birgit, placed in containers filled with 2% SA solution, which were then sealed and treated with HHP. After treatment, the slices are drained, VP and stored (6 °C/15 days) *(Publication No. 3).*

4) The effect of a UV-C dose of 2.70 kJ m^{-2}, HHP (400 MPa, 3 min) and the effect of combined treatment (first UV-C/2.70 kJ m^{-2}, then HHP/400 MPa, 3 min) on the microbiological safety, quality, sensory properties and chemical composition (phenols, fructose, glucose and sucrose) of raw FCP, stored at 6 °C for up to 23 days, and on the sensory properties of boiled (100 °C/15 min) and fried (180 °C/5 min) FCP, and acrylamide and PAH content in fried FCP. FCP is produced from the Birgit cultivar, treated with SA (2%) for 3 min, VP and UV-C and HHP treated *(Publication No. 4).*

The following was achieved through this dissertation:

1) knowledge of the influence of different conditions of UV-C irradiation and HHP treatment, and storage time, on the quality, safety and shelf-life of FCP
2) knowledge of the changes in the chemical constituents of raw FCP due to the influence of UV-C irradiation and HHP and their influence on the content of primary acrylamide and also PAH in fried FCP
3) knowledge of sensory changes in UV-C and HHP treated FCP prepared for consumption
4) the optimal conditions for UV-C and HHP treatment were determined under the conditions of this experiment for the production and storage of FCP to achieve adequate quality and shelf life
5) contribution to the updating the production of FCP, with the aim of increasing knowledge on the safety and quality of FCP through the use of innovative technologies

Chapter 2

Publications

Publication No 1: Effect of UV-C Irradiation on the Shelf Life of Fresh-Cut Potato and Its Sensory Properties after Cooking

*Food Technology and Biotechnol*ogy

1. *Publication No 1:*

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Zrinka Čošić: Investigation, Writing − review and editing

Kata Galić: Investigation

Mario Ščetar: Investigation

Maja Repajić: Formal analysis, Revision

Sandra Pedisić: Writing − original draft

Zorić Zorić: Formal analysis

Branka Levaj: Conceptualization, Data interpretation, Revision, Writing – review and editing

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Effect of UV-C Irradiation on the Shelf Life of Fresh-Cut Potato and Its Sensory Properties after Cooking

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SUMMARY

Research background. Potato tissue is damaged during fresh-cut production, which makes fresh-cut potato susceptible to the quality loss and microbiological spoilage. At the same time, such products are desirable due to their convenience; however, they are extremely sensitive and have short shelf life. The main challenge of the fresh-cut potato industry is to find possibilities to overcome these drawbacks. UV-C treatment, known for its antibacterial activity, is a promising technique and it shows a potential to improve shelf life of fresh-cut potato products.

Experimental approach. The influence of the UV-C treatment on the safety and quality, as well as sensory traits of fresh-cut potato (*Solanum tuberosum* L. cv. Birgit) during storage was examined. For this purpose, 0-, 3-, 5- and 10-min UV-C irradiation was applied on vacuum-packed potato slices pretreated with sodium ascorbate solution. During 23 days of storage at (6±1) °C, microbiological, physicochemical and sensory properties of raw samples were monitored, along with sensory properties of boiled and fried fresh-cut potatoes.

Results and conclusions. The 5- and 10-min UV-C treatments significantly reduced microbial growth, increased total solids and lightness (*L**), and positively affected odour and firmness of raw potatoes. Cooked UV-C-treated samples were described with more pronounced characteristic potato odour and taste. Overall, UV-C-treated fresh-cut potato retained its good quality and sensory traits up to 15 days at (6±1) °C.

Novelty and scientific contribution. To the best of our knowledge, this is the first scientific article dealing with the effect of UV-C light on durability (safety, quality and sensory traits) of fresh-cut potato cv. Birgit and its suitability for boiling and frying. In general, UV-C treatment is a known antimicrobial technique, but its application on fresh-cut potato is poorly explored. Results confirmed that vacuum-packed fresh-cut potato treated only with UV-C and sodium ascorbate as anti-browning agent, without the addition of chemical preservatives, had twofold longer shelf-life at (6±1) °C than the fresh-cut potato not treated with UV-C. Fresh-cut potato treated with UV-C retained good overall quality and sensory properties either raw, boiled or fried. Results of this study could also be useful for producers in terms of potential UV-C application as a strategy for prolonging the shelf-life of fresh-cut potato.

Keywords: potato cv. Birgit; firmness; CIELAB colour; sodium ascorbate treatment; vacuum packaging; principal component analysis (PCA)

INTRODUCTION

The popularity and commercial importance of the fresh-cut products are growing due to extreme convenience for the preparation of home meals, catering industry and in many other food services. The processing of fresh-cut fruits and vegetables includes only washing, trimming, peeling and/or cutting and packing to maintain their freshness and high nutritional value (*1*). During that process they are susceptible to microbial growth, water loss, off-odour, tissue softening, browning and general loss of quality, which makes them very perishable and limits their shelf life (*2*). During processing of fresh-cut products,

enzymes and their substrates are delocalized due to cell integrity damage, which results in higher enzymatic activity responsible for oxidative reactions. These reactions lead to the formation of brown melanoid pigments (*3*).

Fresh-cut potato is a potentially interesting potato product (*4*) and many studies are focused on finding solutions to preserve the quality and safety of fresh-cut potato and to extend its shelf life. For this purpose, appropriate cultivar, antimicrobial and antibrowning agents, packaging materials and conditions as well as storage conditions have been investigated (*5*,*6*). According to our latest published study, fresh-cut potato cv. Birgit pretreated with sodium ascorbate solution and vacuum-packed showed promising results during 8 days of storage at 10 °C (*5*). Besides the above-mentioned approach, non-thermal UV-C technology has been investigated, especially in terms of prolonging shelf life by preventing microbial growth and enzyme activity (*7*). Antimicrobial effect of UV-C has a maximum effect at 254 nm and its effectiveness is based on structural changes in the DNA of microorganisms, caused by cross-linking between pyrimidine bases, which consequently contributes to the inability of transcription and replication of the cells (*8*). However, the irradiated plant tissue can be damaged using high UV-C doses (*9*). Besides, effectiveness of UV-C irradiation against enzyme activity depends on the applied dose and the sensitivity of enzymatic proteins, which is highly correlated with their nature (*10*,*11*). By exposing the enzyme to irradiation, their spatial structure can change, enabling better exposure of active sites, which leads to an initial increase in the enzyme activity (*12*). Thus, to extend the shelf life of fresh-cut products, it is necessary to evaluate the optimal doses of UV-C irradiation considering plant properties and the already mentioned antibrowning agents, packaging materials and packaging conditions, as well as storage conditions.

According to Teoh *et al*. (*6*), the optimal UV-C dose was 684 mJ/cm^2 for potato slices dipped in ascorbic acid and calcium chloride solution, closed in permeable plastic boxes and stored for 10 days at 4 °C. This dose decreased the activity of polyphenol oxidase, phenylalanine ammonia lyase and peroxidase. Moreover, a significant decrease in browning and enzyme activity as well as increase in firmness were observed in the study of Xie *et al*. (*13*), where potato slices were treated with sodium acid sulphate, irradiated with UV-C for 3 min and stored in polyethylene bags for 25 days at 4 °C.

Selection of the packaging material is also very important, particularly if slices are packed and then UV-C treated. The permeability of materials to UV-C irradiation depends on the type of the used polymers as well as on its thickness. It was found that 40 µm thick polyamide/polyethylene laminate was permeable for 80 % UV-C irradiation (*11*).

Furthermore, UV-C treatment showed a positive effect on soft rot prevention in potato seed tubers (*14*). Also, irradiation of tubers reduced the accumulation of fructose and glucose during cold storage, which consequently reduced the formation of toxic acrylamide during frying (*15*) and increased brightness of the fries (*16*).

However, although there is a number of studies that have dealt with the quality properties of cooked potatoes without UV-C treatment (*17*,*18*) or with UV-C pretreatment of tubers (*16*,*19*–*21*), reports regarding the effect of UV-C light on the quality and sensory attributes of raw and cooked fresh-cut potatoes are scarce.

Therefore, the aim of this study is to investigate the effect of different UV-C irradiation doses and 23 days of storage at (6±1) °C on microbial growth, quality and sensory properties of fresh-cut potato cv. Birgit, pretreated with sodium ascorbate solution and vacuum packed, as well as on the sensory properties of fresh-cut potatoes after boiling and frying.

MATERIALS AND METHODS

Plant material

Potato (*Solanum tuberosum* L.) tubers of cv. Birgit were harvested in Slavonia region, Croatia (45°40'N, 17°1'E) during 2019, treated with anti-sprouting agent (Gro Stop Basis and Gro Stop Fog, Certis Europe, Great Abington, UK) and stored for one month in the dark (8 °C and relative humidity approx. 100 %) before analysis.

Sample preparation

Undamaged and uniform potato tubers were selected, washed, drained, hand-peeled and sliced (0.4 cm) using a commercial slicer (SFS 1001 GR; Sencor, Říčany, Czech Republic). Immediately after slicing, potatoes were dipped in sodium ascorbate solution (2 %, *m/V*) for 3 min according to the procedure described by Dite Hunjek *et al*. (*18*). After draining, potato samples (4–6 slices) were vacuum packed (SmartVac SV 750; Status, Metlika, Slovenia) in a single layer in the polyamide/polyethylene (PA/PE) double-layered (100 and 130 µm) vacuum pouches (Status).

UV-C treatment

The potato slices were treated in an UV-C chamber (UVpro EKB 100; Orca GmbH, Kürten, Germany) equipped with 4 UV-C lamps (4×HNSL 24 W, maximal emission at 253.7 nm; UVpro). The samples were irradiated for 0 (control), 3 (3-UV-C), 5 (5-UV-C) and 10 min (10-UV-C) to obtain doses of 0, 162, 270 and 540 mJ/cm^2 outside and 0, 108, 180 and 360 mJ/cm^2 inside the vacuum bags (UVC *pro* radiometer; Orca GmbH). Afterwards, the untreated and UV-C-treated samples were stored at (6±1) °C and analysed at the beginning of the storage (day 0), on the 8th day, because in our previous study (*5*) we found that 8-day stability can be achieved using vacuum packing and sodium ascorbate treatment (under the same conditions as described in the paragraph *Sample preparation*), and on the 11th, 15th and 23rd days of storage. Experiment was done in duplicate.

Determination of oxygen permeability of packaging

Oxygen permeability ($cm^3/(m^2 \cdot day \cdot kPa)$) of packing was determined using manometric method on a permeability tester (GDP-C; Brugger Feinmechanik GmbH, Munich, Germany). The increase in the pressure during the test period was evaluated and displayed by an external computer. Data were recorded and permeability was calculated automatically. The sample temperature (23±1) °C was adjusted using an external thermostat (Haake F3 K circulating water bath chiller/heater; Haake GmbH, Karlsruhe, Germany). All measurements were carried out in duplicates.

Microbiological analysis

Total aerobic mesophilic bacteria count (TAMBC) was determined at 30 °C according to HRN EN ISO 4833-1:2013 method (*22*). Dilutions were made with peptone water (0.1 %, *m/V*) and surface plated (1 mL) in duplicate on a plate count agar (Biolife, Milan, Italy). The plates were incubated at (30±1) °C for (72±3) h in dry heat oven (FN-500; Nüve, Ankara, Turkey). Analyses were performed on raw samples and the results were expressed as mean value of log CFU/g.

Determination of total solids, soluble solids and pH

The raw potato slices were homogenized (MSM89160 blender; Robert Bosch GmbH, Gerlingen-Schillerhöhe, Germany) and used for determination of total solids, soluble solids and acidity. Total solids were calculated as a percentage of the mass ratio before and after drying potato samples at (105±1) °C (FN-500; Nüve) to a constant mass, while soluble solids were determined by a digital refractometer (DR201-95; A. Krüss Optronic GmbH, Hamburg, Germany) at 20 °C and expressed as °Brix (g/100 g). The pH was measured by a pH meter (WTW Lab pH meter inoLab® pH 7110; Xylem Analytics Germany GmbH, Weilheim, Germany). All measurements were carried out in duplicates and results were expressed as mean value±standard error (S.E.).

Firmness analysis

The firmness of raw fresh-cut potato samples was determined using a texture analyser (Fruit Texture Analyzer, Agrosta, Serqueux, France) with 5 kg load cell and 2 mm punch probe. High and low speeds were set to 1 mm/s and stroke after contact to 2 mm. Firmness was determined by measuring the maximum force (N) required to puncture the slices. The measurements were performed on two slices of each sample with 2 punctures on each slice and the results were expressed as mean value±S.E.

Colour analysis

The colour of raw fresh-cut potato slices was measured by a colorimeter (CR-5; Konica Minolta, Tokyo, Japan), equipped with D65 light source and 2° standard observers using CIELAB colour parameters: L^* (lightness), a^* (red/green) and b^* (yellow/blue). Measurements were performed on two slices of each sample and results were expressed as the mean value±S.E.

Cooking treatments

Immediately after the treatment and on the 8th, 11th, 15th and 23rd day of storage, raw samples were cooked according to Dite Hunjek *et al.* (*18*). Samples were boiled in distilled water Φ(water, sample)=5:1 at 100 °C for 15 min. Other samples were fried in sunflower oil (m(sample)/V(oil))=120 g/L at initial temperature of 180 °C for 5 min. The surface moisture and oil of cooked potatoes were removed with paper towel.

Sensory monitoring

Quantitative descriptive analysis (QDA) of raw, boiled and fried potato samples was conducted in a sensory laboratory equipped according to the ISO 8589:2007 (*23*) guidelines at ambient temperature (20 °C) by a panel of six trained people from the faculty and according to the ISO procedures 6658:2017 and 8586:2012 (*24*,*25*). Panellists had 3-day training before the evaluation in order to get acquainted with the product sensory descriptors and its evaluation. The panellists judged the quality and ranked each sample served at ambient temperature on coded plastic plates using a standard five-point scale from 1 (the lowest grade) to 5 (the highest grade) as described by Dite Hunjek *et al.* (*5*,*18*). Briefly, colour, as the browning intensity, was scored as follows: 1=no browning (white or cream), 2=no browning (yellow), 3=light browning, 4=average browning and 5=complete browning. Intensity of odour and off-odour was described as follows: 1=absent to 5=very pronounced, moistness from 1=very dry to 5=very moist and firmness from 1=very soft to 5=very firm. Additional sensory attributes of boiled and fried potatoes were evaluated: potato-, sweet, sour, salty, bitter and off-taste from 1=absent to 5=very pronounced. Creaminess of boiled potato was scored from 1=absence of creamy texture to 5=melting in the mouth, while oiliness and crispness, as fried potato attributes, were graded with 1=absent to 5=very pronounced. All tested attributes are given in the tables as mean value±S.E. (N=6).

Statistical analysis

The statistical analysis by parametric statistical tests was carried out to observe the effect of the UV-C treatment and storage time on the quality properties of raw, boiled and fried potato. The TAMBC, soluble solids, total solids, pH, firmness, colour parameters and sensory attributes were dependent measurable variables, while UV-C treatment and storage time were independent variables. Dependent variables were analysed by multivariate analysis of variance (MANOVA), while differences between specific group means (equal sample sizes) were determined by applying Tukey's HSD test. The analysis was performed using Statistica v. 8.0 software (*26*). In

order to examine possible grouping of the samples, principal component analysis (PCA) was performed on the correlation matrix using XLSTAT v. 5.1 software (*27*), wherein principal components (PC) with eigenvalue >1 and variables with communalities ≥0.5 were considered. The significance level for all tests was $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Influence of UV-C treatment on permeability of packing material

Although a slight increase of permeability of packing material (1200 and 1300 $cm^3/(m^2 \cdot day \cdot kPa)$) was noticed for the samples 5-UV-C and 10-UV-C, respectively, this was not significantly different from control (900 $cm^3/(m^2 \cdot day \cdot kPa)$; data not shown). Sample 3-UV-C had identical value as the control. Tarek *et al.* (*28*) also concluded that the applied UV-C doses of 46.7–746 mJ/cm (for 0.5 to 8 min at 23 °C) did not affect surface properties of polyethylene (PE) film used for cucumber packing. It was also found that UV-C transmittance through polymeric films depends on their characteristics (such as thickness, composition, level of crystallinity and number of layers in the film). Thus, for example PE film (24.7 μm) shows transmittance of 75.5 %, multilayer films composed of six or more layers exhibit 0 % transmission (*29*), while PA/PE laminate is 80 % permeable to UV-C (*11*), similar to polypropylene film (*30*). Although the effect of UV-C treatment on polymeric films has been investigated by several authors (*30*,*31*), it seems that this treatment does not affect barrier properties (*28*), while different observations were noticed for the mechanical and surface morphology of the polymers (*29*,*31*).

Aerobic mesophilic bacterial count affected by UV-C treatment and storage time

The TAMBC in untreated and UV-C-treated raw fresh-cut potato during storage is presented in **Fig. 1**. Statistical results showed significant differences ($p<0.01$) in TAMBC among fresh-cut potato samples. The initial microbial load of control sample was 2.30 log CFU/g. At the beginning of the storage, the lowest TAMBC was noticed in 10-UV-C samples (2.18 log CFU/g). When comparing all UV-C treatments with control throughout the storage period, the significant log CFU/g values decreased in 5- and 10-UV-C samples, especially until the 15th day. On that day, measured values for 5- and 10-UV-C samples were 8.36 and 8.17 log CFU/g, respectively. These results indicated that UV-C treatment longer than 5 min did not significantly improve the decontamination effect. Similar results were reported in a study of Manzocco *et al.* (*32*) on fresh-cut melon cubes. The possible reason could be low UV-C light transmittance through the tissue as well as the rough surface of the fresh-cut product, which can partially overshadow the microorganisms and thus reduce the effect of radiation (*32*,*33*). At the end of storage, all applied UV-C treatments were equally effective on TAMBC reduction in fresh-cut potatoes compared to the control. However, it should be mentioned that for this type of foodstuff (fresh-cut potato intended for further cooking) there is no information provided by the EC regulations (*34*,*35*) related to microbiological criteria regarding TAMBC. Similarly, the Croatian Agency for Agriculture and Food (*36*) issued borderline level of TAMBC only for ready-to-eat vacuum packed and refrigerated vegetables, and it is $\geq 10^8$ CFU/g.

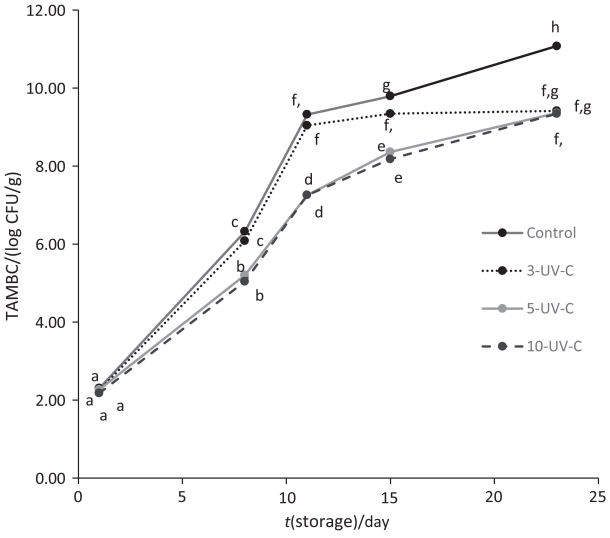

Fig. 1. Total aerobic mesophilic bacteria count (TAMBC) of untreated and UV-C-treated raw fresh-cut potatoes during storage, expressed as mean values of log CFU/g ($p<0.01$, $\alpha \leq 0.05$). 3-, 5- and 10-UV-C=samples treated with UV-C for 3, 5 and 10 min respectively

Effect of UV-C treatment and storage time on total and soluble solids, and pH of fresh-cut potato

As presented in **Table 1**, total solid content was affected by UV-C treatment ($p=0.046$), while storage time did not have a significant influence ($p=0.054$). Mean value of total solids in control sample was 21.7 %. The highest values were obtained in 10–UV-C samples (23.2 %) and generally on the 11th day of storage (23.1 %). With regard to the UV-C treatment, all treated samples had higher total solid content, which increased with the increase of UV-C dose. The grand mean value of total solids was 22.24 %, which was quite similar to that already reported (20.72 %) by Dite Hunjek *et al.* (*5*) for cv. Birgit potatoes (harvested in 2018). The slight differences could be a result of different treatment, as well as crop year or growing conditions (*37*). Total solid content obtained in the present study represents an acceptable value in terms of frying, considering that potato dry matter content of 20–24 % is appropriate for chips (*38*). Higher potato dry matter will result in harder crust and drier potato inside texture (*39*).

However, the UV-C treatment and storage time had a significant influence ($p \leq 0.01$) on total soluble solid content, which varied from 4.18 to 4.80 g/100 g (°Bx) (**Table 1**). In comparison with control (4.59 g/100 g), the total soluble solid

Table 1. The influence of UV-C treatment and storage time on total soluble (TSS) and total solids, pH, firmness and colour parameters of raw fresh-cut potatoes

Source of variation	*w*(total solid)/%	TSS/(g/100 g)	pH	Firmness/N	*L**	*a**	*b**
Treatment	p=0.05*	p=0.01*	p<0.01*	p<0.01*	p<0.01*	p=0.22	p=0.33
Control	(21.7±0.4)^{a}	(4.59±0.06)^{b}	(5.64±0.01)^{c}	(7.77±0.09)^{c}	(71.8±0.4)^{ab}	(1.6±0.2)^{a}	(40.0±0.9)^{a}
3-UV-C	(21.9±0.4)^{ab}	(4.58±0.06)^{ab}	(5.63±0.01)^{bc}	(7.00±0.09)^{a}	(71.1±0.4)^{a}	(1.4±0.2)^{a}	(38.4±0.9)^{a}
5-UV-C	(22.2±0.4)^{ab}	(4.44±0.06)^{a}	(5.59±0.01)^{ab}	(7.35±0.09)^{ab}	(73.2±0.4)^{b}	2.0±0.2)^{a}	(40.3±0.9)^{a}
10-UV-C	(23.2±0.4)^{c}	(4.30±0.06)^{a}	(5.57±0.01)^{a}	(7.37±0.09)^{b}	(73.0±0.4)^{b}	(2.0±0.2)^{a}	(40.5±0.9)^{a}
t(storage)/day	p=0.05	p<0.01*	p<0.01*	p=0.14	p=0.38	p=0.10	p=0.25
0	(21.9±0.1)^{a}	(4.80±0.07)^{b}	(5.99±0.01)^{d}	(7.4±0.1)^{a}	(71.6±0.5)^{a}	(1.7±0.3)^{a}	(4077±1.0)^{a}
8	(21.8±0.4)^{a}	(4.40±0.07)^{a}	(5.62±0.01)^{c}	(7.5±0.1)^{a}	(72.8±0.5)^{a}	(2.2±0.3)^{a}	(39.9±1.00)^{a}
11	(23.1±0.4)^{a}	(4.26±0.07)^{a}	(5.51±0.01)^{b}	(7.4±0.1)^{a}	(71.9±058)^{a}	(1.3±0.3)^{a}	(39.6±1.0)^{a}
15	(21.6±0.4)^{a}	(4.18±0.07)^{a}	(5.42±0.01)^{a}	(7.2±0.1)^{a}	(72.6±0.5)^{a}	(219±0.3)^{a}	(41.0±1.0)^{a}
23	(22.9±0.4)^{a}	(4.75±0.07)^{b}	(5.50±0.01)^{b}	(7.3±0.1)^{a}	(72.4±0.5)^{a}	(1.5±0.3)^{a}	(37.9±1.0)^{a}
Grand mean	22.24	4.48	5.61	7.37	72.24	1.74	39.80

*Statistically significant variable at α≤0.05. Results are expressed as mean value±S.E. Different letters in the same column mean statistically different values at α≤0.05. 3-UV-C, 5-UV-C and 10-UV-C=samples treated with UV-C for 3, 5 and 10 min respectively

content decreased with the increase of UV-C dosage, where the lowest value was measured in 10-UV-C sample (4.30 g/100 g). These results are in accordance with the results of Islam *et al.* (*40*), who treated tomatoes with UV-C. This could be related to the impact of UV-C on conjugated structural bonds of some soluble solids, which leads to their degradation or alteration (*41*). In this study, a significant decrease in soluble solid content was observed after 8 days of storage (4.40 g/100 g), after which it remained stable until the end of storage, when it significantly increased. Kasim and Kasim (*42*) also reported oscillations of total soluble solids during storage depending on the applied dose of UV-C on fresh-cut melon cubes.

UV-C treatment and storage time significantly affected the pH of raw fresh-cut potatoes (p<0.01), which ranged from 5.42 to 5.99. When compared to the control (5.64), the lowest pH value was observed in 10-UV-C samples (5.57) and after 15 days of storage (5.42) (**Table 1**). The pH decreased with the increase of UV-C dosage, similarly to the results of Islam *et al.* (*40*), who also reported an increase of the titratable acidity of treated tomatoes with the increase of UV-C doses. Moreover, pH also decreased during storage probably due to the respiration rate increase and CO_2 production, which is in accordance with the results of Dite Hunjek *et al.* (*5*) and Rocha *et al.* (*43*). Lower pH can contribute to lower enzyme activity and consequently to the reduced intensity of browning (*44*).

Firmness of fresh-cut potatoes influenced by UV-C treatment and storage time

Firmness was significantly affected by the UV-C treatment (p<0.01) without significant effect of storage duration (p=0.14) (**Table 1**). The firmness grand mean value was 7.37 N, which is in accordance with the results for cv. Birgit (7.42 N) (*18*). Control sample was described with the highest firmness value (7.77 N) as well as the samples on the 8th day of storage (7.5 N). The firmness of fresh-cut potatoes was lower in the UV-C-treated samples than of the control. However, increase of the UV-C dose caused firmness increase, which could be linked to the possible reduction of activity of plant cell wall degrading enzymes (*45*). A similar observation was also previously reported when fresh-cut pineapples were treated with UV-C (*46*).

Colour of fresh-cut potatoes influenced by UV-C treatment and storage time

The effect of UV-C treatment and storage time on the colour parameters of raw fresh-cut potatoes is shown in **Table 1**, where it can be observed that UV-C significantly affected only *L** (p<0.01), while storage period had no significant effect on the colour during 23 days (p>0.05). The *L** values were in the range from 71.1 to 73.2, *a** values from 1.4 to 2.0 and *b** values from 38.4 to 40.5 (**Table 1**). The lightness was considerably higher of 5-UV-C and 10-UV-C and lower of 3-UV-C samples than of control. Similar trend was also noticed in UV-C-treated watermelon, where *L** values increased with the increase of the applied UV-C dose (*33*). This occurrence could be associated with the effect of UV-C light on the inactivation of enzymes such as polyphenol oxidase or with reduced carotenoid content (*47*). In this study the parameter *b**, whose positive values describe yellow colour and usually reflect a presence of carotenoids in the potato (*48*), was not significantly reduced. The obtained colour parameters for fresh-cut potatoes are consistent with the European Cultivated Potato Database (*49*) data, where the colour of tuber flesh cv. Birgit is listed as yellow and also very resistant to enzymatic browning.

Sensory attributes of raw, boiled and fried fresh-cut potato affected by UV-C treatment and storage time

Raw fresh-cut potato samples

All sensory attributes of raw fresh-cut potatoes were significantly affected by UV-C treatment and storage time (p<0.05), except moistness (p>0.05) (**Table 2**). The colour was rated from 1.58 in 3-UV-C to 1.98 in control, indicating negligible occurrence of browning. Furthermore, all UV-C-treated

Table 2. The influence of UV-C treatment and storage time on sensory properties of raw fresh-cut potatoes

Source of variation	Browning	Odour	Off-odour	Moistness	Firmness
Treatment	p<0.01*	p<0.01*	p<0.01*	p=0.09	p=0.03*
Control	(1.98±0.04)^{b}	(3.40±0.03)^{a}	(1.53±0.03)^{b}	(1.55±0.02)^{a}	(4.97±0.05)^{b}
3-UV-C	(1.58±0.04)^{a}	(3.47±0.03)^{a}	(1.53±0.03)^{b}	(1.52±0.02)^{a}	(4.75±0.05)^{a}
5-UV-C	(1.66±0.04)^{a}	(3.48±0.03)^{a}	(1.43±0.03)^{b}	(1.50±0.02)^{a}	(4.82±0.05)^{ab}
10-UV-C	(1.65±0.04)^{a}	(3.67±0.03)^{b}	(1.17±0.03)^{a}	(1.50±0.02)^{a}	(4.85±0.05)^{ab}
t(storage)/day	p<0.01*	p<0.01*	p<0.01*	p=0.06	p=0.01*
0	(1.50±0.05)^{a}	(4.00±0.04)^{b}	(1.00±0.03)^{a}	(1.56±0.02)^{a}	(4.65±0.06)^{a}
8	(1.50±0.05)^{a}	(4.00±0.04)^{b}	(1.00±0.03)^{a}	(1.52±0.02)^{a}	(4.92±0.06)^{b}
11	(1.73±0.05)^{b}	(3.98±0.04)^{b}	(1.00±0.03)^{a}	(1.50±0.02)^{a}	(4.90±0.06)^{b}
15	(1.94±0.05)^{c}	(3.98±0.04)^{b}	(1.02±0.03)^{a}	(1.50±0.02)^{a}	(4.88±0.06)^{b}
23	(1.94±0.05)^{c}	(1.56±0.04)^{a}	(3.06±0.03)^{b}	(1.50±0.02)^{a}	(4.90±0.06)^{b}
Grand mean	1.72	3.51	1.42	1.52	4.85

*Statistically significant variable at α≤0.05. Results are expressed as mean±S.E. Different letters in the same column mean statistically different values at α≤0. 3-UV-C, 5-UV-C and 10-UV-C=samples treated with UV-C for 3, 5 and 10 min respectively

samples showed a significant discoloration and were graded as brighter than control, which is in accordance with previously discussed *L** values (**Table 1**). Similar results were also reported by Manzocco *et al.* (*32*). The 10-UV-C samples showed more pronounced odour and less pronounced off--odour than other samples. All UV-C-treated samples were less firm than control, but the most pronounced reduction in firmness was observed for 3–UV-C samples, which is in accordance with the results measured by the instrument (**Table 1**).

During storage, potato colour was scored from 1.50 to 1.94 indicating no degradation in terms of browning. The odour was stable until the 15th day of storage, but at the end of storage the development of off-odour was notable. The lowest firmness was observed at the beginning of storage, but by the end of storage the fresh-cut potatoes maintained uniform firmness. Generally, the results of this study showed that UV-C treatment preserved sensory attributes of colour, odour, moistness and firmness of raw fresh-cut potatoes during 15 days of storage. However due to the off-odour development, the samples were not sensorially acceptable at the end of storage.

Boiled fresh-cut potato samples

Table 3 shows that the majority of the evaluated sensory attributes of boiled potatoes were significantly affected by UV-C treatment and storage duration (p<0.05). Sour, bitter and off-taste were not influenced by storage time nor off--odour and moistness by UV-C treatment (p>0.05). As observed for raw samples, all UV-C-treated samples had brighter colour. The 5- and 10-UV-C samples had more intense boiled potato odour, sweet, salty and potato taste. The desirable boiled potato flavour is a result of many naturally present characteristic compounds (glutamic and other amino acids) and the ones produced during cooking (*e.g.* guanosine--5′-monophosphate and other 5′-ribonucleotides). Many other components such as methional, aliphatic alcohols and aldehydes also contribute to potato flavour. Besides, the desirable flavour of boiled potato derives from 2-isopropyl-3-methoxypyrazine, a compound with extremely low threshold present in raw and boiled potato (*50–52*). Obviously, UV-C treatment did not have a negative impact on flavour compounds, even stimulated their formation or better expression. All UV-C-treated samples had lower firmness and more pronounced creaminess than the control, where higher decrease in firmness and increase in creaminess were noticed when the UV-C dose was increased. The increased UV-C dose could probably induce some structural changes in the potato tissue, which can consequently be observed in a softer texture of the boiled potatoes. The softening degree of the boiled potatoes during cooking is influenced by starch characteristics such as amylose to amylopectin ratio, cell separation and cell wall softening (*37*). Some functional properties of starch can be changed as a result of prolonged UV-C treatment, such as capability of absorbing and holding water during gelatinization, reduction in amylose content, appearance of fractures and exocorrosion on the surface of the starch granule or a drop of crystallinity (*53*).

After the 15th day of storage browning was slightly more pronounced. Throughout the storage the odour was highly rated, while the off-odour was more pronounced only at the end of storage, and it received lower scores in boiled than in the raw samples. This could be explained by the volatility of compounds responsible for off-odour of raw potato. This was also observed previously by Dite Hunjek *et al.* (*5*). The firmness and creaminess showed variations in scores during storage; however, at the beginning of storage firmness was rated with the lowest scores and creaminess achieved the highest scores. On the 11th day, sweet taste was the most evident compared to other days, while a salty taste was the most prominent on the 8th day. Generally, boiled 5- and 10-UV-C samples were characterised by desirable odour, creaminess and taste, as well as appropriate colour and acceptable firmness. These favourable sensory attributes were preserved for 23 days of storage.

Table 3. The influence of UV-C treatment and storage time on sensory properties of boiled fresh-cut potatoes

Source of variation	Browning	Odour	Off-odour	Moistness	Firmness	Creaminess	Potato taste	Sweet taste	Sour taste	Salty taste	Bitter taste	Off-taste
Treatment	p<0.01*	p<0.01*	p=0.17	p=0.70	p<0.01*	p<0.01*	p<0.01*	p<0.01*	p=0.39	p<0.01*	p=0.53	p=0.57
Control	(2.40±0.05)^{c}	(4.70±0.03)^{a}	(1.07±0.03)^{a}	(2.07±0.03)^{a}	(2.30±0.08)^{c}	(3.70±0.07)^{a}	(4.35±0.05)^{a}	(1.05±0.04)^{a}	(1.05±0.03)^{a}	(1.00±0.04)^{a}	(1.03±0.02)^{a}	(1.00±0.01)^{a}
3-UV-C	(1.95±0.05)^{a}	(4.78±0.03)^{a}	(1.08±0.03)^{a}	(2.08±0.03)^{a}	(1.97±0.08)^{b}	(4.23±0.07)^{b}	(4.93±0.05)^{b}	(1.12±0.04)^{ab}	(1.00±0.03)^{a}	(1.00±0.04)^{a}	(1.00±0.02)^{a}	(1.00±0.01)^{a}
5-UV-C	(2.13±0.05)^{b}	(4.92±0.03)^{b}	(1.03±0.03)^{a}	(2.12±0.03)^{a}	(1.72±0.08)^{b}	(4.38±0.07)^{b}	(4.92±0.05)^{b}	(1.23±0.04^{b}	(1.03±0.03)^{a}	(1.20±0.04)^{b}	(1.00±0.02)^{a}	(1.02±0.01)^{a}
10-UV-C	(2.03±0.05)^{ab}	(5.00±0.03)^{b}	(1.00±0.03)^{a}	(2.10±0.03)^{a}	(1.12±0.08)^{a}	(4.72±0.07)^{c}	(4.92±0.05)^{b}	(1.45±0.04)^{c}	(1.00±0.03)^{a}	(1.50±0.04)^{b}	(1.02±0.02)^{a}	(1.02±0.01)^{a}
t(storage)/day	p<0.01*	p<0.01*	p<0.01*	p<0.01*	p<0.01*	p<0.01*	p=0.03*	p<0.01*	p=0.36	p<0.01*	p=0.13	p=0.10
0	(1.50±0.05)^{a}	(5.00±0.04)^{c}	(1.00±0.03)^{a}	(2.00±0.03)^{a}	(1.46±0.09)^{a}	(4.58±0.07)^{b}	(4.69±0.05)^{a}	(1.10±0.05)^{a}	(1.00±0.03)^{a}	(1.08±0.05)^{ab}	(1.00±0.02)^{a}	(1.00±0.01)^{a}
8	(1.92±0.05)^{b}	(4.52±0.04)^{a}	(1.00±0.03)^{a}	(2.17±0.03)^{b}	(2.10±0.09)^{b}	(4.13±0.07)^{a}	(4.83±0.05)^{a}	(1.06±0.05)^{a}	(1.00±0.03)^{a}	(1.48±0.05)^{c}	(1.00±0.02)^{a}	(1.00±0.01)^{a}
11	(1.67±0.05)^{a}	(5.00±0.04)^{c}	(1.00±0.03)^{a}	(2.30±0.03)^{b}	(1.83±0.09)^{bc}	(4.23±0.07)^{a}	(4.88±0.05)^{a}	(1.75±0.05)^{b}	(1.00±0.03)^{a}	(1.27±0.05)^{b}	(1.00±0.02)^{a}	(1.00±0.01)^{a}
15	(2.65±0.05)^{c}	(5.00±0.04)^{c}	(1.00±0.03)^{a}	(2.00±0.03)^{a}	(1.58±0.09)^{ab}	(4.23±0.07)^{a}	(4.85±0.05)^{a}	(1.10±0.05)^{a}	(1.04±0.03)^{a}	(1.04±0.05)^{a}	(1.00±0.02)^{a}	(1.00±0.01)^{a}
23	(2.92±0.05)^{d}	(4.73±0.04)^{b}	(1.23±0.03)^{b}	(2.00±0.03)^{a}	(1.90±0.09)^{bc}	(4.13±0.07)^{a}	(4.65±0.05)^{a}	(1.04±0.05)^{a}	(1.06±0.03)^{a}	(1.00±0.05)^{a}	(1.06±0.02)^{a}	(1.04±0.01)^{a}
Grand mean	2.13	4.85	1.05	2.09	1.78	4.26	4.78	1.21	1.02	1.18	1.01	1.01

*Statistically significant variable at α≤0.05. Results are expressed as mean±S.E. Different letters in the same column mean statistically different values at α≤0.05. 3-UV-C, 5-UV-c and 10-UV-C=samples treated with UV-C for 3, 5 and 10 min respectively

Table 4. The influence of UV-C treatment and storage days on sensory properties of fried fresh-cut potatoes

Source of variation	Browning	Odour	Off-odour	Oiliness	Firmness	Crispiness	Potato taste	Sweet taste	Sour taste	Salty taste	Bitter taste	Off-taste
Treatment	p<0.01*	p<0.01*	p=0.53	p=0.85	p<0.01*	p=0.53	p<0.01*	p<0.01*	p=0.53	p<0.01*	p=0.56	p=0.53
Control	(2.33±0.03)^{b}	(4.63±0.04)^{a}	(1.03±0.02)^{a}	(1.07±0.03)^{a}	(2.32±0.07)^{b}	(2.00±0.02)^{a}	(3.98±0.05)^{a}	(1.00±0.04)^{a}	(1.03±0.02)^{a}	(1.00±0.04)^{a}	(1.05±0.03)^{a}	(1.03±0.02)^{a}
3-UV-C	(2.11±0.03)^{a}	(4.75±0.04)^{ab}	(1.02±0.02)^{a}	(1.03±0.03)^{a}	(2.40±0.07)^{b}	(2.02±0.02)^{a}	(4.32±0.05)^{b}	(1.00±0.04)^{a}	(1.02±0.02)^{a}	(1.00±0.04)^{a}	(1.03±0.03)^{a}	(1.02±0.02)^{a}
5-UV-C	(2.15±0.03)^{a}	(4.80±0.04)^{bc}	(1.00±0.02)^{a}	(1.05±0.03)^{a}	(2.30±0.07)^{ab}	(2.03±0.02)^{a}	(4.33±0.05)^{b}	(1.15±0.04)^{b}	(1.00±0.02)^{a}	(1.17±0.04)^{b}	(1.00±0.03)^{a}	(1.00±0.02)^{a}
10-UV-C	(2.15±0.03)^{a}	(4.93±0.04)^{c}	(1.00±0.02)^{a}	(1.05±0.03)^{a}	(2.03±0.07)^{a}	(2.00±0.02)^{a}	(4.68±0.05)^{c}	(1.52±0.04)^{c}	(1.00±0.02)^{a}	(1.40±0.04)^{c}	(1.00±0.03)^{a}	(1.00±0.02)^{a}
t(storage)/day	p<0.01*	p<0.01*	p=0.53	p<0.01*	p<0.01*	p=0.53	p<0.01*	p<0.01*	p=0.53	p<0.01*	p=0.55	p=0.53
0	(2.00±0.04)^{a}	(5.00±0.05)^{c}	(1.00±0.01)^{a}	(1.00±0.04)^{a}	(2.27±0.08)^{ab}	(2.00±0.02)^{a}	(4.21±0.05)^{a}	(1.29±0.05)^{b}	(1.00±0.02)^{a}	(1.20±0.04)^{bc}	(1.00±0.03)^{a}	(1.00±0.02)^{a}
8	(2.00±0.04)^{a}	(4.58±0.05)^{a}	(1.00±0.02)^{a}	(1.00±0.04)^{a}	(2.15±0.08)^{ab}	(2.00±0.02)^{a}	(4.54±0.05)^{c}	(1.29±0.05)^{b}	(1.00±0.02)^{a}	(1.25±0.04)^{c}	(1.00±0.03)^{a}	(1.00±0.02)^{a}
11	(2.00±0.04)^{a}	(4.63±0.05)^{a}	(1.00±0.02)^{a}	(1.00±0.04)^{a}	(2.46±0.08)^{b}	(2.04±0.02)^{a}	(4.17±0.05)^{a}	(1.13±0.05)^{ab}	(1.00±0.02)^{a}	(1.03±0.04)^{a}	(1.00±0.03)^{a}	(1.00±0.02)^{a}
15	(2.52±0.04)^{b}	(4.75±0.05)^{ab}	(1.02±0.02)^{a}	(1.13±0.04)^{b}	(2.35±0.08)^{ab}	(2.02±0.02)^{a}	(4.25±0.05)^{ab}	(1.13±0.05)^{ab}	(1.04±0.02)^{a}	(1.08±0.04)^{ab}	(1.04±0.03)^{a}	(1.02±0.02)^{a}
23	(2.42±0.04)^{b}	(4.94±0.05)^{bc}	(1.04±0.02)^{a}	(1.13±0.04)^{b}	(2.08±0.08)^{a}	(2.00±0.02)^{a}	(4.48±0.05)^{bc}	(1.00±0.05)^{a}	(1.02±0.02)^{a}	(1.00±0.04)^{a}	(1.06±0.03)^{a}	(1.04±0.02)^{a}
Grand mean	2.17	4.78	1.01	1.05	2.26	2.01	4.33	1.17	1.01	1.14	1.02	1.01

*Statistically significant variable at α≤0.05. Results are expressed as mean±S.E. Different letters in the same column mean statistically different values at α≤0.05. 3-UV-C, 5-UV-C and 10-UV-C=samples treated with UV-C for 3, 5 and 10 min respectively

Fried fresh-cut potato samples

Most of the analysed sensory attributes of fried potato were significantly affected by the UV-C treatment and storage time ($p<0.01$), with an exception of off-odour, crispiness, sour, bitter and off-taste (**Table 4**). Oiliness was significantly influenced only by storage time ($p<0.01$), but numerical differences were very slight (in a range from 1.00 to 1.13). All UV-C-treated samples had slightly brighter colour (2.11 to 2.15) after frying than fried control samples (2.33), and browning was not observed. According to the results of Sobol *et al.* (*16*), UV-C irradiation applied on potato tubers increased the brightness of the fried potatoes, which is in line with present results. Lin *et al.* (*15*) reported lower content of fructose and glucose in irradiated tubers during storage. During processing at high temperatures, reducing sugars and amino acids participate in Maillard's reactions, which are responsible for colour and volatile compound formation in fried products (*54*). Presumably, increased brightness could be linked to lowering of reducing sugars caused by UV-C treatment. Firmness of 10-UV-C samples significantly decreased, as it was observed in boiled ones (**Table 3**). Odour and potato, sweet and salty taste significantly increased in fried 10-UV-C potatoes. Potato taste intensity increased with applied UV-C dose, while potato off-taste was not pronounced, a similar observation was for boiled fresh-cut potatoes.

Even though storage time showed a significant effect ($p<0.01$) on more than half of the evaluated properties, numerical differences were very slight. The browning scores were in the range of 2.00–2.52, and they were more pronounced on the 15th and 23rd days, like in boiled samples. Moreover, the sweet and salty taste of fried potatoes decreased and oiliness increased with storage time. The potato taste and odour were highly scored, and off-odour was not noticed regardless of the fresh-cut potato storage duration. These results indicate that the observed changes in off-odour of stored raw fresh-cut potatoes do not have an influence on the odour of fried potatoes, which is in accordance with observations for boiled potatoes. Generally, UV-C treatments positively affected the taste, odour and colour formation in fried potatoes regardless of storage time.

Results of PCA analysis of the applied UV-C treatment and storage time

PCA was used to visualize relations among the analysed parameters and to determine possible grouping of raw, boiled and fried fresh-cut potato samples in relation to the applied UV-C treatment and storage time (**Fig. 2**, **Fig. 3** and **Fig. 4**, respectively).

In terms of raw fresh-cut potato samples, TAMBC, pH, total soluble solids, *L**, *a**, *b** and all sensory attributes except sensorial firmness were included in the test (**Fig. 2**). PC1 and PC2 together described 66.81 % of the total data variance, where PC1 correlated very strongly with TAMBC (r=0.908), strongly with pH (r=−0.842) and moderately with browning

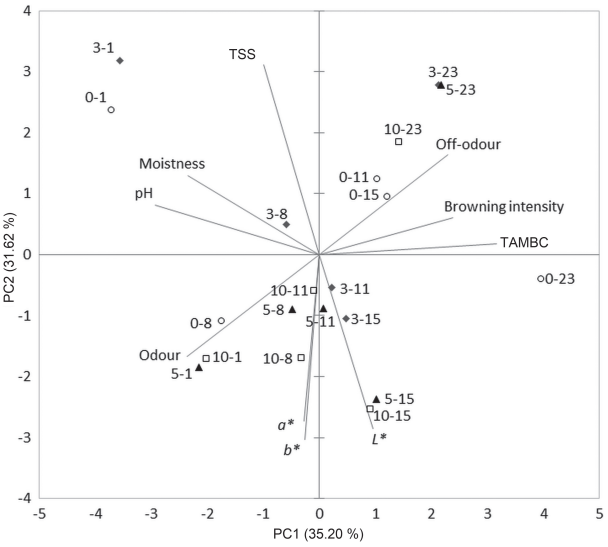

Fig. 2. Biplot related to the raw fresh-cut potatoes. The first number in the sample label indicates UV-C treatment (min) and the second number indicates storage day. TAMBC=total aerobic mesophilic bacteria count, TSS=total soluble solids

intensity (r=0.686), odour (r=−0.678), off-odour (r=0.659) and moistness (r=−0.672). On the other hand, PC2 showed a very strong correlation with total soluble solids (r=0.848) and *b** (r=−0.826) and strong correlation with *L** (r=−0.778) and *a** (r=−0.743), while moderate correlation was present between this PC and odour (r=−0.453) as well as off-odour (r=0.444). Considering UV-C treatment duration, almost all 5- and 10-UV-C-treated raw samples were placed among negative PC2 values since they received higher scores for colour parameters and odour. Moreover, 3-UV-C samples were not perceived as a separate group, while 0-UV-C samples were distributed mainly among positive PC1 and PC2 values. Furthermore, grouping was observed in relation to storage time, where all samples from the 23rd day of storage were also placed in the upper right quadrant, characterized by higher values of TAMBC, browning and off-odour. The 0-UV-C samples taken on the 11th and 15th days of storage were also positioned in this part of the factorial plane.

Considering the boiled fresh-cut potato samples, browning intensity, odour, moistness, sensorial firmness, creaminess, potato taste and bitterness were selected as PCA-active variables and PC1 and PC2 explained 63.92 % of the total data variance (**Fig. 3**). PC1 showed a strong correlation with browning intensity (r=−0.750), creaminess (r=0.699), potato taste (r=0.770), sweetness (r=0.626), saltiness (r=0.611) and bitterness (r=−0.746) as well as a moderate correlation with off-odour (r=−0.501), while a strong/moderate correlation was present between PC2 and off-odour (r=0.602), creaminess (r=0.430), saltiness (0.402) and bitterness (r=0.493). Clear separation of the samples can be noticed with regard to UV-C treatment. The major distinction of the samples was observed for 10-UV-C-treated samples, which were distributed among the positive values of PC1 and PC2 and were characterized by positive sensorial attributes: creaminess, saltiness,

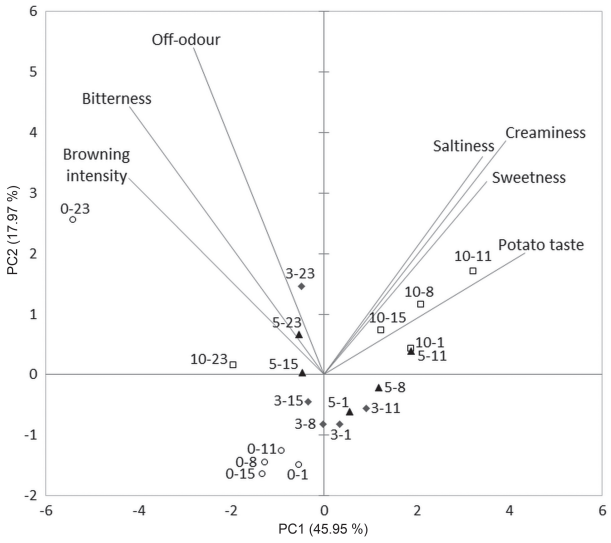

Fig. 3. Biplot related to the boiled fresh-cut potatoes. The first number in the sample label indicates UV-C treatment (min) and the second number indicates storage day

sweetness and characteristic potato taste. On the other hand, almost all control samples were placed among the negative values of PC1 and PC2. Also, 3- and 5-UV-C samples were situated around the centre of the factorial plane. Besides, boiled fresh-cut potatoes on the 23rd storage day were again separated by negative PC1 values, and were correlated with scores for browning intensity, bitterness and off-odour, which were especially high in the control sample.

As for fried potato samples, browning intensity, off-odour, oiliness, sensorial firmness, potato taste, sweetness, saltiness, bitterness and off-taste were considered and the first two PCs described 81.03 % of the total data variance (**Fig. 4**). A very strong/strong correlation was present between browning

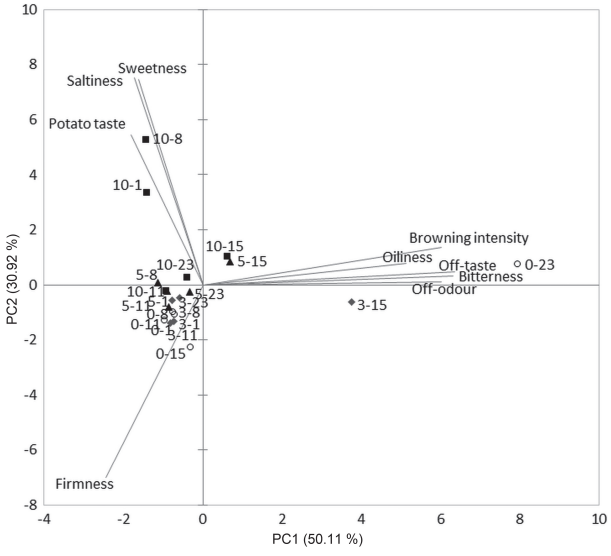

Fig. 4. Biplot related to the fried fresh-cut potatoes. The first number in the sample label indicates UV-C treatment (min) and the second number indicates storage day

intensity (r=0.918), off-odour (r=0.918), bitterness (r=0.962), off-taste (r=0.969), oiliness (r=0.783) and PC1, while PC2 correlated strongly/very strongly with sensorial firmness (r=−0.838), sweetness (r=0.895), saltiness (r=0.901) and potato taste (r=0.654). The grouping of the fried potato samples in terms of UV-C treatment is rather poor, where only 10-UV-C samples, which received the highest scores for sweetness, saltiness and potato taste, were slightly distanced from the rest of the samples, especially from the samples fried at the beginning of the storage (1st and 8th day). Again, control sample from the 23rd day of storage was separated from the rest of the samples with the highest scores for undesirable sensory attributes, *i.e.* browning, oiliness, off-taste, bitterness and off-odour.

CONCLUSIONS

UV-C technology is promising and it has a potential practical application in fresh-cut industry, especially since it has already been approved for application in food industry, specifically for liquid systems or surface disinfection. Furthermore, it is considered as environmentally friendly with low costs of energy, equipment and maintenance.

The results of this study could contribute to UV-C application in fresh-cut industry since UV-C treatment in combination with sodium ascorbate and vacuum packaging showed high efficiency in the reduction of microbial count in raw fresh-cut potato cv. Birgit during storage at (6±1) °C and in extension of its shelf life. UV-C treatments for 5 and 10 min were particularly effective. Generally, good quality and sensory attributes of fresh-cut potato were retained for up to 15 days of storage. The treatment also contributed to the reduction of browning and affected the odour of raw fresh-cut potatoes positively, and acceptable firmness was retained as well. Furthermore, UV-C-treated fresh-cut potatoes after boiling and frying were also sensorially desirable as they were characterized with more pronounced characteristic potato odour and taste than untreated samples.

On a potential large-scale production of fresh-cut potatoes UV-C treatment could present relatively short additional operation for ensuring safety and extended shelf life. Namely, it could be the final operation after potato slicing, treatment by antibrowning agents (*e.g.* sodium ascorbate solution) and after vacuum packaging. However, further investigation is needed in order to determine all parameters necessary to confirm the use of UV-C technology on a real scale in the fresh-cut potato industry.

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CONFLICT OF INTEREST

Authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

Z. Pelaić conducted the experiment, analysed data, conducted and interpreted statistical analysis and drafted the original manuscript. Z. Čošić contributed to the experiment preparation and editing of the manuscript. K. Galić and M. Šćetar contributed to the experiment preparation. M. Repajić contributed to the analysis and interpretation of the statistical data as well as the revision of the manuscript. S. Pedisić participated in writing the original draft, Z. Zorić participated in the formal analysis, while B. Levaj developed and conceptualized the idea and methodology of the study, contributed to the data interpretation and revision of the manuscript.

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MDPI

Article

Effect of UV-C Irradiation, Storage and Subsequent Cooking on Chemical Constituents of Fresh-Cut Potatoes

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Abstract: UV-C irradiation successfully reduces the growth of microorganisms, but it can also affect the content of phenolics and sugars of fresh-cut potatoes (FCP). This could consequently alter antioxidant capacity of FCP or its potential for acrylamide formation. Therefore, this paper investigates the influence of UV-C irradiation on the content of phenolics [chlorogenic acid (CA)] and individual sugars during storage of FCP as well as after cooking. Acrylamide was also monitored in FCP after frying. Potato slices pre-treated with sodium ascorbate solution and vacuum-packaged were UV-C irradiated for 0, 3, 5, and 10 min in order to obtain irradiation doses of 0, 1.62, 2.70, and 5.40 kJ m^{-2}, respectively, stored for 23 days (+6 °C), and subsequently boiled and fried. As the applied dose and storage duration increased, the CA content in raw FCP decreased (it retained for 75.53–88.34%), while the content of sugars as well as acrylamide in fried FCP increased. Although the increase was the most noticeable at the applied dose of 2.70 kJ m^{-2}, the acrylamide content was always below proposed limit. Boiling and frying reduced the content of CA and sugars. In spite of certain alterations, applied doses of irradiation can ensure acceptable product in regard to phenolics and sugars, and acrylamide content particularly.

Keywords: UV-C; fresh-cut potatoes; storage; cooking; phenolics; sugars; acrylamide

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1. Introduction

Minimal processing (washing, peeling, cutting, etc.) of fruits and vegetables leads to tissue disruption and increased microbial growth, enzymatic activity, respiration rate, and ethylene production as well as other undesirable changes. All of these alterations cause quality deterioration and consequently a reduced shelf-life of fresh-cut products [1,2]. With the aim to prevent a microbiological spoilage, multiple methods, and techniques are being investigated, including non-ionizing UV-C technology at optimal wavelength of 254 nm. It has already been proven as an effective method in this regard and therefore can extend the shelf-life of fresh-cut products [3,4]. In accordance with this primary role of UV-C irradiation in food processing, it should preserve the quality of the product which greatly depends on the applied intensity of irradiation and exposure time [5]. Moreover, a number of other factors affect the effectiveness of irradiation, such as the properties of the plant material, the anti-browning agents or packaging material used [6,7]. The UV-C irradiation can inhibit enzyme activity and, consequently, reduce the browning of fresh-cut products [8]. Further, it can modify the flavor [9] or increase the content of phenolics and other bioactive compounds [9,10]. Increased content of phenolics may be, inter alia, a result of beneficial effect of UV-C, which stimulates the production of phenylalanine ammonia-lyase (PAL) [11]. In turn, this enzyme catalyzes the synthesis of phenolics what can consequently lead to an improved resistance to microorganisms. However, some of the authors observed a negative irradiation effect, such as induced browning, through the storage [12], breakages of cellular membranes [13], increased respiration rate [2], and

decreased content of phenolics as well as antioxidant capacity through the storage, when higher UV-C irradiation was applied [14].

Regarding potatoes, the effect of tuber irradiation was mainly studied on weight loss, rot resistance, or the content of sugars during storage [15–17]. An alleviated accumulation of reducing sugars (fructose and glucose) was observed during low-temperature storage of irradiated tubers [15], which consequently can lead to a decreased ability of acrylamide formation. However, a recent study showed that UV-C irradiation of potato tubers two days before the preparation of semi-finished products can increase the acrylamide content in fried potatoes, although the content of sugars in tubers was not analyzed in this study [18]. Reducing sugars, along with free amino acid asparagine, are the precursors in Maillard's reactions in which acrylamide is formed in potatoes fried at temperatures above 120 °C [19]. Acrylamide is a neurotoxic organic compound, probably cancerogenic to humans, as it is classified in group 2A by the International Agency for Research on Cancer (IARC) [20]. According to the EU Commission Regulation (2017/2158) [21], upper acrylamide limit in potato products is 750 μg kg^{-1} of fresh weight (FW). Once acrylamide is distributed throughout the organs, it is metabolized, inter alia, to glycidamide, the formation of which is considered to be the basis of the acrylamide genotoxicity and carcinogenicity (EFSA 2015) [22].

Currently, only few studies have addressed the effect of UV-C irradiation on fresh-cut potatoes (FCP), primarily investigating its effect on enzymes and the content of phenolics [7,23]. Phenolics are non-nutritional phytochemicals and present a significant group of compounds in potatoes, primarily due to their antioxidant properties. Besides, they are involved in enzymatic reactions of browning which alters the appearance and quality of products. PAL is wound-induced enzyme and its activity is enhanced due to minimally processing, by which, as already mentioned, the formation of phenolics increases [24]. Phenolics act then as substrates in oxidation reactions catalyzed by polyphenol oxidase (PPO) and peroxidase (POD) enzymes. PPO catalyzes the hydroxylation of monophenols in o-diphenols and the oxidation of o-diphenols into o-quinones of which dark pigment melanin is formed by non-enzymatic reactions [25,26]. According to previous research, UV-C irradiation can reduce PPO activity and increase the content of total phenolics in FCP [7]. Still, although reduced, PPO activity was significantly increased with the increased UV-C dose [7]. On the other hand, Xie et al. [23] did not observe significant differences in PPO activity until the 13th day of storage, after which a significant decrease compared to control trend was present till 19th day storage.

The scientific data on the effect of UV-C irradiation on the chemical constituents of FCP are scarce and mainly on raw samples [7]. Therefore, the aim of this study was to examine the effect of several doses of UV-C irradiation (0, 1.62, 2.70, and 5.40 kJ m^{-2}) on the content of phenolics and sugars in FCP as well as on the content of acrylamide formed in fried FCP. Additionally, this study also included the monitoring of these compounds influenced by FCP storage time and cooking method.

2. Material and Methods

2.1. Plant Material

Potato (*Solanum tuberosum* L.) tubers of cv. Birgit were used for the experiment. Tubers were harvested in the Croatian region of Slavonia during 2019 and prior storage were treated with an anti-sprouting agent (Gro Stop Basis and Gro Stop Fog, Certis Europe B.V., Cambridge, UK). Before the analysis, tubers were stored one month in the dark at 8 °C and relative humidity app. 100%.

2.2. Chemicals and Standards

Formic acid, *n*-hexane, acetonitrile (HPLC grade) and methanol (HPLC grade) were purchased from Sigma-Aldrich (Steinheim, Germany) as well as standards: acrylamide (>99%), chlorogenic acid, caffeic acid, *p*-coumaric acid, catechin, rutin, D-(−)-fructose (≥99% GC), D-(+)-glucose (≥99.5% GC), and D-(+)-sucrose (≥99.5% GC). The QueChERS salt packet (4 g $MgSO_4$ and 0.5 g NaCl) and QueChERS d-SPE salts (150 mg $MgSO_4$ and

50 mg PSA) were purchased from Agilent Technologies (Santa Clara, CA, USA). Water was of Milli-Q quality (Millipore Corp., Bedford, MA, USA).

2.3. Sample Preparation

Sample preparation was conducted according to the procedure described by Dite Hunjek et al. [27]: only uniform and undamaged tubers were selected, washed, drained, and hand-peeled. Afterwards, tubers were sliced (0.4 cm) using a commercial slicer (SFS 1001 GR, Sencor, Ricany, Czech Republic) and dipped for 3 min into sodium ascorbate solution (2%, w/v) with a sample/solution (g mL^{-1}) ratio of 1:4. Using SmartVac SV 750 (Status, Metlika, Slovenia) 4–6 drained slices were then vacuum packaged in one single layer within the polyamide/polyethylene double-layered (100 and 130 µm) vacuum bags (Status, Metlika, Slovenia).

2.4. UV-C Treatment

After vacuum packaging, potato slices were UV-C treated using an UV-C chamber (UVpro EKB 100, Orca GmbH, Kürten, Germany) equipped with four UV-C lamps (4xHNSL 24 W, maximal emission at 253.7 nm, UVpro) with two of them located 22 cm above and the other two under the perforated shelf. After 20 min of initial stabilization of the UV-C lamps, the samples (four bags) were placed on the certain place of the perforated shelf (previously tested) to ensure the uniformity of dose application. Doses of 0, 1.62, 2.70, and 5.40 kJ m^{-2} (UVCpro UVC-LOG radiometer, Orca GmbH, Kürten, Germany) were achieved by, 3 (3-UV-C), 5 (5-UV-C), and 10 min (10-UV-C) of irradiation and are expressed as a mean of 10-dose readings within the selected area. In order to compare UV-C treated and untreated FCP, control sample (control, 0) was also prepared by the same procedure described in Section 2.3 without further UV-C treatment. Samples were then stored at 6 ± 1 °C for 23 days. At the beginning of the storage (0) and on the 8th, 11th, 15th, and 23rd day of storage samples were cooked (boiled and fried), and raw samples as well as cooked ones were analyzed.

2.5. Cooking Treatments

Boiled potato slices were prepared by boiling in water (water:sample = 5:1) at 100 °C for 15 min, while fried ones by frying in sunflower oil (oil:sample = 1.5 L:180 g) at initial temperature of 180 °C for 5 min. A paper towel was used to remove excess water or oil from boiled or fried potatoes, respectively.

All samples (raw and cooked) were frozen at −60 °C for 24 h, freeze-dried (CoolSafe PRO, Labogene, Denmark) and ground. Such homogenized powder of raw, boiled, and fried FCP was analyzed for phenolics and sugars, while acrylamide content was determined only in fried samples.

2.6. Phenolics Analysis

2.6.1. Extraction of Phenolics

Extraction of phenolics was conducted as previously described by Dite Hunjek et al. [28]. Briefly, phenolics from homogenized freeze-dried samples (0.5 g) were extracted with 5 mL of 80% methanol with 1% formic acid (v/v), using ultrasonic bath (Elmasonic 40H, Elma, Germany) for 30 min at 50 °C. After centrifugation at 3000 rpm/10 min (Hettich® Rotofix 32a, Tuttlingen, Germany), the procedure was repeated by adding 5 mL of extraction solvent to precipitate. Supernatants were combined into a 10 mL flask and made up with solvent. Extracts were filtered (0.45 µm membrane filter, Macherey-Nagel GmbH & Co. KG, Düren, Germany) into vials and stored at −20 °C until the UPLC MS^2 analysis. Extractions were performed in a duplicate (n = 2).

2.6.2. UPLC MS^2 Analysis of Phenolics

UPLC MS^2 analysis was performed using an Agilent series 1290 RRLC instrument linked to a triple quadrupole mass spectrometer (6430) (Agilent Technologies, Santa Clara,

CA, USA)) with an ESI ion source. Zorbax Eclipse Plus C18 column (100 × 2.1 mm, 1.8 µm) (Agilent Technologies) was used for the separation. Chromatographic conditions, as well as instrument settings, solvent composition, and gradient conditions were as previously described by Elez Garofulić et al. [29]. Briefly, column temperature was set at 35 °C, the injection volume was 2.5 µL, and flow rate 0.3 mL min^{-1}. The eluent A was 0.1% of formic acid (*v*/*v*) and eluent B 0.1% formic acid in acetonitrile (*v*/*v*). Ionization was performed by electrospray (ESI) in negative and positive mode (*m*/*z* 100–1000). Data were collected in the dynamic multiple reaction monitoring mode (dMRM). The retention time and mass spectra of the phenolic standards were used to identify compounds, while quantification was performed using calibration curves obtained from the standards. Analytical parameters for chlorogenic acid standard were: six concentrations in a range of 1.625–30 mg L^{-1}, regression equation: y = 3639.4x + 575.69, R^2 = 0.9999, LOD = 0.453 mg L^{-1}, and LOQ = 1.371 mg L^{-1}. Results are expressed as mg 100 g^{-1} of dry weight (DW). Dry weight was determined by drying lyophilized potato samples at 103 ± 1 °C (FN-500, Nüve, Ankara, Turkey) to constant weight (AOAC, 1990) [30].

2.7. Sugar Analyses

2.7.1. Extraction of Sugars

The extraction of sugars was performed according to the method described by Dite Hunjek et al. [28]. The 4 mL of 80% methanol (*v*/*v*) was added into 0.4 g of the ground freeze-dried sample. The mixture was homogenized using vortex and thermostated in a water bath at 60 °C for 60 min. After centrifugation at 6000 rpm/15 min supernatant was filtered and collected into a 5 mL flask and made up with solvent. Extracts were filtered through 0.45 µm membrane filter into vials and stored at +4 °C until the analyses. Extractions were performed in a duplicate (*n* = 2).

2.7.2. HPLC Analysis of Sugars

HPLC analysis of sugars (fructose, glucose, and sucrose) was performed using an Agilent 1260 Infinity quaternary LC system (Agilent Technologies) equipped with refractive index detector (RID). Compounds were separated on a Cosmosil Sugar-D, 5 µm, 250 × 4.6 mm I.D. (Nacalai Tesque, INC., Kyoto, Japan) column. The chromatographic conditions were as described by Dite Hunjek et al. [28]: mobile phase (80% acetonitrile, *v*/*v*) was in isocratic elution mode at flow rate of 1.3 mL min^{-1}, injection volume was 10 µL, and the column temperature was set at 45 °C. Identification and quantification of sugars was conducted by comparing retention times and peak areas with the one obtained from standard solutions. Standard solutions were prepared in 80% ethanol (*v*/*v*) and a fixed concentration of each sugar standard was used for quantification. The results are expressed as g 100 g^{-1} DW.

2.8. Acrylamide Analysis

2.8.1. Extraction of Acrylamide

In order to determine the content of acrylamide in fried FCP, the method given by Al-Taher [31] was applied with some modifications and without using internal standard [24]. Freeze-dried fried samples (1 g) were homogenized on a vortex with 5 mL of *n*-hexane, after which 10 mL of water and 10 mL of acetonitrile were added and vortexed for 3 min. In such prepared mixture QueChERS salt packet was added and it was strongly shaken for 1 min. After centrifugation at 5000 rpm/5 min, the hexane layer was discarded and 1 mL from acetonitrile layer was transferred into 2 mL vial packed with QueChERS d-SPE salts. Mixture was homogenized at vortex and centrifuged at 5000 rpm/1 min. Supernatant (0.5 mL) was transferred into vials and analyzed by UPLC MS^2. Extractions were performed in a duplicate (*n* = 2).

2.8.2. UPLC MS^2 Analysis of Acrylamide

The UPLC MS^2 analysis of acrylamide was performed as previously described by Dite Hunjek et al. [28] by Agilent UPLC system (Section 2.6.2). A Hypercarb TM col-

umn (5 µm, 50 mm × 2.1 mm) with a guard column (5 µm, 10 mm × 2 mm) (Thermo Hypersil-Keystone, Bellefonte, PA, USA) was used for the separation, column temperature was set at 22 °C, injection volume was 10 µL, and flow rate 0.7 mL min^{-1}. Mobile phase was 10% methanol with 0.1% formic acid. Ionization was done by electrospray (ESI) in positive ion mode. The identification of acrylamide was confirmed by comparing the peak ratios of MRM transitions m/z 72 → 55.1 from sample extracts and standard solutions. Quantification was performed using a calibration curve from extracted acrylamide standard solutions. Analytical parameters for acrylamide standard were: six concentrations in a range of 20–500 ng mL^{-1}, regression equation: y = 55.042x − 124.76, R^2 = 0.9999, LOD = 7.479 ng mL^{-1}, and LOQ = 22.666 ng mL^{-1}. The results are expressed as µg kg^{-1} DW.

2.9. Statistical Analysis

The statistical analysis was carried out to examine the influence of the UV-C treatment (0, 3, 5, and 10 min), storage time (0, 8, 11, 15, and 23 days) and cooking method (raw, boiled, and fried FCP) on the content of chlorogenic acid, fructose, glucose, and sucrose as well as on the content of acrylamide in fried FCP. The experimental data were analyzed using Statistica ver. 12.0 software (Statsoft Inc., Tulsa, OK, USA). Data were tested for normality by the Shapiro–Wilk test, while homoscedasticity was tested by Levene's test. All dependent variables were examined using ANOVA (parametric data) or Kruskal–Wallis test (nonparametric data). Means within groups were compared with Tukey's HSD test or Kruskal–Wallis test. The statistically obtained results are shown in Tables 1 and 2 as mean values ± standard error (SE). SE is expressed as the standard deviation of the sampling distribution for all analyzed samples which were taken in statistical processing and calculated by the above-mentioned software. The grand mean represents the mean of all results obtained for a particular chemical component. The relationships between compounds (chlorogenic acid and reducing sugars in raw FCP and acrylamide in fried FCP) were tested by calculated Spearman's rank correlation coefficients. For Principal Component Analysis (PCA) XLSTAT ver. 2020.5.1 software (Addisoft, Paris, France) was applied. PCA was based on a correlation matrix of samples using values of chlorogenic acid, fructose, glucose, and sucrose in order to examine the possible grouping of the samples by the UV-C treatment, storage time, and cooking method. Analysis involved principal components (PC) with eigenvalue > 1 and variables with communalities ≥ 0.5. The significance level for all tests was $p \leq 0.05$.

Table 1. The influence of UV-C treatment, storage days, and cooking method on chlorogenic acid (mg 100 g^{-1} DW) and sugars (g 100 g^{-1} DW) in fresh-cut potato.

Source of Variation	Chlorogenic Acid	Fructose	Glucose	Sucrose
UV-C treatment	p = 0.052	p = 0.005 *	p = 0.078	p < 0.001 *
Control	11.32 ± 1.06 ^{a}	0.179 ± 0.006 ^{a}	0.259 ± 0.015 ^{a}	0.212 ± 0.012 ^{a}
3-UV-C	10.00 ± 0.80 ^{a}	0.191 ± 0.012 ^{a}	0.259 ± 0.012 ^{a}	0.226 ± 0.011 ^{a}
5-UV-C	8.82 ± 0.66 ^{a}	0.267 ± 0.022 ^{b}	0.364 ± 0.035 ^{a}	0.435 ± 0.058 ^{b}
10-UV-C	8.55 ± 0.57 ^{a}	0.210 ± 0.014 ^{ab}	0.286 ± 0.013 ^{a}	0.253 ± 0.014 ^{ab}
Storage days	p = 0.5968	p < 0.001 *	p = 0.06	p = 0.069
0	9.98 ± 1.14 ^{a}	0.150 ± 0.005 ^{a}	0.238 ± 0.011 ^{a}	0.257 ± 0.013 ^{a}
8	9.65 ± 0.95 ^{a}	0.177 ± 0.011 ^{ab}	0.296 ± 0.024 ^{a}	0.307 ± 0.040 ^{a}
11	9.57 ± 0.90 ^{a}	0.196 ± 0.011 ^{bc}	0.276 ± 0.022 ^{a}	0.307 ± 0.063 ^{a}
15	9.58 ± 0.77 ^{a}	0.260 ± 0.021 ^{c}	0.309 ± 0.023 ^{a}	0.323 ± 0.037 ^{a}
23	9.59 ± 0.81 ^{a}	0.275 ± 0.020 ^{c}	0.341 ± 0.035 ^{a}	0.214 ± 0.017 ^{a}
Cooking method	p < 0.001 *	p = 0.001 *	p < 0.001 *	p < 0.001 *
Raw	15.20 ± 0.52 ^{b}	0.260 ± 0.018 ^{b}	0.397 ± 0.023 ^{b}	0.393 ± 0.044 ^{b}
Boiled	6.77 ± 0.14 ^{a}	0.194 ± 0.009 ^{a}	0.244 ± 0.009 ^{a}	0.231 ± 0.014 ^{a}
Fried	7.05 ± 0.19 ^{a}	0.181 ± 0.008 ^{a}	0.235 ± 0.011 ^{a}	0.220 ± 0.012 ^{a}

Table 1. *Cont.*

Source of Variation	Chlorogenic Acid	Fructose	Glucose	Sucrose
UV-C treatment x storage days	$p = 0.360$	$p = 0.766$	$p = 0.603$	$p = 0.293$
Control × 0	11.47 ± 3.00 ^{a}	0.152 ± 0.003 ^{a}	0.232 ± 0.009 ^{a}	0.228 ± 0.010 ^{a}
3-UV-C × 0	9.16 ± 2.60 ^{a}	0.149 ± 0.006 ^{a}	0.228 ± 0.017 ^{a}	0.227 ± 0.020 ^{a}
5-UV-C × 0	10.44 ± 2.31 ^{a}	0.147 ± 0.016 ^{a}	0.227 ± 0.031 ^{a}	0.266 ± 0.030 ^{a}
10-UV-C × 0	8.83 ± 1.33 ^{a}	0.154 ± 0.014 ^{a}	0.266 ± 0.027 ^{a}	0.305 ± 0.030 ^{a}
	$p = 0.324$	$p = 0.003$ *	$p = 0.240$	$p = 0.020$ *
Control × 8	10.48 ± 2.29 ^{a}	0.165 ± 0.008 ^{ab}	0.234 ± 0.029 ^{a}	0.235 ± 0.030 ^{ab}
3-UV-C × 8	10.36 ± 1.74 ^{a}	0.138 ± 0.010 ^{a}	0.269 ± 0.019 ^{a}	0.207 ± 0.017 ^{a}
5-UV-C × 8	8.79 ± 1.81 ^{a}	0.253 ± 0.022 ^{b}	0.417 ± 0.072 ^{a}	0.525 ± 0.125 ^{b}
10-UV-C × 8	8.98 ± 2.10 ^{a}	0.154 ± 0.010 ^{ab}	0.265 ± 0.021 ^{a}	0.261 ± 0.015 ^{ab}
	$p = 0.176$	$p = 0.051$	$p = 0.416$	$p = 0.294$
Control × 11	11.13 ± 2.64 ^{a}	0.191 ± 0.006 ^{a}	0.247 ± 0.019 ^{a}	0.202 ± 0.034 ^{a}
3-UV-C × 11	10.69 ± 1.84 ^{a}	0.169 ± 0.009 ^{a}	0.272 ± 0.047 ^{a}	0.226 ± 0.030 ^{a}
5-UV-C × 11	8.54 ± 1.30 ^{a}	0.250 ± 0.036 ^{a}	0.345 ± 0.064 ^{a}	0.586 ± 0.223 ^{a}
10-UV-C × 11	7.91 ± 1.16 ^{a}	0.174 ± 0.011 ^{a}	0.240 ± 0.028 ^{a}	0.213 ± 0.009 ^{a}
	$p = 0.415$	$p = 0.015$ *	$p = 0.120$	$p = 0.020$ *
Control × 15	11.38 ± 2.04 ^{a}	0.177 ± 0.017 ^{a}	0.270 ± 0.052 ^{a}	0.2140 ± 0.020 ^{a}
3-UV-C × 15	9.54 ± 1.89 ^{a}	0.241 ± 0.025 ^{ab}	0.252 ± 0.019 ^{a}	0.265 ± 0.031 ^{ab}
5-UV-C × 15	8.40 ± 1.21 ^{a}	0.360 ± 0.053 ^{b}	0.407 ± 0.053 ^{a}	0.530 ± 0.097 ^{b}
10-UV-C × 15	8.98 ± 0.82 ^{a}	0.261 ± 0.032 ^{ab}	0.305 ± 0.029 ^{a}	0.281 ± 0.051 ^{ab}
	$p = 0.329$	$p = 0.104$	$p = 0.528$	$p = 0.575$
Control × 23	12.12 ± 2.65 ^{a}	0.210 ± 0.016 ^{a}	0.313 ± 0.047 ^{a}	0.179 ± 0.032 ^{a}
3-UV-C × 23	10.27 ± 1.22 ^{a}	0.260 ± 0.032 ^{a}	0.274 ± 0.030 ^{a}	0.206 ± 0.024 ^{a}
5-UV-C × 23	7.91 ± 0.52 ^{a}	0.324 ± 0.065 ^{a}	0.423 ± 0.130 ^{a}	0.267 ± 0.052 ^{a}
10-UV-C × 23	8.06 ± 0.95 ^{a}	0.306 ± 0.018 ^{a}	0.353 ± 0.025 ^{a}	0.203 ± 0.019 ^{a}
Cooking method × storage days	$p < 0.001$ *	$p = 0.094$	$p = 0.001$ *	$p = 0.003$ *
Raw × 0	17.28 ± 1.07 ^{b}	0.159 ± 0.008 ^{a}	0.278 ± 0.011 ^{b}	0.308 ± 0.020 ^{b}
Boiled × 0	6.32 ± 0.20 ^{a}	0.158 ± 0.010 ^{a}	0.248 ± 0.020 ^{b}	0.256 ± 0.020 ^{ab}
Fried × 0	6.33 ± 0.35 ^{a}	0.134 ± 0.008 ^{a}	0.189 ± 0.011 ^{a}	0.206 ± 0.012 ^{a}
	$p < 0.001$ *	$p = 0.235$	$p = 0.001$ *	$p = 0.009$ *
Raw × 8	15.83 ± 0.50 ^{b}	0.198 ± 0.021 ^{a}	0.388 ± 0.050 ^{b}	0.448 ± 0.100 ^{b}
Boiled × 8	6.93 ± 0.50 ^{a}	0.149 ± 0.010 ^{a}	0.205 ± 0.012 ^{a}	0.220 ± 0.010 ^{a}
Fried × 8	6.20 ± 0.30 ^{a}	0.185 ± 0.023 ^{a}	0.296 ± 0.029 ^{ab}	0.253 ± 0.040 ^{a}
	$p < 0.001$ *	$p = 0.018$ *	$p < 0.001$ *	$p = 0.027$ *
Raw × 11	15.02 ± 1.20 ^{b}	0.239 ± 0.028 ^{b}	0.395 ± 0.038 ^{b}	0.503 ± 0.169 ^{b}
Boiled × 11	6.64 ± 0.31 ^{a}	0.170 ± 0.007 ^{a}	0.228 ± 0.013 ^{a}	0.256 ± 0.031 ^{ab}
Fried × 11	7.04 ± 0.21 ^{a}	0.178 ± 0.007 ^{ab}	0.204 ± 0.007 ^{a}	0.161 ± 0.025 ^{a}
	$p < 0.001$ *	$p = 0.006$ *	$p < 0.001$ *	$p = 0.031$ *
Raw × 15	14.21 ± 0.99 ^{b}	0.348 ± 0.044 ^{b}	0.414 ± 0.039 ^{b}	0.459 ± 0.084 ^{b}
Boiled × 15	7.01 ± 0.25 ^{a}	0.243 ± 0.016 ^{ab}	0.291 ± 0.022 ^{a}	0.285 ± 0.043 ^{ab}
Fried × 15	7.51 ± 0.40 ^{a}	0.188 ± 0.019 ^{a}	0.221 ± 0.018 ^{a}	0.224 ± 0.022 ^{a}
	$p = 0.001$ *	$p = 0.014$ *	$p = 0.001$ *	$p = 0.002$ *
Raw × 23	13.65 ± 1.60 ^{b}	0.357 ± 0.042 ^{b}	0.512 ± 0.071 ^{b}	0.247 ± 0.041 ^{b}
Boiled × 23	6.97 ± 0.22 ^{a}	0.250 ± 0.019 ^{ab}	0.247 ± 0.017 ^{a}	0.140 ± 0.008 ^{a}
Fried × 23	8.15 ± 0.49 ^{a}	0.219 ± 0.021 ^{a}	0.264 ± 0.026 ^{a}	0.255 ± 0.008 ^{b}
Cooking method × UV-C treatment	$p < 0.001$ *	$p = 0.012$ *	$p = 0.003$ *	$p < 0.001$ *
Raw × Control	19.29 ± 0.45 ^{c}	0.193 ± 0.009 ^{a}	0.343 ± 0.026 ^{a}	0.234 ± 0.023 ^{a}
Raw × 3-UV-C	15.73 ± 0.43 ^{b}	0.225 ± 0.025 ^{ab}	0.333 ± 0.018 ^{a}	0.278 ± 0.009 ^{a}
Raw × 5-UV-C	13.27 ± 0.93 ^{a}	0.381 ± 0.044 ^{b}	0.575 ± 0.055 ^{b}	0.754 ± 0.112 ^{b}
Raw × 10-UV-C	12.50 ± 0.57 ^{a}	0.242 ± 0.031 ^{ab}	0.337 ± 0.018 ^{a}	0.306 ± 0.031 ^{a}
	$p = 0.204$	$p = 0.492$	$p = 0.206$	$p = 0.245$
Boiled × Control	7.07 ± 0.18 ^{a}	0.169 ± 0.007 ^{a}	0.210 ± 0.012 ^{a}	0.201 ± 0.019 ^{a}
Boiled × 3-UV-C	7.09 ± 0.42 ^{a}	0.193 ± 0.023 ^{a}	0.239 ± 0.009 ^{a}	0.210 ± 0.023 ^{a}
Boiled × 5-UV-C	6.53 ± 0.25 ^{a}	0.209 ± 0.019 ^{a}	0.257 ± 0.019 ^{a}	0.288 ± 0.037 ^{a}
Boiled × 10-UV-C	6.40 ± 0.14 ^{a}	0.204 ± 0.019 ^{a}	0.270 ± 0.022 ^{a}	0.226 ± 0.021 ^{a}

Table 1. *Cont.*

Source of Variation	Chlorogenic Acid	Fructose	Glucose	Sucrose
	$p = 0.050$ *	$p = 0.136$	$p = 0.219$	$p = 0.052$
Fried × Control	7.59 ± 0.24^{b}	0.174 ± 0.014^{a}	0.225 ± 0.017^{a}	0.200 ± 0.019^{a}
Fried × 3-UV-C	7.19 ± 0.58^{ab}	0.156 ± 0.006^{a}	0.206 ± 0.011^{a}	0.190 ± 0.009^{a}
Fried × 5-UV-C	6.64 ± 0.13^{a}	0.210 ± 0.021^{a}	0.259 ± 0.030^{a}	0.262 ± 0.038^{a}
Fried × 10-UV-C	6.76 ± 0.41^{ab}	0.184 ± 0.019^{a}	0.250 ± 0.020^{a}	0.227 ± 0.008^{a}
Grand mean	9.67	0.212	0.292	0.281

* Values are significant at $p \leq 0.05$. Results are expressed as mean ± SE. Different letters within column mean statistically different values at $p \leq 0.05$.

Table 2. The influence of UV-C treatment, storage, and cooking method on acrylamide (μg kg^{-1} DW) in fried fresh-cut potato.

Source of Variation	Acrylamide
UV-C treatment	$p < 0.001$ *
Control	480 ± 17.0^{a}
3-UV-C	558 ± 10.2^{a}
5-UV-C	763 ± 26.5^{b}
10-UV-C	590 ± 21.4^{ab}
Storage days	$p = 0.187$
0	530 ± 35.6^{a}
8	573 ± 30.5^{a}
11	586 ± 47.7^{a}
15	628 ± 45.1^{a}
23	670 ± 44.9^{a}
UV-C treatment × storage days	$p = 0.003$ *
Control × 0	390 ± 15.9^{a}
3-UV-C × 0	544 ± 25.1^{bc}
5-UV-C × 0	649 ± 20.5^{c}
10-UV-C × 0	539 ± 4.8^{b}
	$p = 0.006$ *
Control × 8	490 ± 11.9^{a}
3-UV-C × 8	558 ± 7.4^{a}
5-UV-C × 8	701 ± 28.1^{b}
10-UV-C × 8	544 ± 23.2^{a}
	$p = 0.001$ *
Control × 11	481 ± 15.3^{a}
3-UV-C × 11	518 ± 15.2^{a}
5-UV-C × 11	798 ± 29.6^{b}
10-UV-C × 11	547 ± 7.3^{a}
	$p = 0.001$ *
Control × 15	502 ± 14.4^{a}
3-UV-C × 15	572 ± 9.3^{ab}
5-UV-C × 15	818 ± 32.6^{c}
10-UV-C × 15	620 ± 10.7^{b}
	$p = 0.001$ *
Control × 23	537 ± 12.5^{a}
3-UV-C × 23	597 ± 11.2^{a}
5-UV-C × 23	847 ± 15.5^{c}
10-UV-C × 23	699 ± 25.1^{b}
Grand mean	670

* Values are significant at $p \leq 0.05$. Results are expressed as mean ± SE. Different letters within column mean statistically different values at $p \leq 0.05$.

3. Results and Discussion

3.1. Phenolics Analysis

According to the obtained results of phenolics, chlorogenic acid was the predominant compound in all FCP samples, while caffeic acid and rutin were present in concentrations below LOQ values, while *p*-coumaric acid and catechin were not detected. Therefore, only the results of chlorogenic acid are given in Table 1. Previously, other authors also found chlorogenic acid with its isomers as the most abundant phenolic compound (90%) in tubers [32]. It is located mostly in potato peel, followed by outer flesh. Catechin, rutin, and *p*-coumaric acid are also mainly located in potato peel but, depending on variety, they can be found in outer and/or inner flesh of potato tuber [32]. Generally, the phenolics content in potatoes is determined by various factors, such as cultivar type, growing and harvesting conditions, climatic conditions, crop maturity, and storage conditions [33–35].

Grand mean (GM) value of chlorogenic acid content was 9.67 mg 100 g^{-1} DW, which is slightly higher when compared to the chlorogenic acid GM of the same potato variety in the 2017 harvest (7.46 mg 100 g^{-1} DW) [28]. Statistical analysis did not show a significant effect of UV-C treatment on the content of chlorogenic acid, although a slight decrease with increasing of UV-C dose can be observed. This trend was additionally proved by the interaction of the cooking method vs. UV-C treatment, which distinguished the raw unirradiated control samples from the raw UV-C treated ones. The content of chlorogenic acid was significantly lower in UV-C treated samples, and it decreased with higher dose applied. It could be suggested that under the conditions of the present experiment, irradiation of FCP could have increased the activity of PPO, but more likely it could have decreased the activity of the PAL. In support of this, noticeable browning was not observed in irradiated samples during the experiment. The decrease of total phenolics due to increased UV-C dose was also reported for irradiated fresh-cut spinach [14]. On the contrary, Teoh et al. [7] noticed an increase of total phenolics in FCP which were irradiated before packaging and stored at +4 °C in permeable plastic boxes. This disagreement with the results of the present study could be, among other things, the result of various experimental conditions. However, when observing the influence UV-C treatment 75.53% of the initial amount of chlorogenic acid was retained after 10-UV-C, and 88.34% after 3-UV-C. Higher retention of chlorogenic acid is favorable since it has diverse health benefits, such as preventing cancer, cardiovascular diseases, and diabetes as well as anti-inflammatory effects [33,36,37]. In addition, chlorogenic acid from potatoes is found to produce an increase in insulin sensitivity and a decrease in gut glucose absorption as well as it prevents gluconeogenesis [33,38]. However, in terms of the browning process, lower content of chlorogenic acid is preferable [39].

No significant changes in the content of chlorogenic acid were observed during storage of FCP. The interaction of UV-C treatment vs. storage days did not show significant differences in the amount of chlorogenic acid between the FCP samples, although numerically, control had slightly higher values in comparison with UV-C treated samples during the entire storage period. However, the interaction of cooking method vs. storage days gives a better insight of the influence of storage time on the content of chlorogenic acid in raw FCP. Its levels decreased during the whole storage period, still retaining 78.99% at the 23rd day. Other authors also observed a decrease in phenolics during storage of FCP [7] which could be explained by the participation of chlorogenic acid as a substrate for PPO in oxidation reactions leading to tissue browning [40].

Boiling and frying significantly reduced the levels of chlorogenic acid when compared to raw samples. The same occurrence was observed by Tudela et al. [41]. In their study all cooked (boiled, steam boiled, fried, and microwaved) FCP samples of cv. Mona Lisa had a significantly lower content of caffeic acid derivates (50% of their initial amount). Additionally, the same authors reported higher values of caffeic acid derivates in boiled potatoes in comparison with fried ones. Contrary, Blessington et al. [42] observed higher levels of phenolics in cooked potato samples as opposed to raw samples, while the lowest content of phenolics was found in boiled potatoes compared to baked, fried, and microwaved

ones. Although the statistical analysis in the present study did not show the difference between boiled and fried samples with respect to chlorogenic acid amounts, the loss of chlorogenic acid was more pronounced in boiled (55.5%) than in fried (53.6%) FCP. Reduction in phenolics in cooked FCP could be associated to cell degradation which occurs during cooking at high temperatures, thus resulting in more easily release of phenolics and their further dissolution in water [43]. Furthermore, the content of phenolics in cooked potatoes depends not only on the method and conditions of cooking [42–44], but as well on the other factors such as oxidative enzyme action, solubility, interconversion of compounds, etc. [34]. Despite the decrease of chlorogenic acid amounts in raw FCP during storage, its content in cooked FCP was fairly uniform regardless of storage day (interaction cooking method vs. storage days). The interaction of cooking method vs. UV-C treatment did not show a clear effect of irradiation on the content of chlorogenic acid in the cooked samples.

3.2. Sugars Analysis

As presented in Table 1, glucose (GM 0.292 g 100 g^{-1} DW) and sucrose (GM 0.281 g 100 g^{-1} DW) were the most abundant sugars, followed by fructose (GM 0.212 g 100 g^{-1} DW). The content of reducing sugars was higher, while the amount of sucrose was lower than it was observed by Dite Hunjek et al. [28] who reported GM of glucose 0.17 g 100 g^{-1} DW, GM of fructose 0.13 g 100 g^{-1} DW, and GM of sucrose 0.54 g 100 g^{-1} DW in FCP of the same cultivar harvested in 2017. The differences in levels of sugars were probably caused by different treatment, pre- and post-harvest factors, such as specific climatic conditions during growth [45,46].

UV-C treatment significantly affected fructose and sucrose, in particular, 5-UV-C treatment significantly increased its amount. Their values were approximately 1.5- to 2.0-fold higher when compared to their values in control or 3-UV-C treated samples. The same trend was observed for glucose (1.4-fold higher), although it was not significant. The UV-C radiation can affect the activity of several enzymes related to sugar metabolism, and therefore alter sugars amount in fruits and vegetables [15,47]. It could be assumed that UV-C irradiation, primarily 5-UV-C applied on FCP, also affected enzyme activity resulting in sugars increase. Therefore, for better understanding of the effect of UV-C irradiation on FCP and consequently on the content of sugars, additional studies should be performed. Still, in comparison with other FCP samples, higher amounts of sugars in 5-UV-C treated samples were clearly noticeable throughout the entire storage period except at the first day (UV-C treatment vs. storage days). It can also be observed that the levels of sugars in 3-UV-C and 10-UV-C irradiated FCP did not differ significantly from the control. These results indicate the importance of selecting the most adequate irradiation dose that would result in a lower increase of sugars, since it is associated with a lower potential of acrylamide forming during frying [48].

According to the statistical analysis, fructose content significantly increased during storage and it was even more pronounced after the 15th day. Although it was statistically insignificant, the content of glucose and sucrose increased as well, while sucrose content decreased after the 15th day. These changes during refrigerated storage could be the result of a low-temperature sweetening [15,49], as well as a consequence of sucrose hydrolysis by enzyme invertase. Similar increase in glucose and fructose amounts was observed in the last days of storage in UV-C treated peaches [47].

Regardless of the cooking method, the sugar content decreased and difference between boiled and fried samples was almost indistinguishable. This reduction in boiled FCP samples was probably due to solubility of sugars in water and sugars leaking [50,51] and in fried samples reducing sugars can undergo Maillard reaction to form color and aroma compounds and, to a lesser extent, acrylamide by reaction with L-asparagine [20,52,53]. Literature data showed variability in the content of sugars in cooked potatoes according to the cooking method and conditions [15,54]. Observing the interaction of cooking method vs. UV-C treatment for the raw samples, it can be noticed that all analyzed sugars were present in the highest amounts in raw 5-UV-C irradiated samples. Despite this significant

excess of sugars in raw 5-UV-C samples, further cooking lowered it remarkably and there were no significant differences in levels of sugars between the samples after cooking. Regardless of the storage day, raw FCP was characterized with significantly higher content of sugars (cooking method vs. storage days), while there was no particular trend for cooked FCP samples.

3.3. Acrylamide Analysis

UV-C treatment of raw FCP had a significant influence on the content of acrylamide in fried FCP, while the influence of raw FCP storage on the acrylamide amounts was not observed (Table 2). GM of acrylamide content was 597.47 μg kg^{-1} DW.

It was observed that all samples treated with UV-C were described with higher acrylamide content in comparison with control, however, 5-UV-C irradiated raw samples had the highest acrylamide content of 762.47 μg kg^{-1} DW what was approx. 1.5-fold higher when compared to control and 3-UV-C treated samples. Here it should be noted that the highest content of reducing sugars (0.96 g 100 g^{-1} DW) was also found in raw 5-UV-C treated samples. Since reducing sugars are precursors in Maillard's reactions, their increased content could have a significant role in acrylamide formation [55]. Accordingly, calculated Spearman's correlation coefficient showed a strong positive correlation between the content of acrylamide in fried and reducing sugars in raw samples (r = 0.74), while moderate positive correlation (r = 0.53) characterized the relation of acrylamide and sucrose amounts. This is in line with previously reported observations [28,55]. The proposed level of reducing sugars in potato tubers intended for roasting or frying is below 1 g kg^{-1} FW and it can ensure a formation of acrylamide below 500 μg kg^{-1} FW [56]. As it can be seen, regardless of the applied UV-C treatment the content of sugars (Table 1) and acrylamide (Table 2) was always below the assumed limits which according to ECR 2017/2158 for acrylamide is 750 μg kg $^{-1}$ FW, noting that the values expressed as DW are about three-fold higher than those expressed as FW. Similar increase in acrylamide level was observed by Sobol et al. [18] in fried potatoes produced from irradiated potato tubers.

Storage of raw FCP did not significantly affect the acrylamide amounts in fried FCP, although a numerical increase was observed, reaching the highest level on the 23rd day (669.77 μg kg^{-1} DW). The results of interaction UV-C treatment vs. storage days confirmed the significant impact of UV-C treatment where the highest levels of acrylamide were detected in 5-UV-C sample regardless of the day of storage. However, all obtained acrylamide values were below the assumed limits. Furthermore, there was a strong negative correlation (r = −0.77) between the content of acrylamide in fried FCP and chlorogenic acid in raw samples, which is in accordance with Zhu et al. [57] and Kalita et al. [58] who also found a negative correlation between the amounts of acrylamide and total phenolics as well as acrylamide and chlorogenic acid.

3.4. PCA Analysis

In addition to ANOVA, PCA was also performed in order to test a possible separation of the FCP samples by the content of chlorogenic acid and individual sugars with respect to UV-C treatment, storage days, and cooking method. Obtained biplots of the distribution of FCP samples in relation to the storage time and method of cooking are presented in Figure 1, while the biplots of the distribution of raw, boiled, and fried FCP according to the applied UV-C treatment are given in Figure 2.

In terms of storage days and cooking method, PC1 and PC2 together described 84.65% of total variance. Strong positive correlation was present between PC1 and fructose (r = 0.86), glucose (r = 0.95), and sucrose (r = 0.80), while chlorogenic acid was in moderate positive correlation (r = 0.45) with this PC. On the other hand, a very strong negative correlation (r = −0.89) described the relation of chlorogenic acid and PC2. As it can be seen in Figure 1a, FCP samples did not distinguished by the days of storage, which confirms their fairly uniform composition over 23 days. Considering the effect of cooking method, a clear separation of raw FCP samples from the cooked ones is visible (Figure 1b). Raw

samples were mostly at positive PC1 values and were described with higher amounts of chlorogenic acid and sugars, unlike the majority of boiled and fried samples grouped mainly at negative PC1 values.

Regarding influence of UV-C treatment on raw FCP samples, PC1 and PC2 explained 87.74% of total variance (Figure 2a). PC1 was in negative strong correlation with chlorogenic acid (r = −0.78), while positive strong/very strong correlation was present between this PC and fructose (r = 0.91), glucose (r = 0.88), and sucrose (r = 0.71). PC2 showed positive moderate correlation only with sucrose (r = 0.65). Biplot showed separation of 5-UV-C treated samples, which were located mainly at positive PC1 values being characterized with higher levels of sugars. This is in accordance with previously discussed results (Table 1).

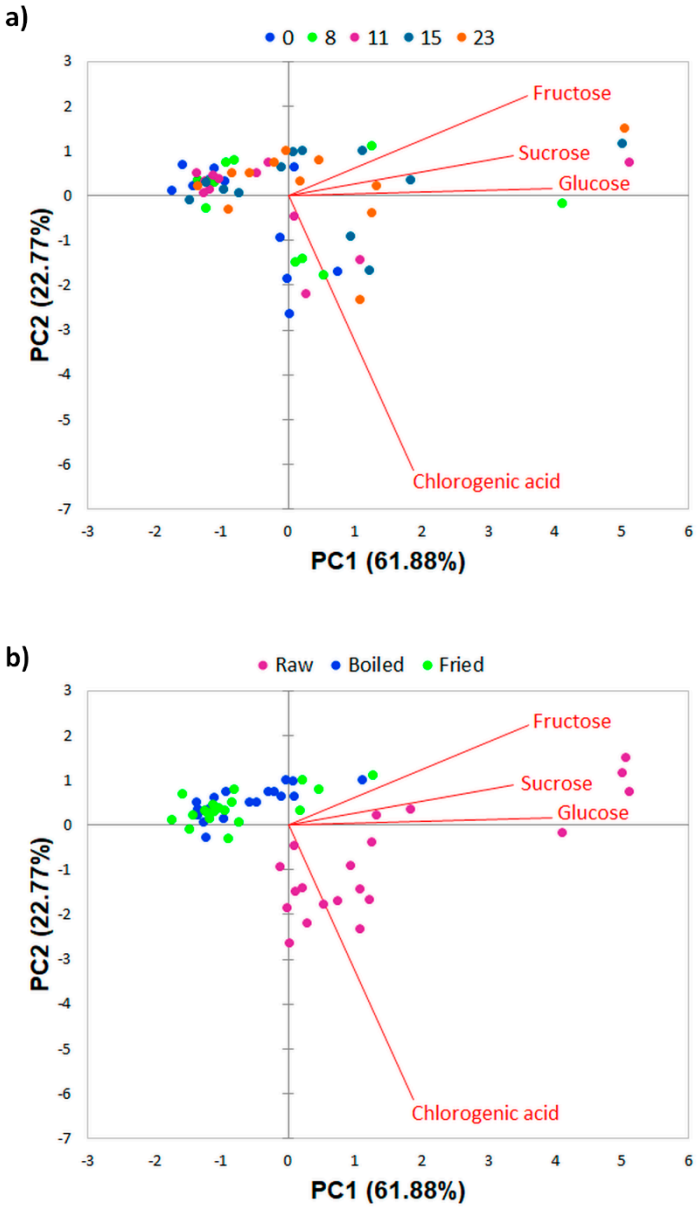

Figure 1. Distribution of UV-C untreated and treated fresh-cut potatoes in two-dimensional coordinate system defined by the first two principal components (PC1 and PC2) in relation to the (**a**) storage days and (**b**) cooking method.

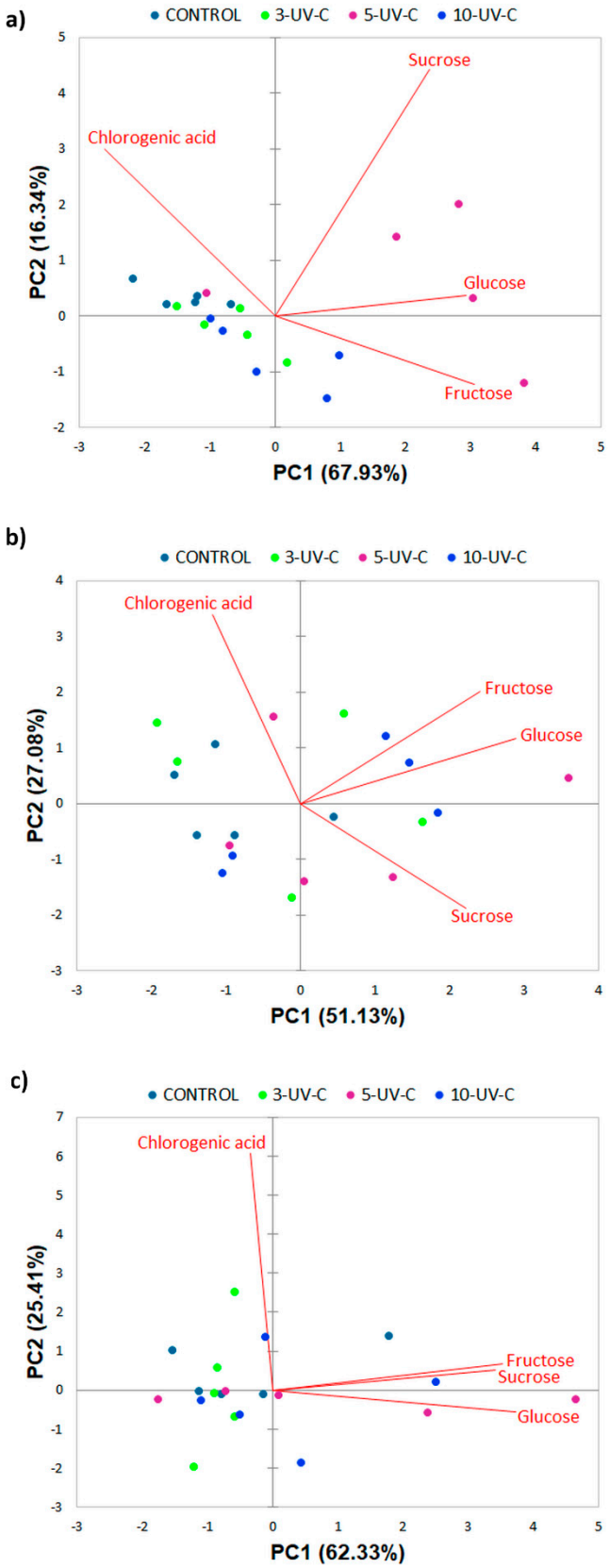

Figure 2. Distribution of (**a**) raw, (**b**) boiled, and (**c**) fried UV-C untreated and treated fresh-cut potatoes in two-dimensional coordinate system defined by the first two principal components (PC1 and PC2).

As for boiled FCP, total variation of the analytical parameters was 78.21% (Figure 2b) PC1 was in strong positive correlation with fructose (r = 0.76) and sucrose (r = 0.70) and in very strong correlation with glucose (r = 0.91), while PC2 was in strong positive correlation with chlorogenic acid (r = −0.78). As it can be seen, the majority of the control samples were grouped at negative values of PC1, having a lower content of sugars. According to the effect of UV-C irradiation on fried samples, PC1 and PC2 together described 87.74% of the variance (Figure 2c). Correlation between PC1 and fructose, glucose, and sucrose was positive and very strong (r = 0.90, 0.95 and 0.87, respectively), while positive very strong correlation described the relation between PC2 and chlorogenic acid (r = 0.99). A certain grouping of control and 3-UVC samples is noticeable at negative values of PC1, being characterized with lower levels of sugars when compared to 5-UV-C and 10-UV-C samples. These results are in line with already discussed observations given by interaction cooking method vs. UVC treatment (Table 1).

4. Conclusions

The obtained results revealed that applied UV-C treatments caused the slight reduction of chlorogenic acid and the increase of total sugars in the raw FCP samples, but still in acceptable concentrations. The observed increase in sugars, which was particularly pronounced when 5-UV-C irradiation was applied, did not affect the acrylamide safety of the product, as all fried samples contained acrylamide levels below the limit value approved by EFSA and EU Commission Regulation 2017/2158. Furthermore, FCP samples maintained a relatively stable chemical composition during 23 days of storage. The results of this study showed that UV-C irradiation could certainly be of interest to the fresh-cut industry along with the well-known germicidal action, but further studies are needed.

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Effect of high hydrostatic pressure on the quality and shelf-life of fresh-cut potato

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Summary

The influence of high hydrostatic pressure (HHP) treatment (400 MPa/0, 3, 5 and 10 min) on the quality and sensory properties as well as microbial stability of fresh-cut potato was investigated along with the stability of the best evaluated samples during 15 days' storage in vacuum packaging at 6 °C. Potato slices immersed in sodium ascorbate solution (NaAsc) were treated by HHP and afterwards, slices were analyzed for color (CIELAB), firmness (texture analyzer) and aerobic mesophilic bacteria count (AMB). Slices were also boiled and fried, and all samples were sensory evaluated. Treatment reduced AMB, and did not significantly affect firmness, but it did lightness, where slices treated for 5 and 10 min were brighter. Same samples showed mechanical damage during frying, and they were sensory lower graded. Consequently, the stability of 0 and 3 min HHP treated and vacuum-packaged samples (0'-HHP; 3'-HHP) were examined during storage (8, 11 and 15 days). AMB increased during storage, but it was lower in 3'-HHP. Storage duration did not significantly affect firmness, but it did lightness (increase). Only 0'-HHP was sensory acceptable till the 8th storage day. Despite the excellent results of HHP on AMB, potato slices treated by HHP in NaAsc showed poor sensory properties.

Keywords: fresh-cut potato, high hydrostatic pressure, sensory, firmness, color

Introduction

Regarding preservation method, fresh-cut fruit and vegetables are exception among other fruit and vegetable (F&V) products which are mostly preserved by thermal treatment (heat or freezing). They are produced by minimal processing, which includes washing, peeling and cutting without thermal treatment due to its main characteristic, freshness which they should fulfill. Further, they should be simple to use and be ready to eat or to make easier and faster meal preparation, respectively. Due to its freshness and convenience consumers prefer such products, but its weakness is susceptibility to enzymatic browning, microbiological growth and losing quality traits and accordingly undesirable short shelf-life (Lamikanra, 2002) In order to overcome its sensitivity, fast deterioration and to preserve and insure its freshness, safety and excellent sensorial attributes, alternative preservation techniques for thermal treatment and use of chemical preservatives are being explored. Although Larson et al. reported in 1918 that high hydrostatic pressure (HHP) treatment destroyed bacteria and even 4 years earlier Hite, Giddings and Weakly studied the possibility of preserving fruit and vegetables with HHP, it started to be interesting in industrial food processing in late eighties of the last century (Rastogi et al., 2007) and it is still very actual topic which preoccupies

scientists. In F&V processing, application of HHP could be desirable replacement for thermal treatment since it can be effective in enzyme and microbial (MO) inactivation as well in preserving some very sensitive components or traits. This is especially important in fresh-cut sector considering that thermal treatment is not applicable. In general, HHP mostly affects non-covalent but not covalent bonds, thus components responsible for flavor, color and nutritive value remain almost unchanged oppositely to thermal treatment (Rastogi et al., 2007). During HHP treatment the material is instantaneously and evenly compressed by pressure regardless of its shape and size, hence it could be effective to enzyme or MO inactivation at ambient temperature (Eshtiaghi and Knorr, 1993). Pressure from 100 to 1000 MPa [commercially, up to 600 MPa (Duardo et. al., 2019)] could usually be applied, and its effectivnes mainly depends on the pressure strength, the exposure time and temperature (-20 to 60 °C), but there are also many others factors as well as nature of food matrix and MO as well as enzymes (Oey et al., 2008; Rendueles et al., 2011). In general, MO inactivation could be the result of permeabilization of cell membrane (Farr, 1990) and enzyme inactivation due to acting on non-covalent bonds and protein denaturation, some conformational changes and decompartmentalization (Gomes and Ledward, 1996). In spite of promissing results, HHP showed some limitations, e.g., it seems that enzymes could not be completely inactivated if only HHP is applied (Gomes and Ledward, 1996). Numerous researches has dealt with the impact of application of HHP treatment in combination with other methods or anti-browning agents on F&V behavior and changes, where for example fruit could be immersed in a sugar solution with or without addition of anti-browning agents in adequate pouch. Therefore, Argyri et al. (2014) investigated apricot, peach, and pear immersed in sucrose solution with addition of ascorbic acid or $SnCl_2$ and their interaction influenced by HHP 600 MPA/5 min at 10 °C, while Wolbang et al. (2007) explored melon cubes immersed in sucrose solution influenced by 600 MPA/10 min at ambient temperature. Moreover, HHP treatment of vacuum packaged vegetable was also studied, e.g., green beans treated by HHP 500 MPa/1 min at ambient temperature (Krebbers et al., 2002), carrots, green beans and broccoli treated by 600 or 400 MPa/2 min (McInerney et al., 2007) and onion by interactions of 5 min treatment by 100 – 400 MPa at 5 to 50 °C where 400 MPa/5 °C were the best conditions in preserving onion biological value Roldán-Marín (2009). Considering potato, Saraiva and Rodrigues (2011) found that HHP treatment of tubers by 50 and 100 MPa for 5 and 10 min was effective on sprouting prevention, what was generally confirmed later by Alexandre et al. (2015) reported that treatment of 30 MPa for 10 min at 60 °C was the most successful. In Eshtiaghi and Knorr (1993) study MO reduction and polyphenoloxidase inactivation was achieved in potato cubes immersed in citric acid solution and treated by 400 MPa for 15 min at 20 °C. Further, Al-Khusaibi and Niranjan (2012) reported that HHP treatment of vacuum packaged potato slices by 200 – 800 MPa/5 min at 25 °C caused higher oil uptake during frying when compared to control samples. However, Kuldiloke and Eshtiaghi (2008) reported opposite findings in case of HHP treated (400 or 600 MPa/5 min at 20 to 60 °C) vacuum packaged, subsequently frozen and then fried potato sticks. Duardo et al. (2019) gave an overview of HHP treatment application on potato, and pointed to an opening of the tissue structure exposed to HHP as well as the cell permeability increase what contributes to easier diffusion if pressure of 100 to 400 MPa was applied (Sopanangul et al., 2002). Still, HHP treatment could cause incomplete and ununiformed inactivation of enzymes, harder or even softer texture (Basak and Ramaswamy, 1998; Tangwangchai et al, 2000; Oey et al., 2008), color and flavor alteration (Oey et al., 2008).

In spite of general assume that HHP has no negative influence on sensory traits of F&V, obviously it depends on treatment conditions as well as nature of food matrix.
Therefore, the aim of this study was to investigate the influence of HHP treatment (400 MPa/0, 3, 5 and 10 min) in NaAsc solution on the microbial stability and quality of raw fresh-cut potato and its sensory properties before and after thermal treatment as well as stability of the best evaluated and vacuum-packaged samples during 15 days at 6 °C.

Materials and Methods

Plant material

In this experiment potato (*Solanum tuberosum* L.) tubers (cv. Birgit) harvested in 2019 and stored for one month in the dark (8 °C/RH app. 100 %) were used. Tubers originated from Slavonia region (Croatia).

Sample preparation and HHP treatment

Undamaged healthy potatoes of uniform size were washed under tap water, peeled with sharp hand peeled and sliced (0.4 cm) by hand slicer. Obtained slices (200 g) were packaged in 300 mL plastic jars and filled with NaAsc solution (2 %, *w/v*). Plastic jars were closed tightly and then vacuum packaged (LAVEZZINI START GAS, Italy) in polyamide/polyethylene (PA/PE) bags with film thickness 90 µm and afterwards HHP treated.
For HHP treatment Stansted Fluid Power device (Great Britain) was used. The pressure fluid was glycerol. Potato slices were treated by 400 MPa during 3, 5 and 10 min at ambient temperature and samples were coded as 3'-HHP, 5'-HHP and 10'-HHP, respectively. After treatment, slices were drained in colander to reduce surface moisture and packaged in vacuum in 90 µm PA/PE bags. Slices dipped for 3 min in SA solution, drained, and vacuum packed without HHP treatment were used as control sample (0'-HHP). After HHP and thermal treatments sensory evaluation of raw and thermally treated slices was conducted. The HHP treatment which gave the best sensory results was selected for further experiment. In order to examine stability during storage whole procedure under selected conditions was repeated followed by draining and vacuum packaging. Control samples and HHP treated samples were stored at 6 °C/15 days. At the same day of treatment and after 8, 11 and 15 days samples were analyzed, thermally treated and sensory evaluated.

Thermal treatment

All samples were boiled and fried. Slices were put in boiling (at 100 °C) distilled water (ratio water: sample=5:1) for 15 min and drained (boiled samples), while frying of slices was carried out in sunflower oil (ratio oil:sample=5:1) at initial temperature of 180 °C for 5 min (fried samples). The surface moisture or oil of cooked slices was removed with paper towel.

Microbiological analysis

Aerobic mesophilic bacteria count (AMB) was determined in several raw slices of each sample (n=2) by HRN EN ISO 4833-1:2013 (ISO 4833-1: 2013, EN ISO 4833-1:2013) method and the results were expressed as mean values of $\log_{10}$ CFU/g.

Firmness analysis

The firmness of raw fresh-cut potato samples was determined using a texture analyzer by TA.HD.plus Texture Analyser (Stable Micro Systems, UK) with 5 kg load cell and 2 mm stainless-steel punch probe. Pre-test speed was set to 1 mm/s and test speed to 0.5 mm/s. Firmness was determined by measuring the maximum force (N) required for probe to penetrate into the slices. The measurements were performed on three slices of each sample with 1 puncture on each slice (n=3) and the results were expressed as mean value± standard error (SE).

Color analysis

The color of raw FCP slices was measured by a colorimeter (CR-5, Konica Minolta, Tokio, Japan) equipped with D65 light source with 2° angle observer and measuring plate with 30 mm diameter hole. CIELAB color parameters L^* (lightness), a^* (red/green) and b^* (yellow/blue) were recorded, but only L^* values are presented. Measurements were performed on three slices (n=3) and results were expressed as the mean value ±SE.

Sensory evaluation

Sensory evaluation was performed by 5 trained panelists and according to the procedure (ISO, 1985, 2012) and previously described method by Dite Hunjek et al. (2020b), slightly modified. Briefly, quantitative descriptive method was used with a standard five-point scale from 0 to 5. Color of the raw and boiled FCP was evaluated as intensity of browning, where 0=absent and 5=complete browning, while color of fried potato was evaluated as characteristic color (0=absence of characteristic color to 5=complete characteristic color). Intensity of characteristic potato taste and off-taste were evaluated by 0=absent to 5=very pronounced. Firmness of raw potatoes was tested by palpation of the slices, while firmness of thermally treated samples was evaluated by chewing, and scored from 0=very soft to 5=very firm. The sensory evaluation included more attributes but for this results presentation only the major ones were selected.

Statistical analysis

The statistical analysis was carried out using one-way and two-way analysis of variance (ANOVA) and marginal means were compared using Tukey's post-hoc test. The significance level for all tests was $\alpha \leq 0.05$. The analysis was performed using Statistica ver. 10.0 software (Statsoft Inc., Tulsa, OK, USA).

Results and Discussion

Microbiological analysis

The started AMB count in the control sample was low (Fig. 1) and much lower than reported earlier (Estiaghi and Knor, 1993), but it was similar to data in our previous study related to fresh-cut apples also treated with anti-browning agents (Levaj et al., 2020; Putnik et al., 2017). The AMB reduction in 10'-HHP treated samples was 1 $\log_{10}$CFU/g unlike of reported 4 log cycles also achieved with 400 MPa but during 15 min (Estiaghi and Knor, 1993). At the same time, it was the highest AMB reduction (50 % to 0'-HHP), while between 0'-HHP and 3'-HHP the reduction was only 15 %, between 3'-HHP and 5'-HHP only 5 % and between 5'-HHP and 10'-HHP even 38 %. In further part of the experiment only 0'-HHP and 3'-HHP were analyzed during storage. Although AMB was reduced by the treatment, it increased with storage time, but much slower in 3'-HHP when compared to 0'-HHP (Fig. 1). On the 15th day AMB in 3'-HHP was under the limit set by the Regulations although it refers to ready-to-eat fresh-cut F&V, which fresh-cut potato does not represent considering it is ready-to-use product intended for further thermal treatment.

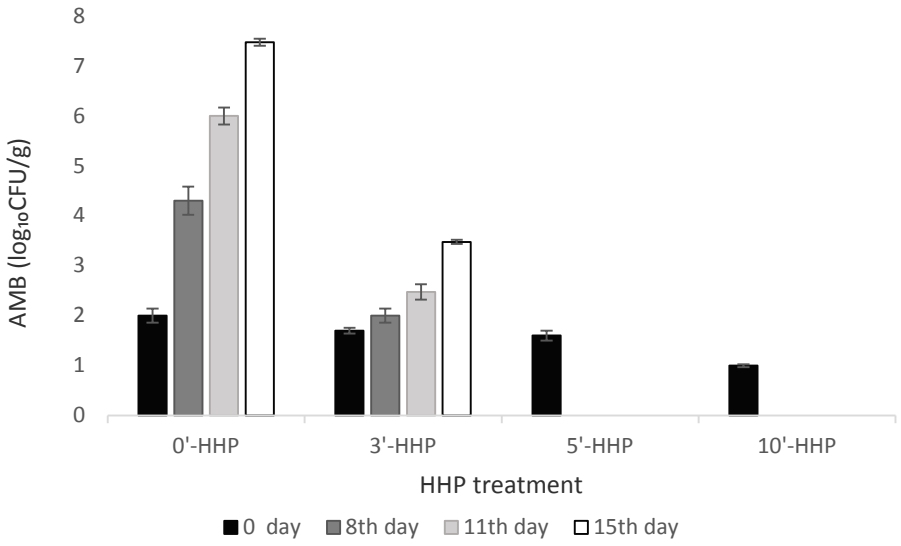

Figure 1. Microbial analysis of aerobic mesophilic bacteria (AMB) expressed as log CFU/g of raw fresh-cut potatoes during 15 days storage

Influence of HHP treatment

Treatment significantly affected sensory evaluated firmness, but not firmness instrumentally measured (Table 1) although according to numerical values treated samples were firmer (8.06 – 9.17 N) than 0'-HHP (7.32 N) (Fig 2a). Similar observation was reported by Al-Khuseibi et al. (2005). Firmness of 0'-HHP sample was similar to already obtained results for the same potato cultivar (Dite Hunjek et al., 2020a). HHP treatment could cause a cell disruption and incomplete enzymes inactivation, and consequently enabled contact of pectinmethylesterase and high methoxy-pectin what leads to its deesterification likely followed by gel-formation responsible to

firmer texture (Oey et al., 2018). If such alteration of molecular structure has occurred, it was not recognized sensorially. HHP treatment significantly affected lightness (Table 1) which was measured in the range of 61.06 (3'-HHP) – 66.17 (5'-HHP), where slices treated for 5 and 10 min were brighter (Fig. 2b). Such values are slightly lower to already obtained results for the same potato cultivar (Dite Hunjek et al., 2020a) likely due to different harvesting year. Sensory color was monitored in terms of browning appearance, and no browning was noticed at all. Cv. Birgit is known as very resistant to browning (European Cultivated Potato Database, 2017; Dite Hunjek et al. 2020a; Dite Hunjek et al., 2020b). Moreover, increase of *L** in HHP treated tomato purée was also reported by Sánchez-Moreno et al. (2006). Textural alterations which occur during HHP could influence on distribution of surface reflectance (Oey et al., 2018), what could be the reason for brighter slices and not the pigment losses (MacDougall, 2002).

Table 1. Influence of HHP treatment on firmness (instrumental and sensory) and color (*L**) of raw fresh-cut potatoes and sensory attributes of boiled and fried fresh-cut potatoes

HHP	**Raw**		
(min)	Firmness (N)	*L**	Sensory-firmness
	p=0.10	p=0.02*	p=0.05*
0	7.32±0.45^{a}	61.75±0.95^{a}	4.7±0.3^{b}
3	9.17±0.45^{a}	61.06±0.95^{a}	4.3±0.3^{b}
5	8.06±0.45^{a}	66.17±0.95^{b}	3.3±0.3^{a}
10	8.41±0.45^{a}	64.53±0.95^{ab}	3.3±0.3^{a}
	Boiled - sensory		
	Sensory-firmness	Potato taste	Off-taste
	p=0.97	p=0.01*	p=0.05*
0	1.7±0.6^{a}	4.3±0.5^{b}	0.7±0.6^{a}
3	1.3±0.6^{a}	3.0±0.5^{b}	1.0±0.6^{a}
5	1.3±0.6^{a}	1.7±0.5^{ab}	2.0±0.6^{b}
10	1.3±0.6^{a}	1.3±0.5^{a}	2.7±0.6^{b}
	Fried - sensory		
	Sensory-firmness	Potato taste	Off-taste
	p=0.92	p=0.01*	p=0.05*
0	2.7±0.8^{a}	4.7±0.5^{b}	0.3±0.3^{a}
3	2.7±0.8^{a}	4.3±0.5^{b}	0.7±0.3^{a}
5	2.3±0.8^{a}	3.0±0.5^{ab}	1.7±0.3^{b}
10	2.0±0.8^{a}	2.0±0.5^{a}	1.7±0.3^{b}

*HHP=high hydrostatic pressure, *Statistically significant variable at p≤0.05. Results are expressed as mean±SE. Values with different letters within column are statistically different at p≤0.05.*

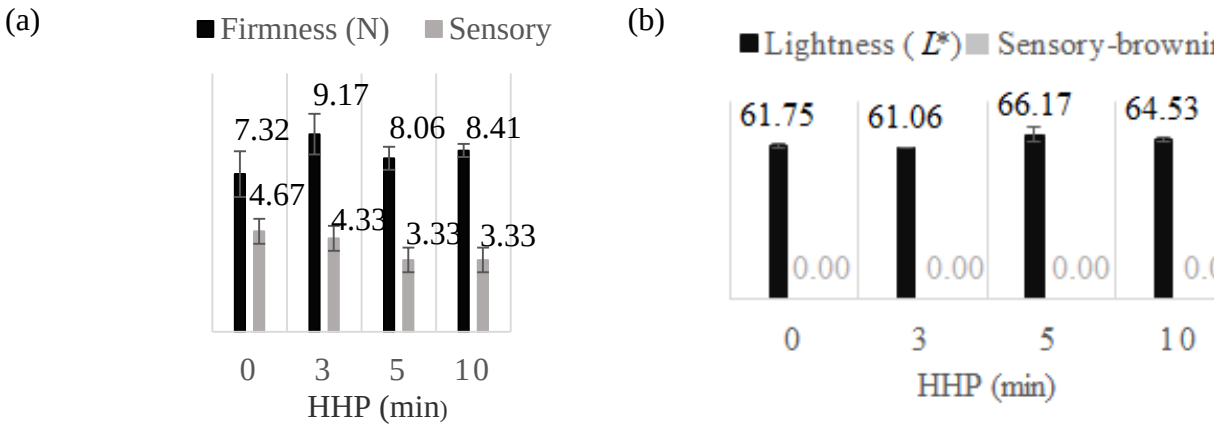

Figure 2. Firmness (a) and color (b) of raw fresh-cut potatoes influenced by HHP treatment (0, 3, 5, 10 min)

Sensory evaluation of boiled and fried HHP treated slices

Due to necessity of thermal treatment the potato prior its consummation and to obtain a complete insight of HHP influence on potato slices, its boiling and frying was performed. HHP significantly affected potato taste and off-taste, but not sensory evaluated firmness and color of boiled and fried slices (Table 1). In boiled potatoes there was no browning observed and in fried ones characteristic color was unchanged (Fig. 3). But longer HHP duration had a negative impact on potato taste and off-taste also appeared. Such results suggest that 5 and 10 min HHP treatment induced some reactions which resulted with the loss of typical potato taste and the appearance of off-taste in cooked potato.

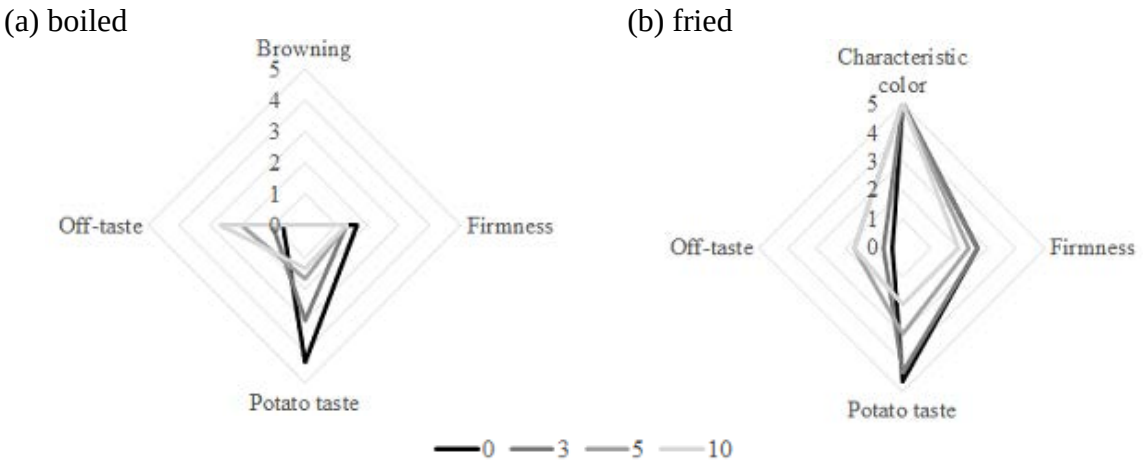

Figure 3. Sensory scores of boiled (a) and fried (b) fresh-cut potatoes influenced by HHP treatment (0, 3, 5, 10 min)

Generally, characteristic taste of boiled or fried potatoes is the result of complex content of different chemical compounds (Jansky, 2010, Thybo et al., 2006), and HHP treatment obviously affected it since HHP can stimulate or slow down enzymatic and chemical reactions

and consequently influence on taste (Oey et al. 2018). Further, Thybo et al. (2006) found that mechanical stress can contribute to potato off-flavor. In spite of no significant influence on firmness, 5'-HHP and 10'-HHP samples experienced certain mechanical damage during frying (Fig. 4) and the oil spattered strongly during their frying due to possible internal tissue damage and solution infusion (Sopanangkul et al., 2002).
Consequently, stability of untreated samples and only ones HHP treated for 3 min was examined during storage at 6 °C (after 8, 11 and 15 days).

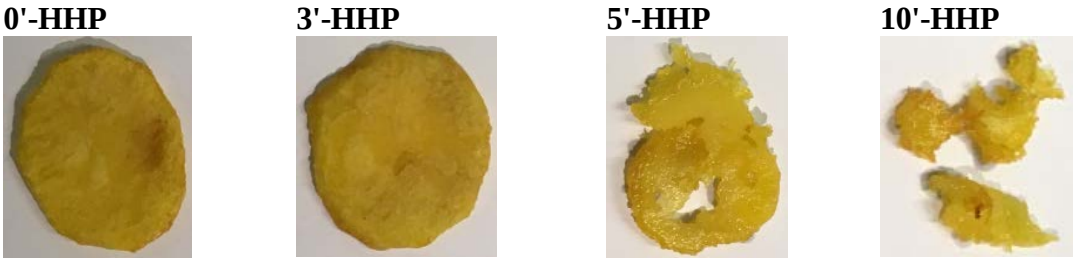

Figure 4. Photo of untreated and HHP-treated potato slices after frying

Influence of HHP treatment and storage

Storage and HHP treatment did not significantly affect sensory evaluated neither instrumentally measured firmness (Table 2) although according to marginal means of instrumentally measured values treated samples were firmer (9.11 N) than 0'-HHP ones (8.27 N). On Fig. 5a certain oscillations during storage can be seen what is similar to previous results (Dite Hunjek et al., 2020a; Dite Hunjek et al., 2020b) but without a statistical significance (Table 2).

Sensory evaluation of boiled and fried HHP treated slices during storage

Storage and HHP treatment significantly affected lightness (Table 2) which was measured in the range of 61.06 (3'-HHP/1st day) – 69.37 (3'-HHP/15th day), where 3'-HHP slices were brighter during storage than 0'-HHP, and during storage both of the samples became brighter (Fig. 5b). Sensory browning was not noticed with an exception of negligible browning of some 3'-HHP slices on 15th storage day, what is in accordance to earlier mentioned resistance to browning of cv. Birgit (European Cultivated Potato Database, 2017; Dite Hunjek et al., 2020a; Dite Hunjek et al., 2020b). Storage and HHP treatment significantly affected sensory evaluated color, potato taste and off-taste, but not firmness of boiled and fried slices (Table 2). During storage, especially on the 15th day in boiled samples slight browning was noticed (less in 3'-HHP) as well as a decrease of characteristic color of fried samples (more in 3'-HHP) (Fig. 6). With storage longer than 8 days a negative impact on potato taste of boiled samples was noticed as well as off-taste appeared and it was more pronounced in 3'-HHP than in 0'-HHP. Similar observations were recognized in fried samples but they were less pronounced. It was also previously reported by Dite Hunjek et al. (2020a, 2020b) that all negative impact on taste during storage is less noticed in fried than in boiled potatoes. Based on the sensory results, 0'-HHP was acceptable till the 8th day and in spite of HHP treatment had a slight positive effect on less pronounced browning of boiled slices, all other attributes were better evaluated in 0'-HHP.

Table 2. Influence of HHP treatment and storage on firmness and color (instrumental and sensory) of raw fresh-cut potatoes and on sensory attributes of boiled and fried fresh-cut potatoes

Source of variation	**Raw**			
	Firmness	*L**	Sensory-browning	Sensory-firmness
HHP (min)	p=0.06	p<0.01*	p=1.0	p=0.83
0	8.27±0.29^{a}	64.91±0.18^{a}	0.1±0.1^{a}	4.2±0.3^{a}
3	9.11±0.29^{a}	66.20±0.18^{b}	0.1±0.1^{a}	4.1±0.3^{a}
Storage (day)	p=0.52	p<0.01*	p=0.15	p=0.39
0	8.25±0.41^{a}	61.41±0.25^{a}	0.0±0.1^{a}	4.5±0.4^{a}
8	8.59±0.41^{a}	66.28±0.25^{b}	0.0±0.1^{a}	3.7±0.4^{a}
11	9.09±0.41^{a}	65.79±0.25^{b}	0.0±0.1^{a}	3.9±0.4^{a}
15	8.83±0.41^{a}	68.74±0.25^{c}	0.3±0.1^{a}	4.4±0.4^{a}
	Boiled - sensory			
	Browning	Sensory-firmness	Potato taste	Off-taste
HHP (min)	p=0.57	p=0.17	p<0.01*	p<0.01*
0	0.3±0.1^{a}	2.0±0.2^{a}	3.0±0.2^{b}	0.9±0.3^{a}
3	0.3±0.1^{a}	2.5±0.2^{a}	1.6±0.2^{a}	2.3±0.3^{b}
Storage (day)	p<0.01*	p=0.10	p<0.01*	p<0.01*
0	0.0±0.1^{a}	1.5±0.3^{a}	3.7±0.3^{c}	0.8±0.4^{a}
8	0.2±0.1^{a}	2.3±0.3^{a}	2.8±0.3^{bc}	1.0±0.4^{a}
11	0.0±0.1^{a}	2.7±0.3^{a}	2.2±0.3^{b}	1.5±0.4^{a}
15	1.0±0.1^{b}	2.7±0.3^{a}	0.5±0.3^{a}	3.2±0.4^{b}
	Fried			
	Characteristic color	Sensory-firmness	Potato taste	Off-taste
HHP (min)	p<0.01*	p=0.17	p<0.01*	p<0.01*
0	4.8±0.1^{b}	2.7±0.4^{a}	4.6±0.1^{b}	0.3±0.2^{a}
3	4.3±0.1^{a}	3.4±0.4^{a}	3.8±0.1^{a}	1.3±0.2^{b}
Storage (day)	p<0.01*	p=0.30	p<0.01*	p=0.05*
0	5.0±0.1^{c}	2.7±0.5^{a}	4.5±0.2^{b}	0.5±0.3^{a}
8	5.0±0.1^{c}	2.5±0.5^{a}	4.8±0.2^{b}	0.3±0.3^{a}
11	4.3±0.1^{b}	3.8±0.5^{a}	4.3±0.2^{b}	0.8±0.3^{a}
15	3.7±0.1^{a}	3.2±0.5^{a}	3.2±0.2^{a}	1.5±0.3^{b}

*HHP=high hydrostatic pressure; *Statistically significant variable at p≤0.05. Results are expressed as mean±SE. Values with different letters within column are statistically different at p≤0.05.*

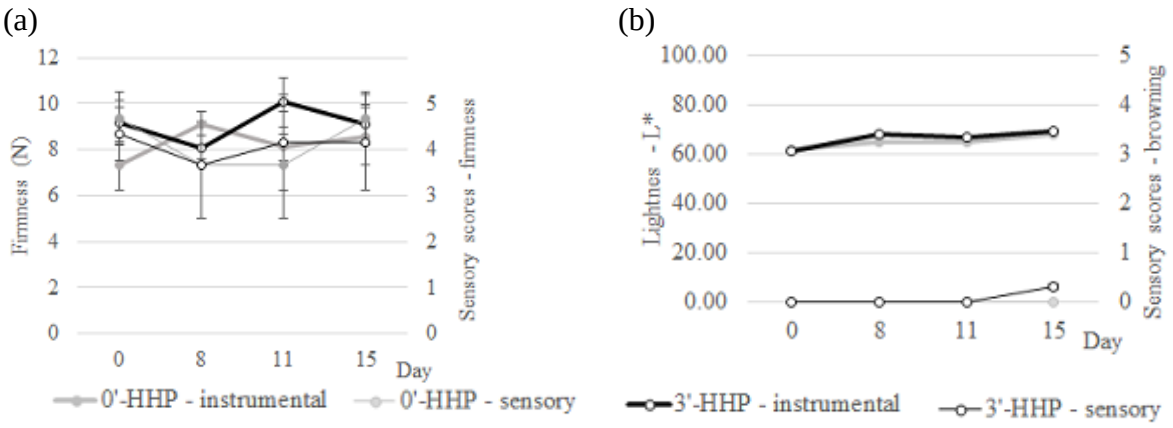

Figure 5. Texture (a) and color (b) of raw fresh-cut potatoes influenced by HHP treatment [0 (0'-HHP) and 3 min (3'HHP) treated] and storage time (0, 8, 11, and 15 days)

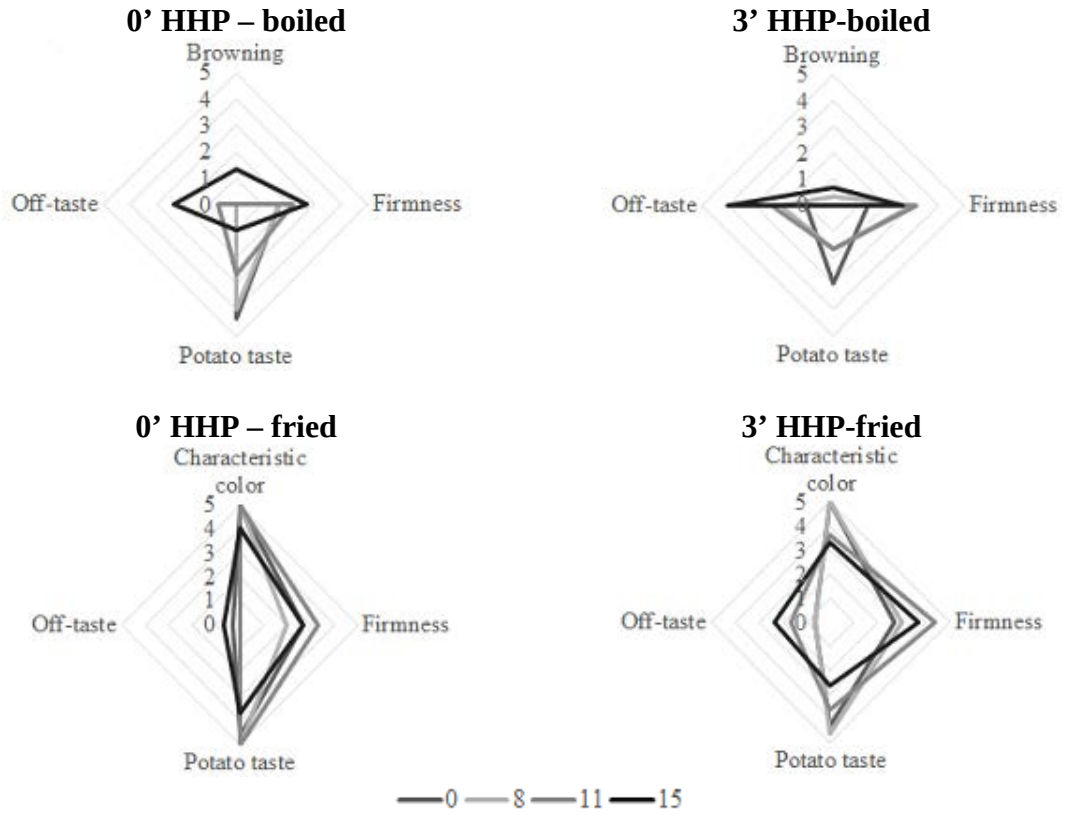

Figure 6. Sensory scores of boiled and fried fresh-cut potatoes influenced by HHP treatment [0 (0'-HHP) and 3 min (3'HHP) treated] and storage time (0, 8, 11, and 15 days)

Conclusions

Regarding sensory properties, only 0'-HHP samples were acceptable till the 8th day of storage. In spite of the excellent results for aerobic mesophilic bacteria count in HHP treated samples (400 MPa/3 min) in sodium ascorbate solution, such treated potato slices showed

poor sensory properties. Moreover, to avoid water diffusion into the potato tissue which disables frying, for the fresh-cut potato intended for frying, treatments without immersing slices in liquid media during HHP should be investigated.

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Publication No 4: Effect of UV-C Irradiation and High Hydrostatic Pressure on Microbiological, Chemical, Physical and Sensory Properties of Fresh-Cut Potatoes

Processes

Publication No. 4

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processes

MDPI

Article

Effect of UV-C Irradiation and High Hydrostatic Pressure on Microbiological, Chemical, Physical and Sensory Properties of Fresh-Cut Potatoes

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Abstract: UV-C irradiation and high hydrostatic pressure (HHP) successfully reduce the number of bacteria and their growth but can also affect phenolic and sugar content, as well as other physicochemical properties. Therefore, in this work, the effect of UV-C irradiation, HHP, and their combination, UV-C/HHP, on total aerobic mesophilic bacteria count (TAMBC), chlorogenic acid and sugar content, and other physicochemical properties of raw FCP were examined. Acrylamide and polycyclic aromatic hydrocarbons (PAH) were also monitored in treated FCP after frying. Vacuum-packed potato slices pretreated with an antibrowning agent were irradiated with UV-C (2.70 kJ m^{-2}), treated with HHP (400 MPa/3 min) and combined UV-C/HHP, and stored for 15 days. The greatest reduction in TAMBC was achieved in the UV-C/HHP-treated samples, followed by the HHP treatment, and they both resulted in the slowest bacterial growth during storage. All treatments decreased the contents of chlorogenic acid, but the greatest reduction was observed in the HHP-treated samples. All treatments increased the content of reducing sugars, and UV-C/HHP did so significantly, which also led to an increase in acrylamide content in the fried FCP. PAH levels were below the established limits. Acceptable sensory attributes of all samples (raw, boiled, and fried) remained relatively stable during storage.

Keywords: chlorogenic acid; acrylamide; reducing sugars; PAH; storage; cooking

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1. Introduction

Damage of the tissue during minimal processing of fruits and vegetables creates favorable conditions for the growth of microorganisms and increased enzyme activity, which, together with other undesirable changes, leads to a deterioration in the quality and safety of the product. Consequently, the mentioned changes shorten the shelf life of the products. The application of UV-C irradiation and high hydrostatic pressure (HHP) to fruits and vegetables has been shown to have a germicidal effect [1–3]. In potatoes, UV-C can significantly slow the growth of total aerobic mesophilic bacteria during storage when applied to potato tubers and slices [1,4], while application of HHP can delay microbial growth during storage or completely inactivate *Enterobacteriaceae* [3,5]. UV light affects the structure of DNA, which prevents cell replication [6–8], and its effectiveness depends on the applied intensity and irradiation time, among other factors. HHP has a complex effect; inter alia, it affects the denaturation of proteins and the destruction of ribosomes, which affects the structural organization of the cell and metabolic processes [9–11]. Its effectiveness depends on the pressure applied, the duration and temperature of the treatment, the properties of the suspension media used, and intrinsic factors such as pH, water activity, microorganism-related factors or the type of enzymes [3,12,13]. In addition, other factors may affect the efficacy of these methods, such as the characteristics of the plant material, packaging, or the antibrowning agent used.

Among the undesirable changes caused by minimal processing of potatoes is enzymatic browning. Polyphenol oxidase (PPO) enzymes catalyze the hydroxylation of monophenols to *o*-diphenols and oxidation to *o*-quinone that polymerize to dark melanin pigment [14,15]. Reducing enzyme activity can prevent browning of fresh-cut potatoes (FCP). Furthermore, the wound-induced phenylalanine ammonia-lyase (PAL) enzyme catalyzes the synthesis of phenolics, which serve as substrates for PPO and peroxidase (POD). Phenolics are not only involved in browning processes but also form an important group of compounds in potatoes due to their antioxidant properties. The most abundant phenolic component in potatoes is chlorogenic acid [16]. It has numerous beneficial effects on health, such as an anti-inflammatory effect or the prevention of cancer, cardiovascular disease, and diabetes [17–19]. In addition, the chlorogenic acid from potatoes can lead to an increase in insulin sensitivity and a decrease in glucose uptake in the intestine [17,20]. According to previous studies, the application of UV-C light and HHP treatment to peeled potato tubers and slices can reduce the content of chlorogenic acid [3,21].

Research on the effects of UV-C light are relatively scarce, and most of it is based on studying the effects on weight loss, germination, rot resistance, or changes in sugar content of potato tubers during storage. Reducing sugars (fructose and glucose), along with asparagine, are precursors of the probably carcinogenic acrylamide. Therefore, increasing their content in raw potatoes can potentially increase the acrylamide content in fried potatoes. Acrylamide is formed by Maillard reactions during frying at temperatures above 120 °C, and the maximum permitted level for potato products set by EU Commission Regulation 2017/2158 is 750 μg kg^{-1} [22]. UV-C treatment of potato tubers may increase acrylamide content in fried potatoes [23] or increase reducing sugars and acrylamide content in irradiated potato slices, depending on the irradiation dose applied [21]. As for the effect of HHP on potato sticks, no significant effect on acrylamide content was found [24].

In addition to acrylamide, polycyclic aromatic hydrocarbons (PAH) are another important group of toxic chemicals to monitor in fried potatoes. PAH are known for their genotoxicity and mutagenicity, which is particularly attributed to PAH heavy fraction with more than four aromatic rings [25]. Balbino et al. (2020) [26] determined the PAH content in fried fresh-cut potato samples and found levels of benzo(a)pyrene and ΣPAH4 of 0.62 and 1.36 μg kg^{-1}, respectively, both below the limits established in EU Regulation 835/2011 [27]. Environmental contamination of potatoes was identified as the most likely source of PAH in fried potatoes.

By monitoring the changes in the color parameters L^*, a^*, and b^*, possible enzymatic browning of fresh-cut potatoes (FCP) is evaluated as an indicator of the effectiveness of the applied UV-C and HHP treatment. According to previous studies, the application of UV-C light can increase the brightness (L^*) of raw FCP and preserve the sensory properties of subsequently thermally treated FCP [1]. HHP can have a negative effect on color in terms of browning, leading to lower L^* but also to increased PPO activity [28], or on the contrary, to a complete inactivation of PPO [29]. It is important to point out that there are numerous factors that affect the final result, and it is necessary to adapt the overall treatment conditions to a particular product.

The available scientific data on the influence of UV-C and HHP on the physicochemical and sensory properties of FCP are relatively modest. To our knowledge, the synergistic effect of UV-C and HHP on fresh-cut potatoes has not been studied so far. Considering the promising results of our previous studies [1,5,21], the aim of this study was to investigate which treatment, UV-C light, HHP, or the combined UV-C/HHP, could achieve the desirable quality and safety of FCP in terms of microbiological stability, physicochemical parameters, chlorogenic acid and sugar content, and sensory attributes in raw samples, as well as sensory attributes in subsequently boiled and fried FCP and also acrylamide and PAH in fried samples.

2. Materials and Methods

2.1. Chemicals and Standards

Standards of acrylamide (>99%), chlorogenic acid, fructose (≥99% GC), D-(+)-glucose (≥99.5% GC), and D-(+)-sucrose (≥99.5% GC) where purchased from Sigma-Aldrich (Steinheim, Germany), as well as solvents: formic acid, *n*-hexane, acetonitrile (HPLC-grade), and methanol (HPLC-grade). The QueChERS salt packet (4 g $MgSO_4$ and 0.5 g NaCl) and QueChERS d-SPE salts (150 mg $MgSO_4$ and 50 mg PSA) were purchased from Agilent Technologies (Santa Clara, CA, USA). The water was of Milli-Q quality (Millipore Corp., Bedford, MA, USA). Isopropyl alcohol, acetonitrile, and ethyl acetate were provided by T.J. Parker (Deventer, The Netherlands) and were of HPLC grade. Mixture of PAH at various concentrations in methylene chloride, methanol (1:1), were purchased from Supelco (Bellefonte, PA, USA). This standard mixture contains the 16 EPA PAH; however, not all 16 EPA PAH can be detected with this method.

2.2. Plant Material, Fresh-Cut Sample Preparation and Further Handling

Potato (*Solanum tuberosum* L.) tubers of cv. Birgit grown in 2019 in the Slavonia region (Croatia) were used for the experiment. Tubers were treated with Gro Stop Basis and Gro Stop Fog sprout inhibitors (Certis Europe, Great Abington, UK) and stored in wooden pallet boxes in the dark for 4 months (8 °C/RH approx. 100%) in a warehouse specialized for potatoes, where, as regular procedure, they were kept at 16 °C for 5 days before processing.

Undamaged and uniform potato tubers were selected for fresh-cut processing. Following the procedure described by Dite Hunjek et al. (2020) [30], tubers were washed with tap water, drained, peeled by hand, and sliced (0.4 cm) using a commercial slicer. After cutting, potatoes were dipped for 3 min at room temperature in a sodium ascorbate solution (2%, *m*/*V*). The drained potato samples (4–6 slices) were vacuum-packed(SmartVac SV 750; Status, Metlika, Slovenia) in a single layer in a polyamide/polyethylene (PA/PE) vacuum bag (Status, Metlika, Slovenia).

The samples prepared in this way were divided into (1) samples that were not to be subjected to further treatment (control); (2) samples for UV-C treatment (UV-C); (3) samples for high hydrostatic pressure (HHP) treatment; and (4) samples for combined UV-C and HHP (UV-C/HHP) treatment. The control samples were immediately stored at 6 °C in the refrigerator until further processing or analysis, while UV-C, HHP, and UV-C/HHP samples were subjected to irradiation and/or pressure treatments. After the treatments, these samples were stored in the refrigerator at 6 °C, like the control samples. On day 0, 8, 11, and 15 of storage, the treated and untreated samples were boiled or fried and analyzed together with the raw treated and untreated samples. On the mentioned storage days, the raw samples were analyzed for pH, total solids, total soluble solids, firmness, and color (instrumentally), while sensory analysis was performed on raw, boiled, and fried samples. In addition, fried and raw samples were frozen at −60 °C/24 h, freeze-dried (CoolSafe PRO, Labogene, Denmark), homogenized by grinding, and stored at −20 °C until further analysis of phenolics and sugars in raw and acrylamide and polycyclic aromatic hydrocarbons (PAH) in fried FCP.

2.3. UV-C, HHP, and Combined UV-C/HHP Treatment

UV-C irradiation of FCP was performed in a UV-C chamber (UVpro EKB 100; Orca GmbH, Kürten, Germany) equipped with 4 UV-C lamps (4 × HNSL 24W, maximum emission at 253.7 nm, UVpro), according to the procedure described by Pelaić et al. (2021) [31]. The vacuum-packed FCP samples were placed on the perforated shelf and irradiated for 5 min to obtain a dose of 2.70 kJ m^{-2}. This dose was chosen based on our previous research [1,21], primarily for its germicidal effect but also for the tested properties of FCP treated in this way.

HHP treatment of the vacuum-packed FCP was performed in a device from Stansted Fluid Power LTD (Stanford, UK) at a pressure of 400 MPa, with a pressure holding time of 3 min and a pressure fluid temperature of 25 °C. The compression rate was 10 MPa/s, and

the decompression rate was 50 MPa/s. Propylene glycol with water (1:1) was used as a pressure fluid. These conditions were chosen after experiments in our laboratory [5], with the specific difference being the packaging of the treated samples. Instead of dipping the potato slices in a sodium ascorbate solution and pressing them, the slices were previously vacuum-packed without liquid and then pressed.

The combined UV-C/HHP treatment was performed such that the samples were first irradiated with UV-C for 5 min and then subjected to the HHP treatment at a pressure of 400 MPa, with a pressure holding time of 3 min and a pressure fluid temperature of 25 °C.

2.4. Microbiological Analysis

Total aerobic mesophilic bacteria count (TAMBC) was determined by the Horizontal method—Colony count technique at 30 °C (HRN EN ISO 4833-1:2013) [32]. Dilutions (in peptone water, 0.1%, w/v) were applied as surface smears (1 mL) on plate count agar (Biolife, Milan, Italy) and incubated at 30 ± 1 °C for 72 ± 3 h in a drying oven (FN -500, Nüve, Ankara, Turkey). Analyses were performed on raw samples in duplicate (n = 2), and results are expressed in log CFU g^{-1} as mean ± standard error (SE).

2.5. Determination of Total Solids, Total Soluble Solids, and pH

Homogenized raw potato slices (Bosch MSM89160 blender, Robert Bosch GmbH, Gerlingen-Schillerhöhe, Germany) were used for determination of total solids (TS), total soluble solids (TSS), and pH. Potato samples were dried at 103 ± 2 °C (FN -500, Nüve) to a constant mass (AOAC, 1990), and TS was calculated as a percentage of the mass ratio before and after drying. The TSS were determined in homogenized FCP at 20 °C using a digital refractometer (DR201-95, A. Krüss Optronic GmbH, Hamburg, Germany) and expressed as °Brix. The pH was determined using a pH meter (SevenEasy pH Meter S20, Mettler Toledo, Greifensee, Switzerland). All measurements were performed in duplicate (n = 2), and results are expressed as mean ± (SE).

2.6. Firmness Analysis

The firmness analysis was performed on raw FCP samples using the TA.HD.plus Texture Analyser (StableMicro Systems, Godalming, UK) with a 5 kg load cell and a 2 mm stainless steel cylinder penetration probe. The pretest speed was 1 mm/s, and the test speed was 0.5 mm/s. Measurements were performed using Exponent Stable Micro System software v 6.1.18. in triplicate (n = 3), and results are expressed as mean (N) ± SE.

2.7. Color Analysis

The color of the raw samples was determined using a colorimeter (Spectrophotometer CM -3500d, Konica Minolta, Tokyo, Japan) equipped with a D65 light source with a 2° angular observer and a measuring plate with a 30 mm diameter hole. Measurements were performed on six slices (n = 6), and the CIELAB color parameters L^* (brightness), a^* (red/green), and b^* (yellow/blue) were determined. Results are expressed as mean ± SE.

2.8. Cooking Treatments

Boiling of FCP was performed in water (m(water):m(sample) = 5:1) at 100 °C/15 min and frying in sunflower oil (V(oil):m(sample)) = 1.0 L:120 g) at an initial temperature of 180 °C/5 min. Excess water or oil from the potatoes prepared in this way was removed with a paper towel. Samples prepared in this way were used for sensory evaluation and additionally fried for acrylamide and PAH analyses.

2.9. Analysis of Phenolics

2.9.1. Extraction of Phenolics

The extraction method previously described by Dite Hunjek et al. (2020) [31] was used for phenolics extraction. Briefly, 0.5 g of homogenized freeze-dried samples was extracted with 5 mL of 80% methanol with 1% formic acid (v/v) in an ultrasonic bath (Elmasonic

40H, Elma, Germany) at 50 °C/30 min and centrifuged at 3000 rpm/10 min (Hettich® Rotofix 32a, Tuttlingen, Germany). Extraction solvent (5 mL) was added to precipitate, and the procedure was repeated. Such obtained supernatants were combined in a 10 mL flask and made up with extraction solvent, filtered into vials (0.45 µm membrane filter, Macherey-Nagel GmbH & Co. KG, Düren, Germany), and stored at −20 °C until UPLC MS^2 analysis. Extractions were performed in duplicate (n = 2).

2.9.2. UPLC MS^2 Analysis of Phenolics

An Agilent 1290 series RRLC instrument with a triple quadrupole mass spectrometer (6430) (Agilent Technologies, Santa Clara, CA, USA) was used for UPLC MS^2 analysis. Zorbax Eclipse Plus C18 column (100 × 2.1 mm, 1.8 µm) (Agilent Technologies) was used for separation. The analysis was performed according to the previously described conditions and instrument settings by Elez Garofulić et al. (2018) [33]. Column temperature was 35 °C, the injection volume was 2.5 µL, and the flow rate was 0.3 mL min^{-1}. Eluent A was 0.1% formic acid (v/v) and eluent B 0.1% formic acid in acetonitrile (v/v). Ionization was performed by electrospray (ESI) in negative and positive mode (m/z 100–1000), and the ionization source parameters were capillary voltage of +4000/−3500 V, nitrogen temperature of 300 °C/flow rate 11 L h^{-1}, and nebulizer pressure of 40 psi. Data acquisition was performed in dynamic multiple reaction monitoring (dMRM) mode. Since in our previous study the other phenolic components were below the LOQ or not detected, in this study, we continued to only observe the changes in chlorogenic acid as the most abundant phenolic component in potatoes. Chlorogenic acid was identified using the retention time and mass spectra of the chlorogenic acid standard and quantified using a calibration curve obtained from the standard. Analytics parameters were as described in our previous study [21]. Results are expressed in mg 100 g^{-1} of dry weight (DW) as mean ± SE.

2.10. Sugar Analyses

2.10.1. Extraction of Sugars

Sugars were extracted according to the method described by Dite Hunjek et al. (2020) [31]. Homogenized freeze-dried samples (0.4 g) were mixed with 4 mL of 80% methanol (v/v), vortex homogenized, thermostated in a water bath at 60 °C/60 min, and centrifuged at 6000 rpm/15 min. The supernatant obtained was filtered into a 5 mL flask and made up with extraction solvent. The extracts were filtered through a 0.45 µm membrane filter into vials and stored at +4 °C until the analysis. Extractions were performed in duplicate (n = 2).

2.10.2. HPLC Analysis of Sugars

The determination of sugars (fructose, glucose, and sucrose) was performed as previously described by Dite Hunjek et al. (2020) [31] using an Agilent 1260 Infinity quaternary LC system (Agilent Technologies) equipped with a refractive index detector (RID). Cosmosil Sugar-D, 5 µm, 250 × 4.6 mm I.D. column (Nacalai Tesque, Inc., Kyoto, Japan) was used to separate compounds. Briefly, 80% acetonitrile (v/v) was used as the mobile phase in isocratic elution mode, and the chromatographic conditions were flow rate of 1.3 mL min^{-1}, injection volume of 10 µL, and column temperature of 45 °C. Sugars were identify by comparing retention times with those of standard solutions, while a fixed concentration of each sugar standard was used for quantification. Results are expressed in g 100 g^{-1} DW as mean ± SE.

2.11. Acrylamide Analysis

2.11.1. Extraction of Acrylamide

Acrylamide was extracted from homogenized, freeze-dried, and fried FCP according to the method described in our previous study [21]. To 1 g of sample, 5 mL of n-hexane was added, followed by 10 mL of water and 10 mL of acetonitrile, and shaken at vortex for 3 min. The QueChERS salt packet was added, shaken strongly for 1 min, and centrifuged at 5000 rpm/5 min. After centrifugation and discarding the hexane layer, 1 mL of the

acetonitrile layer was transferred to a 2 mL vial containing QueChERS d-SPE salts. After homogenization by vortex and centrifugation at 5000 rpm/1 min, 0.5 mL of the supernatant was transferred to vials and analyzed by UPLC MS^2. Extractions were performed in duplicate (n = 2).

2.11.2. UPLC MS^2 Analysis of Acrylamide

UPLC MS^2 analysis of acrylamide was performed using an Agilent UPLC system (Section 2.9.2). A Hypercarb TM column (5 µm, 50 mm × 2.1 mm) with a guard column (5 µm, 10 mm × 2 mm) (Thermo Hypersil-Keystone, Bellefonte, PA, USA) was used for separation. Chromatographic conditions and instrument settings were as previously described by Dite Hunjek et al. (2020) [31]. The temperature of the column was set at 22 °C, the injection volume was 10 µL, and the flow rate was 0.7 mL min^{-1}, and the mobile phase was 10% methanol with 0.1% formic acid. Electrospray (ESI) in positive ion mode was used for ionization. Acrylamide from the sample extracts was identified by comparing the peak ratios of the MRM transitions m/z 72→55.1 with those of the acrylamide standard. The calibration curve obtained from the extracted acrylamide standard solution was used for quantification, and results are expressed in µg kg^{-1} DW. The analytical parameters were as described in our previous study [21].

2.12. Polycyclic Aromatic Hydrocarbons (PAH) Analysis

Freeze-dried and subsequently fried FCP samples were extracted with acetonitrile and QuEChERS extraction salts, and supernatant was separated by centrifugation. The extract was purified with another type of QuEChERS salt, centrifuged, and transferred to a vial. PAH compounds were determined by the gas chromatography (GC) method coupled by mass spectrometer detection (GCMS/MS Thermo Scientific: Trace 1300 GC and TSQ 8000 Evo MS). GC analysis was carried out according to a temperature program with an initial temperature of 60 °C. Temperature was then increased from 35 °C/min to 160 °C, 3.5 °C/min to 260 °C, and 15 °C/min to 290 °C, where it was kept for 15 min. Separation was made on a TG -5SILMS W/5m Safeguard (Thermo Scientific, Waltham, MA, USA) column (30 m × 0.25 mm × 0.25 µm). The injector, electron source, and detector were set at temperatures of 310 °C, 320 °C, and 250 °C, respectively. Individual PAH compounds were identified based on qualifier ions (m/z): acenaphthylene (152.1; 151.1); acenaphthene (153.1; 152.1); fluorene (165.1; 164.1); phenanthrene (178.1; 152.1); anthracene (178.10; 152.1); fluoranthene (202.1; 200.1); pyrene (202.10; 201.10); benzo[a]anthracene (228.1; 226.1); crisis (228.1; 226.1); benzo(b)fluoranthene (250.1; 252.1); benzo(k)fluoranthene (250.1; 252.1); benzo(a)pyrene (250.1; 252.1); indeno(1,2,3-c, d)pyrene (276.1; 274.0); dibenzo(a, h)anthracene (278.1; 276.0); and benzo(g, h, i)perylene (276.1; 274.1). They were quantified through their calibration curves. Results are expressed in µg kg^{-1} DW as mean ± SE.

2.13. Sensory Monitoring

Sensory monitoring was performed according to the procedure described by Dite Hunjek et al. (2020) [30]. Quantitative Descriptive Analysis (QDA) of raw, boiled, and fried potato samples was performed at room temperature (20 °C) by a sensory panel consisting of a group of 6 trained people, following the procedure of ISO (1985, 2012) [34,35]. Quality was assessed using a standard scale from 0 (lowest score) to 5 (highest score). Color, i.e., browning intensity of raw and boiled FCP, was scored as follows: 0—no browning and 5—complete browning. The color of the fry is described as characteristic color. Odor and off-odor intensity were rated from 0—absent to 5—very pronounced, moistness from 0—very dry to 5—very wet, and firmness from 0—very soft to 5—very firm. For boiled and fried FCP, characteristic taste was evaluated and rated from 1—absent to 5—very pronounced. Oiliness and crispness (fried potato) were rated from 0—absent to 5—very pronounced, while creaminess (boiled potato) was scored from 0—absence of creamy texture to 5—melting in the mouth. The results (n = 7) are statistically analyzed and displayed graphically.

2.14. Statistical Analysis

The obtained experimental data were analyzed using XLSTAT ver. 2020.5.1 software (Addisoft, Paris, France). The influence of treatment (UV-C, HHP, and UV-C/HHP) and storage time (0, 8, 11, and 15 days) on TAMBC, chlorogenic acid and sugar content, pH, SS, TSS, firmness and color parameters of raw FCP, and acrylamide and PAH content in fried FCP were investigated. Analysis of variance (ANOVA) followed by Tukey's HSD test was used for dependent variables examination and determination of effect of factors and differences between the applied factor levels. In the case of TAMBC, chlorogenic acid, reducing sugars, and acrylamide, factor interaction was also considered. Standard deviation of the sampling distribution for all analyzed samples taken in statistical processing is expressed as SE. Normality and homoscedasticity of the residuals were tested by Shapiro–Wilk and Levene's test, respectively. In case the ANOVA assumptions were violated, adequate statistical analysis was applied. In the case of heteroscedastic variance, SE were calculated using the HC3 correction. In the case of normality violation, Kruskal–Wallis nonparametric test was used for dependent variables examination, followed by Dunn's post hoc test. The mean of all results obtained for a given property is listed at the end of the tables as the grand mean. Principal Component Analysis (PCA) was conducted for the sensory attributes of the raw and thermally treated samples using principal components (PC) with eigenvalue >1, and variables with communalities $\geq$0.5 were included. The significance level for all tests was $p \leq 0.05$.

3. Results and Discussion

3.1. Microbiological Analysis

All applied treatments significantly reduced TAMBC ($p < 0.01$) (Figure 1). The initial TAMBC of the control samples at the beginning of the storage (day 0) was 2.6 log CFU g^{-1}. The observed reductions on the same day were 1.0, 1.1, and 1.4 log CFU g^{-1} for UV-C, HHP, and UV-C/HHP, respectively.

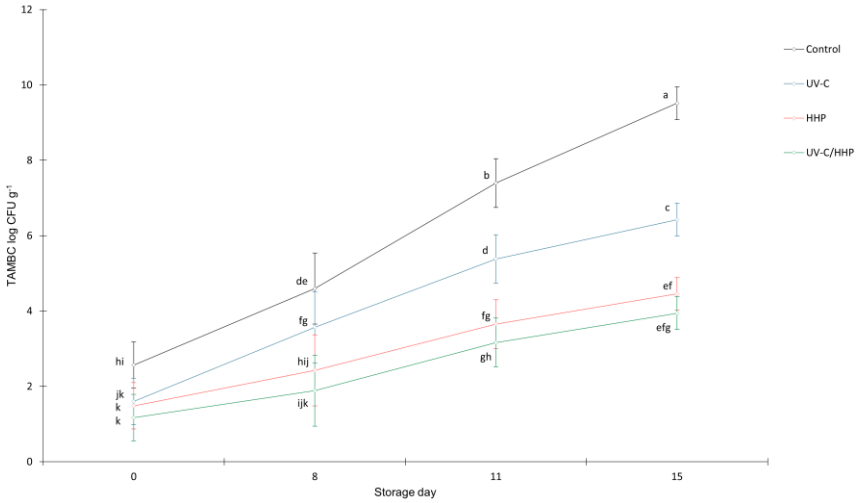


Figure 1. Total aerobic mesophilic bacteria count (TAMBC) of untreated (control) and treated (UV-C, HHP, and UV-C/HHP) raw, fresh-cut potatoes during storage. Error bars represent standard errors; lowercase letters represent a significant difference within means ($p < 0.05$).

During the 15-day storage period, TAMBC increased in all samples, especially in the control (from 2.6 to 9.5 log CFU g^{-1}), followed by UV-C. The increase in UV-C samples could be attributed to a strong repair mechanism—photoreactivation—as well as to replication of bacteria that remained functional after treatment [8,11]. Due to the rugged topography of FCP, some microorganisms may remain in the shade, so UV-C does not affect them. However, the slowest bacterial growth during the 15 days was observed in the HHP and UV-C/HHP samples, from 1.5 to 4.5 and from 1.2 to 3.9 log CFU g^{-1}, respectively. The

microbial inactivation caused by the treatments with HHP is probably related to the damage it causes to the structural organization of the cells, which can lead to damage of the cells, resulting in leakage of the cell contents and consequently cell death [13]. A reduction of 15% of TAMBC was found by Levaj et al. (2020) [5] by the same pressure conditions (400 MPa/3 min) applied on potato slices dipped in 2% sodium ascorbate solution. The greater efficacy of HHP in this study (reduction of 47%) may be due to the different sample preparation for HHP and further handling. In addition, Tsikrika et al. (2021) [3] also observed a significant reduction in aerobic bacterial counts when HHP (600) MPa was applied to peeled and vacuumed potato tubers. UV-C irradiation has also been shown to have an inhibitory effect on fresh-cut products [2,36]. In our previous study [1], UV-C treatment (2.70 kJ m^{-2}) was as effective in slowing down bacterial growth during storage, as in this study.

The EC regulations [37,38] on microbiological criteria for food safety related to TAMBC do not provide any information for fresh-cut food intended for further preparation. According to the Croatian Agency for Agriculture and Food [39], the borderline level of TAMBC for ready-to-eat vacuum-packed and refrigerated vegetables is given as $6 \leq 8$ log CFU g^{-1}. In the present study, TAMBC was below 6.5 log CFU g^{-1} in all samples, except the control sample in the 15th day with 9.52 log CFU g^{-1}.

3.2. TS, TSS, pH, and Firmness Analysis

According to the statistical results, treatment had a significant effect on TS, TSS, and pH and storage on TSS and pH (Table 1) of raw FCP. Firmness was not affected by treatment or storage.

Table 1. The influence of UV-C, HHP, and UV-C/HHP treatment and storage time on total solids content (TS), total soluble solids content (TSS), pH, and firmness of raw, fresh-cut potatoes.

Source of Variation	TS (%)	TSS (°Bx)	pH	Firmness (N)
Treatment	$p < 0.001$ *	$p < 0.001$ *	$p = 0.013$ *	$p = 0.608$
Control	25.19 ± 0.63 ^{b}	3.90 ± 0.06 ^{b}	5.60 ± 0.09 ^{ab}	7.22 ± 0.28 ^{a}
UV-C	27.60 ± 0.73 ^{ab}	4.33 ± 0.06 ^{a}	5.50 ± 0.07 ^{b}	7.22 ± 0.28 ^{a}
HHP	29.81 ± 0.99 ^{a}	4.66 ± 0.06 ^{a}	5.87 ± 0.04 ^{a}	7.32 ± 0.28 ^{a}
UV-C/HHP	29.78 ± 0.78 ^{a}	4.45 ± 0.06 ^{a}	5.81 ± 0.05 ^{ab}	6.82 ± 0.28 ^{a}
Storage day	$p = 0.439$	$p < 0.001$ *	$p = 0.005$ *	$p = 0.959$
0	27.70 ± 1.24 ^{a}	4.14 ± 0.06 ^{b}	5.91 ± 0.04 ^{a}	7.05 ± 0.15 ^{a}
8	29.23 ± 1.16 ^{a}	4.15 ± 0.06 ^{b}	5.71 ± 0.09 ^{ab}	7.13 ± 0.27 ^{a}
11	27.87 ± 0.78 ^{a}	4.44 ± 0.06 ^{ab}	5.59 ± 0.06 ^{b}	7.13 ± 0.37 ^{a}
15	27.58 ± 0.92 ^{a}	4.61 ± 0.06 ^{a}	5.57 ± 0.07 ^{b}	7.27 ± 0.49 ^{a}
Grand mean	28.10	4.33	5.69	7.14

* $p \leq 0.05$. Results are expressed as mean ± SE. Different letters within columns mean statistically different values at $p \leq 0.05$.

The content of TS in the control FCP was 25.2%, which was slightly higher than in the previously studied potatoes of the same Birgit cultivar [1,30]. This difference is probably due to different conditions during growth but also to the different age of the potatoes. The application of HHP and HHP/UV-C treatments resulted in TS increase. HHP treatment increases cell membrane permeability, improves diffusion, and increases the mass transfer, resulting in water loss [40,41]. According to Douardo et al. [24], an equal or lower percentage of moisture was observed in HHP-treated potato samples (0.1, 100, 200, and 400 MPa/5 min) than in untreated samples. The same effect was reported by Tsikrika et al. [42] when FCP was subjected to HHP treatment (600 MPa/3 min), but it differed according to cultivar used. As mentioned earlier, in this study, TS content did not change significantly during storage.

The obtained mean value for TSS of the control sample was 3.90 °Bx, which is lower than the TSS obtained in our previous study [1]. Samples subjected to HHP and combined UV-C/HHP treatment showed a significantly increased content of TSS. This increase could be due to the cell damage caused by treatments, which subsequently leads to the release of sugars and other soluble solids from the cells [43,44]. Similar to our results, Douardo et al. (2020) [24] also found up to a five-fold increase in TSS in external potato water (400 MPa) when compared with the control. According to our results, the content of TSS increased during storage, which may be related to the starch breakdown into SS or cell wall hydrolysis [45].

The pH of the control samples was 5.60, similar to that found in our previous study (5.64) [1]. UV-C treatment slightly decreased pH, while HHP significantly increased it, as did UV-C/HHP. A decrease in pH in potato slices treated with UV-C (2.70 kJ m^{-2}) was previously found by Pelaić et al. (2022) [1], where the value was similar to that in this work (5.59). A lower pH can have an effect on the inhibition of enzymes or create more unfavorable conditions for the growth of microorganisms, but in this way the browning processes can also be controlled [13]. Lu et al. (1991) [46] also observed a decrease in pH in UV-C-treated peaches and apples. As in this study, an increase in the pH of HHP-treated (200, 400, and 600 MPa/5, 15, and 25 min) spinach puree was also observed by Wang et al. (2012) [47]. During storage, the pH decreased until the 11th day, after which it was stable. A decrease in pH during storage has also been observed in vacuum-packed potatoes or potato slices [30,48]. It could be related to the increased respiration rate and CO_2 production [49] which was found for vacuum-packed potatoes stored in refrigerators [50].

The grand mean value of raw FCP firmness was 7.14 N (Table 1). Although the applied treatments resulted in changes in TS and TSS and could damage tuber structure and cell walls, these changes did not significantly affect the measured potato firmness. According to our previous study [1], UV-C decreased the firmness of FCP, while similar observations as in the present study were reported by Levaj et al. (2020) [5] when potato slices were immersed in sodium ascorbate solution and treated with HHP (400 MPa). Douardo et al. (2020) [24] observed a decrease in firmness when potato sticks, immersed in either water or asparaginase solution, were treated with HHP (200 and 400 MPa).

3.3. Color Analysis

The mean values of *L**, *a**, and *b** for the control samples were 62.3, 0.37, and 31.6, respectively (Table 2). All values were lower when compared with the same potato variety previously investigated [1,30], probably due to various effects such as the growing conditions of potatoes or age.

Table 2. The influence of UV-C, HHP, and UV-C/HHP treatment and storage time on the color parameters of raw, fresh-cut potatoes.

Source of Variation	*L**	*a**	*b**
Treatment	$p < 0.001$ *	$p < 0.001$ *	$p = 0.199$
Control	62.3 ± 0.5^{b}	0.37 ± 0.08^{a}	31.6 ± 0.5^{a}
UV-C	64.3 ± 0.5^{a}	-0.19 ± 0.08^{b}	30.9 ± 0.5^{a}
HHP	64.9 ± 0.5^{a}	0.05 ± 0.08^{b}	31.6 ± 0.5^{a}
UV-C/HHP	65.9 ± 0.5^{a}	-1.03 ± 0.08^{c}	30.4 ± 0.5^{a}
Storage day	$p < 0.001$ *	$p < 0.001$ *	$p < 0.001$ *
0	62.1 ± 0.5^{b}	-0.25 ± 0.08^{b}	30.1 ± 0.5^{b}
8	65.3 ± 0.5^{a}	0.10 ± 0.08^{a}	33.2 ± 0.5^{a}
11	65.9 ± 0.5^{a}	-0.49 ± 0.08^{b}	30.1 ± 0.5^{b}
15	64.2 ± 0.5^{a}	-0.17 ± 0.08^{ab}	31.1 ± 0.5^{ab}
Grand mean	64.4	−0.20	31.1

* $p \leq 0.05$. Results are expressed as mean ± SE. Different letters within columns mean statistically different values at $p \leq 0.05$.

All applied treatments significantly increased the L^* value, which expresses brightness, and decreased the a^* value, which as a positive value means redness and as negative value means greenness. The b^*, as yellowness, was not affected by the treatment. The UV-C/HHP-treated samples were the brightest, whereas a^* was more pronounced in the control samples. Our previous study [1] also found that UV-C treatment could increase the brightness of raw potato slices. Although HHP may create favorable conditions for tissue browning due to possible cellular damage, allowing better contact between PPO and phenolic substrate, it can be concluded that this was not the case in the present study, as no browning was observed (L^* increased). In addition, HHP could affect the distribution of surface reflectance due to texture changes, which may be the cause of brighter slices [51,52]. According to previously published studies, Sánchez-Moreno et al. (2006) [53] reported an increase in L^* in tomato puree treated with HHP (400 MPa/15 min), and Zhou et al. (2014) [54] in pumpkin slices treated with HHP. In contrast to our results, Tsikrika et al. (2021) [3] found a decrease in L^* and b^* in peeled potato tubers treated with higher pressure (600 MPa/3 min).

Storage significantly affected the values of L^*, a^*, and b^*. L^* increased significantly on the 8th day and remained stable thereafter until the end of storage. Although the changes in a^* values during storage were significant, no trend of changes was observed, and they remained at values below 1 throughout the storage period. These values of L^* and a^* indicate that no browning occurred during storage. Although the values of b^* (yellow coloration) were statistically the highest on the 8th day of storage, no trend of changes was observed. The yellow color is characteristic of the potato tissue of the Birgit variety (European Cultivated Potato Database [55]).

It can be concluded that UV-C, HHP, and the combined UV-C/HHP treatment can maintain the natural color of the potato tissue during the 15-day storage period.

3.4. Chlorogenic Acid Analysis

Chlorogenic acid is the most abundant phenolic constituent of potato, found primarily in the skin and outer tissue but also in significant amounts in the inner tissue [16]. Because of its important role in the browning processes and its antioxidant properties, the influence of UV-C light, HHP, and the combination of UV-C/HHP treatments on its content, as well as the changes during 15 days of storage, were examined.

The grand mean value of chlorogenic acid was 8.95 mg 100 g^{-1} DW (Table 3). The value obtained in the control samples (15.0 mg 100 g^{-1} DW) was somewhat lower than in our previous study (17.28 mg 100 g^{-1} DW), probably due to the age or growth conditions of the potatoes. In comparison with the control samples, the treatments significantly reduced the content of chlorogenic acid in the raw FCP, which was the most pronounced with the HHP and UV-C/HHP treatments. UV-C reduced the chlorogenic acid content by 30.7%, UV-C/HHP by 58.0%, and HHP by 72.7%. In our previous study [21], a nonsignificant decrease in chlorogenic acid content with increasing UV-C dose was found. However, according to the study by Teoh et al. (2016) [56], the content of total phenolics in fresh-cut potatoes (FCP) increased under the influence of UV-C light. Given the different experimental conditions and the fact that total phenolics were monitored by the aforementioned authors, these results are difficult to compare. Regarding the HHP treatment, Tsikrika et al. (2021) [3] reported a significant decrease in chlorogenic acid (about 65% or 84% depending on cultivar) and an increase in caffeic acid content in treated (600 MPa/3 min), vacuum-packed whole potato tubers, which the authors suggested might be due to the degradation of freeform chlorogenic acid to its constituent, i.e., caffeic acid. It can be assumed that the mentioned degradation could be the cause of such a high decrease in chlorogenic acid content in the examined samples in this study. The decrease in chlorogenic acid content due to the effect of HHP (450, 550, and 650 MPa/5, 10, and 15 min) was also observed in other vegetables [57].

Table 3. The influence of UV-C, HHP, and UV-C/HHP treatment and storage time on the chlorogenic acid and sugar content of raw, fresh-cut potatoes.

Source of Variation	Chlorogenic Acid (mg 100 g^{-1} DW)	Reducing Sugars (g 100 g^{-1} DW)	Sucrose (g 100 g^{-1} DW)	Acrylamide (µg kg^{-1} DW)
Treatment	$p < 0.001$ *	$p < 0.001$ *	$p = 0.001$ *	$p < 0.001$ *
Control	15.0 ± 0.2 ^{a}	0.79 ± 0.03 ^{c}	0.28 ± 0.03 ^{b}	598 ± 16 ^{c}
UV-C	10.4 ± 0.2 ^{b}	1.12 ± 0.04 ^{b}	0.41 ± 0.02 ^{a}	750 ± 13 ^{b}
HHP	4.1 ± 0.1 ^{d}	1.08 ± 0.04 ^{b}	0.39 ± 0.04 ^{ab}	767 ± 20 ^{b}
UV-C/HHP	6.3 ± 0.4 ^{c}	1.54 ± 0.03 ^{a}	0.36 ± 0.01 ^{ab}	2611 ± 43 ^{a}
Storage day	$p < 0.001$ *	$p < 0.001$ *	$p = 0.081$	$p < 0.001$ *
0	7.8 ± 0.4 ^{c}	0.97 ± 0.05 ^{b}	0.32 ± 0.03 ^{a}	920 ± 26 ^{b}
8	8.3 ± 0.1 ^{c}	1.05 ± 0.03 ^{b}	0.35 ± 0.04 ^{a}	1272 ± 20 ^{a}
11	9.4 ± 0.1 ^{b}	1.21 ± 0.04 ^{a}	0.37 ± 0.01 ^{a}	1234 ± 20 ^{a}
15	10.3 ± 0.3 ^{a}	1.29 ± 0.01 ^{a}	0.40 ± 0.01 ^{a}	1298 ± 34 ^{a}
Grand mean	8.95	1.13	0.36	1181

* $p \leq 0.05$. Results are expressed as mean ± SE. Different letters within columns mean statistically different values at $p \leq 0.05$.

According to the statistical results, the storage had a significant effect on the chlorogenic acid content. The content increased during storage from 7.8 mg 100 g^{-1} DW to 10.3 mg 100 g^{-1} DW on the 15th day. The increase in chlorogenic acid content during storage is consistent with previously published studies [58,59]. The influence of the HHP and HHP/UV-C treatments (Figure 2), which resulted in the greatest reduction in chlorogenic acid, is also evidenced by the lowest increase in its content during 15-day storage (0.16 and 1.06 mg 100 g^{-1} DW, respectively). Such minimal increase in chlorogenic acid content in the aforementioned samples during storage could probably be related to the decreased activity of enzymes involved in chlorogenic acid biosynthetic pathways.

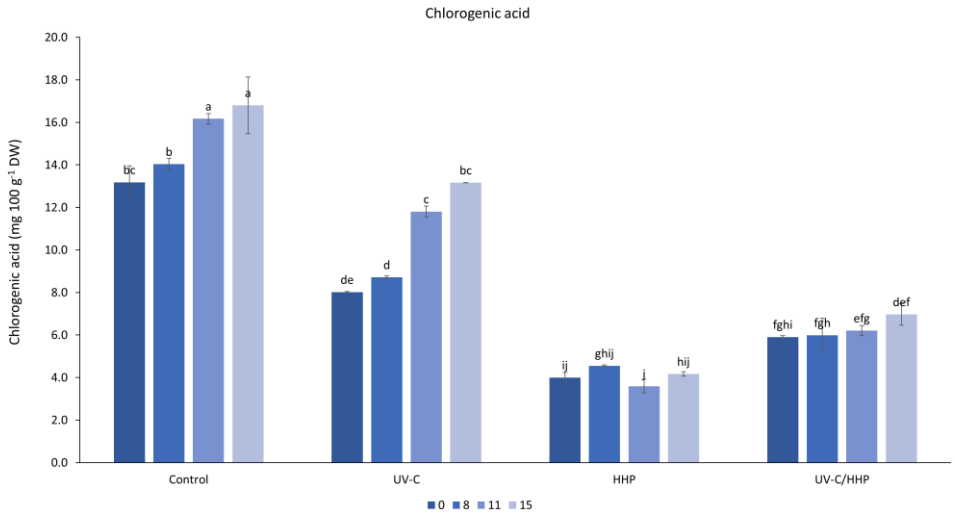


Figure 2. Interaction of treatment (control, UV-C, HHP, and UV-C/HHP) and storage time on chlorogenic acid content. Error bars represent standard errors; lowercase letters represent a significant difference within means ($p < 0.05$).

Observed reduction due to the treatments is useful in terms of preventing the browning process, which, according to the color analysis (Table 2), did not occur in the treated samples.

3.5. Sugars Analysis

The grand mean contents of reducing sugars and sucrose were 1.13 g 100 g^{-1} DW and 0.36 g 100 g^{-1} DW, respectively (Table 3). The mean value of reducing sugars content

for the raw control (0.79 g 100 g^{-1} DW) was slightly higher when compared with the raw control samples of the same cultivar in a previous study [21].

Statistical analysis revealed that the UV-C, HHP, and UV-C/HHP treatments significantly increased the content of reducing sugars (glucose and fructose) and sucrose. Such an effect of UV-C irradiation on the content of reducing sugars content in potatoes was found in our previous study [21]. This change in sugar content could be related to the effect of UV-C irradiation on the activity of various enzymes involved in sugar metabolism [60,61]. Similar to our results for the increased content of reducing sugars by HHP, Ghafoor et al. (2012) [62] observed a significant increase in HHP-treated (400–600 MPa/1 min) red ginseng, whereas Shigematsu et al. (2017) [63] found no change in sugar content in HHP-treated (100–600 MPa/25 °C), vacuum-packed fresh-cut sweet potatoes. The highest increase in reducing sugar (Table 3) was in the UV-C/HHP-treated samples, in which the sugar content approximately doubled when compared with the control samples. The increase in sugar content caused by treatments involving HHP is likely due to the effect of HHP on cell structure [62], which may subsequently lead to higher sugar release and availability. Additional studies are needed to explain this observed effect of combined treatment.

Statistical analysis showed that storage, expressed in days, had a significant effect on the content of reducing sugars. The content increased during storage and reached its maximum on the 15th day (1.29 g 100 g^{-1} DW). According to the results (Figure 3), the content of reducing sugars increased in all samples regardless of treatment, but it was more pronounced in samples treated with UV-C on the 8th and 15th day. Such an increase during the refrigerated storage of fruits and vegetables has been reported previously [21,31]. Sweetening at low temperatures [61,64] during storage may cause such a change.

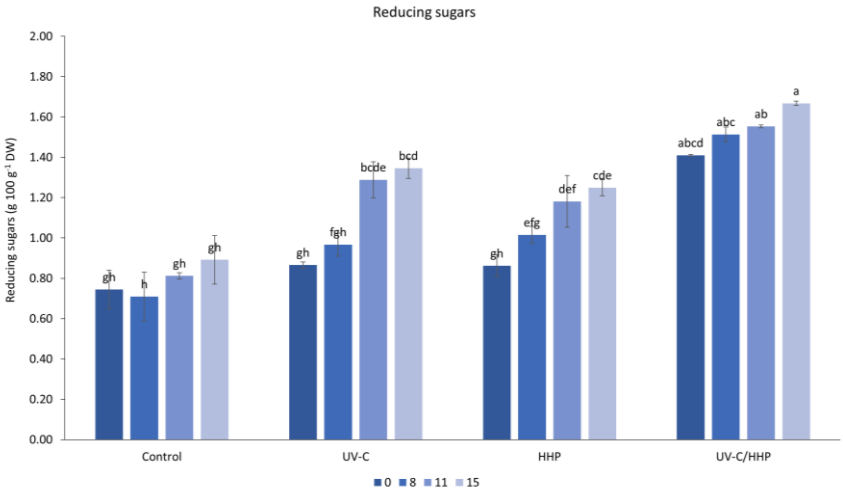


Figure 3. Interaction of treatment (control, UV-C, HHP, and UV-C/HHP) and storage time on reducing sugars. Error bars represent standard errors; lowercase letters represent a significant difference within means ($p < 0.05$).

3.6. Acrylamide Analysis

Acrylamide is a neurotoxic organic compound, classified by the International Agency for Research on Cancer (IARC) [65] as a probable carcinogenic to humans in Group 2A. Its metabolization into glycinamide, after being distributed throughout the organs, is considered to be the basis for its genotoxicity and carcinogenicity (EFSA 2015) [66]. Therefore, the effect of UV-C, HHP and UV-C/HHP treatment on acrylamide content in subsequently fried FCP was investigated.

The acrylamide content obtained in fried FCP ranged from 598 to 2611 µg kg^{-1} DW (Table 3). Although all applied treatments increased acrylamide content, it was about three-fold higher when the combined UV-C/HHP treatment was applied. The increase in reducing sugars is significant with regard to the possible increase in the content of

carcinogenic acrylamide in fried potatoes, as they are one of the precursors of acrylamide. The observed increase in reducing sugars (Table 1, Figure 3) in raw UVC- and HHP-treated samples is followed by an increase in acrylamide content (Figure 4) in fried FCP. However, a disproportionately large increase in acrylamide can be observed for the UV-C/HHP treatment. Since reducing sugars and the free amino acid asparagine are precursors in Maillard reactions in which acrylamide is formed, it could be suggested that this combined treatment, among others, affected some of the precursors or the reaction process itself. Ghafoor et al. (2012) [62] observed an increase in the content of reducing sugars as well as amino acids, including asparagine, under the influence of HHP (400–600 MPa) on red ginseng roots. Additional studies are needed to better elucidate the effects of the combined treatment. However, acrylamide levels in the control, UV-C, and HHP were always below the adopted limit for acrylamide in potato products, which is 750 μg kg^{-1} according to ECR 2017/2158 [22]. It is important to emphasize that the obtained values are expressed as DW and are about three-fold higher than the values expressed as the mass of the fried samples. For UV-C/HHP, acrylamide content exceeded the limit, making them unsafe for consumption. As for previous studies, Sobol et al. (2020) [23] reported an increase in acrylamide content when potato tubers were irradiated with UV-C. In our previous study [21], it was found that the irradiation of raw FCP with UV-C light can slightly increase acrylamide content in fried FCP, depending on the applied radiation dose. A recent study by Douardo et al. (2020) [24] showed that there was no significant change in acrylamide content when HHPs of 100, 200, or 400 MPa/5 min were applied on raw potato sticks immersed in water or asparaginase solution. During storage, a slight increase in acrylamide content was observed on day 8, which remained stable thereafter.

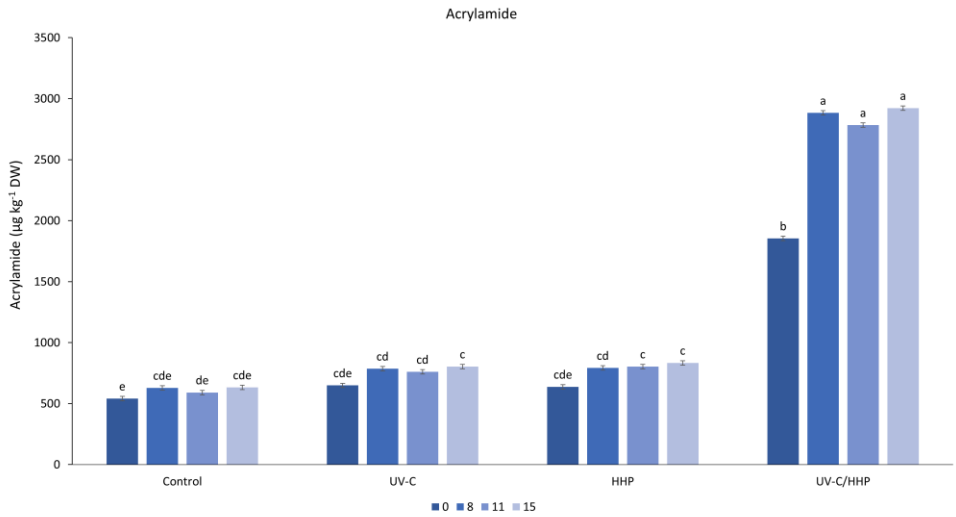
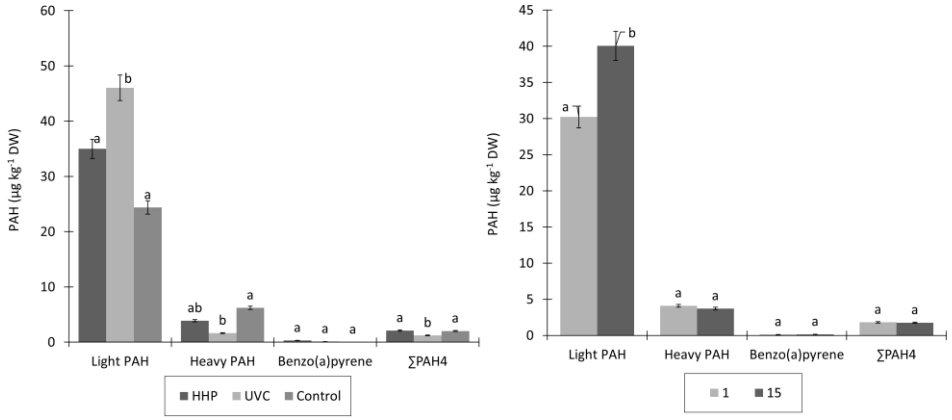


Figure 4. Interaction of treatment (control, UV-C, HHP, and UV-C/HHP) and storage time on acrylamide. Error bars represent standard errors; lowercase letters represent a significant difference within means ($p < 0.05$).

Under the conditions of our experiment, the samples treated with UV-C and HHP were safe in terms of acrylamide content.

3.7. PAH Content

For additional evaluation of the safety of UV-C- and HHP-treated fried FCP, the content of PAH as environmental and processing pollutants was assessed in addition to the acrylamide content, following the recommendations of EFSA (2007) (Figure 5). The analyses of PAH were performed only for the single influence of UV-C and HHP treatment, since the determination was made after the analysis of acrylamide, which showed the inadequacy of the combined treatment in terms of a large increase acrylamide content in fried potatoes.



(**a**) (**b**)

Figure 5. PAH content (µg kg^{-1} DW) in (**a**) control, UV-C-, and HHP-treated fried fresh-cut potatoes at (**b**) 1st and 15th day of storage. Results are expressed as least square (LS) means. Different letters within columns mean statistically different values at $p \leq 0.05$.

The GC–MS method was able to identify a total of 15 PAH, which for clarification purposes were divided into major light fraction (naphthalene, acenaphtylene, acenaphtene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, and chrysene), containing up to four aromatic rings, and heavy fraction (benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, and indeno(1,2,3,-c,d)pyrene), with five or six aromatic rings, while the levels of benzo(g,h,i)perilene were below the detection limit of the method in all samples tested. Phenantrene (4.90–28.63 µg kg^{-1}) and benzo(k)fluoranthene (0.70–6.21 µg kg^{-1}) were the dominant PAH molecules in the light and heavy fractions, respectively. These results differ somewhat from those obtained by Balbino et al. (2020) [26], who considered naphthalene to be dominant in the light fraction and benzo(g,h,i)perylene in the heavy fraction. Moreover, the levels of benzo(a)pyrene and PAH4 were below the limits of EU Regulation 835/2011 [27] in all the samples studied. However, the composition of PAH was influenced by the treatments applied. The contents of the heavy PAH fraction and PAH4 were significantly lower in UV-C-treated samples, while the contents of the light fraction were higher compared with the control. Several authors have studied the effect of UV-C lights of different wavelengths on the degradation and decomposition of PAH in soil, water, and wastewater [67,68]. Their results show that UV-C irradiation causes photocatalytic degradation of PAH at different levels, which depend on the chemical composition of the matrix [69]. The UV-C treatment of fried, fresh-cut potatoes applied in this study could cause the decomposition of heavy PAH compounds to PAH with lower molecular weights. On the other hand, the increase in light PAH fraction after 15 days of storage could be due to partial cell destruction and loss of water content by the applied treatments.

3.8. Results of PCA Analysis of Sensory Data in Relation to UV-C, HHP, and UV-C/HHP Treatment and Storage Time

PCA analysis of sensory data was performed for raw, boiled, and fried samples in order to visualize the relations between the analyzed parameters and to define a possible grouping of samples in relations to the applied treatments (UV-C, HHP, and combined UV-C/HHP) and storage time (days).

Sensory attributes of color (browning), odor, off-odor, firmness, and moistness were included in the PCA evaluation of the raw FCP (Figure 6). PC1 and PC2 described 84.24% of the total data variance. PC1 showed a strong correlation (>0.73) with all sensory attributes, while PC2 correlated strongly with color (browning) (r = −0.619) and off-odor (r = −0.604)

and moderately with odor (r = −0.524) and firmness (r = −0.407). With regard to treatment, all UV-C-treated samples were placed on the positive PC1 due to their higher firmness and odor scores and lower off-odor scores. Almost all HHP- and UV-C/HHP-treated samples were located in the positive PC2 range with the highest scored moistness. In terms of storage, clustering was observed at day 0 and day 8, with almost all samples distributed at positive PC1, as they were characterized by higher scores of firmness and odor. Samples evaluated on the 11th and 15th day were situated mostly on negative PC1 due to higher moistness and color (browning) scores.

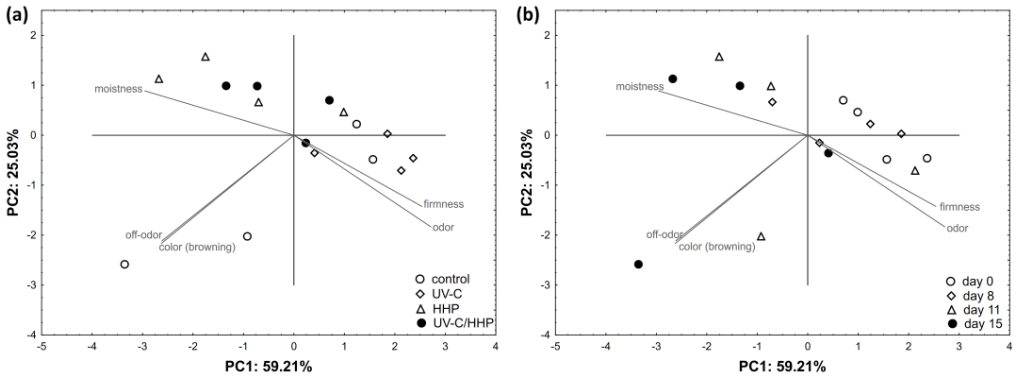


Figure 6. Distribution of raw, fresh-cut potatoes in two-dimensional coordinate system defined by the first two principal components (PC1 and PC2) in relation to the (**a**) treatment and (**b**) storage time.

The boiled FCP sensory attributes of color (browning), odor, off-odor, moistness, firmness, creaminess, and characteristic taste were put in relations with the treatment applied and storage time (Figure 7). PC1 and PC2 explained 83.86% of the total data variance, with PC1 showing a very strong correlation with odor (r = −0.978) and characteristic taste (r = −0.958), a strong correlation with color (browning) (r = 0.808), off-odor (r = 0.885), and moistness (r = 0.669), and a moderate correlation with creaminess (r = −0.539). It was noticeable that the samples treated with UV-C were grouped in the upper left quadrant, which is characterized by more pronounced creaminess and odor. Control samples were grouped on positive PC2, defined by increased creaminess and color (as browning). Pronounced firmness was the most evident in the HHP- and UV-C/HHP-treated samples. Separation of samples stored for 0 and 8 days was noticeable at negative PC1 and correlated with higher odor, firmness, creaminess, and characteristic taste scores. Most samples on day 15 were associated with increased color (browning) values.

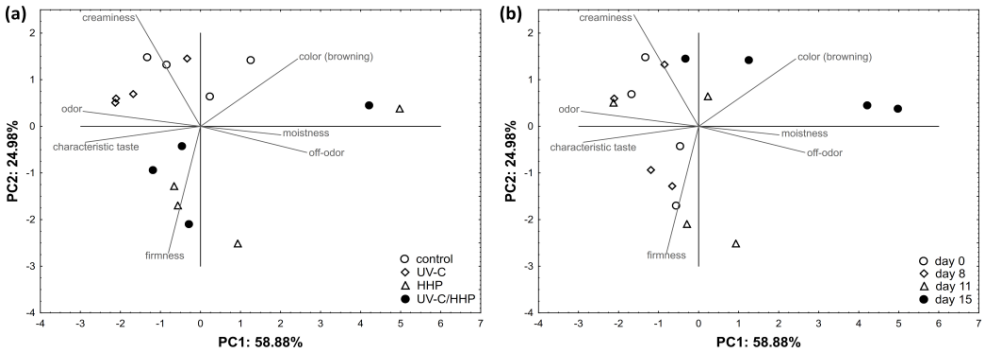


Figure 7. Distribution of boiled, fresh-cut potatoes in two-dimensional coordinate system defined by the first two principal components (PC1 and PC2) in relation to the (**a**) treatment and (**b**) storage time.

PCA results for fried FCP are shown in Figure 8. PC1 and PC2 described 79.86% of the total data variance. The sensory attributes of color, odor, oiliness, firmness, crispiness, and taste were evaluated. A strong correlation was found between odor (r = −0.890), oiliness

(r = 0.714), crispiness (r = 0.850), and taste (r = −0.863) and PC1, as well as between color (r = −0.773), and firmness (r = 0.763), and PC2. Color and firmness correlated moderately with PC1 and oiliness with PC2. Clear separation from other samples by PC2 was visible for the control and UV-C samples. UV-C samples were grouped on the negative PC2 based on higher color and odor scores, while the control samples showed high correlation with color and oiliness. The HHP- and UV-C/HHP-treated samples were situated on the positive side of PC2, mainly due to the lower color and oiliness scores and higher firmness scores. Regarding storage, all samples scored at day 0 and day 8 were distributed on the negative PC1 side due to the more pronounced positive attributes of color, odor, crispness, and taste. In contrast, all samples on the 15th day were placed on the positive PC1 due to the lower scored attributes previously mentioned but also due to the more pronounced oiliness.

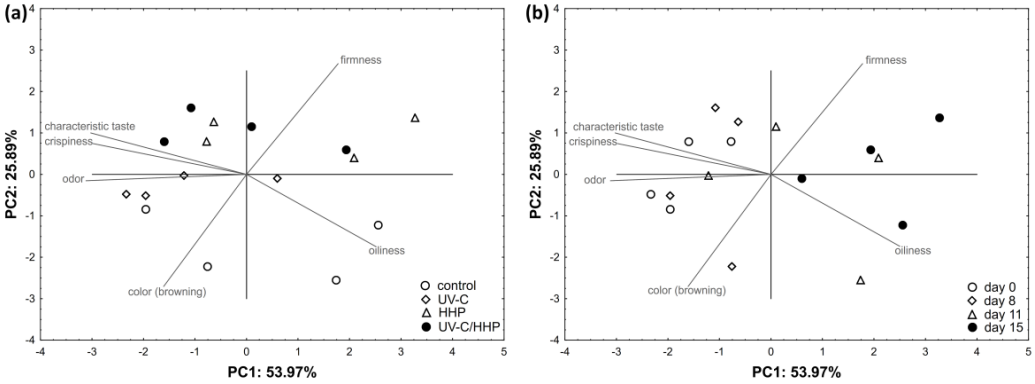


Figure 8. Distribution of fried, fresh-cut potatoes in two-dimensional coordinate system defined by the first two principal components (PC1 and PC2) in relation to the (**a**) treatment and (**b**) storage time.

Overall, the occurrence of some negative changes in sensory attributes was mainly influenced by the storage time, which on the 15th day resulted in a slightly pronounced browning and off-odor of the raw and boiled control samples and oiliness in the control fried samples. From all of the above, it appears that the sensory attributes of the UV-C, HHP-, and UV-C/HHP-treated samples were satisfactorily maintained, regardless of the treatment itself or the storage time.

4. Conclusions

All applied treatments reduced the TAMBC of raw FCP, but the combined treatment of UV-C/HHP was the most effective, followed by HHP alone. Both treatments slowed bacterial growth during storage when compared with the UV-C treatment and even more to the control. After 15 days of storage, only the control had unsatisfactory TAMBC. In addition, all treatments, but especially HHP, reduced the chlorogenic acid content in the raw FCP. The reducing sugar content was the most increased when UV-C/HHP was applied, and this treatment significantly increased the acrylamide content in the subsequently fried FCP, even above the benchmark level (EU Commission Regulation 2017/2158). The UV-C and HHP treatments kept the acrylamide content below the specified limit. Additional studies are needed to clarify the effect of the combined treatment. PAH levels were below the limits set by the EU Regulation 835/2011 in all analyzed samples. Photocatalytic degradation of heavy PAH to PAH with lower molecular weights might have occurred with UV-C treatment. Despite some changes in sensory attributes, the raw and thermally treated samples were sensory acceptable during the 15-day storage period. The combined UV-C/HHP treatment gives very desirable results in terms of suppressing the growth of microorganisms under the conditions tested but is not applicable due to the high acrylamide content in fried samples; so, an adjustment of the conditions is recommended. However, a relatively short UV-C treatment, despite lower antimicrobial effect, and HHP treatment when an antibrowning agent and vacuum packaging are used, have the potential to ensure safety and satisfactory quality and to somewhat extend the shelf life of FCP. Nevertheless,

at the level of the fresh-cut potato industry, it is necessary to examine their effect on a real scale.

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Conflicts of Interest: The authors declare no conflict of interest.

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Publication No 5: Maintaining the Quality and Safety of Fresh-Cut Potatoes (Solanum tuberosum): Overview of Recent Findings and Approaches

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5. *Publication No 5:*

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Review

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

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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.

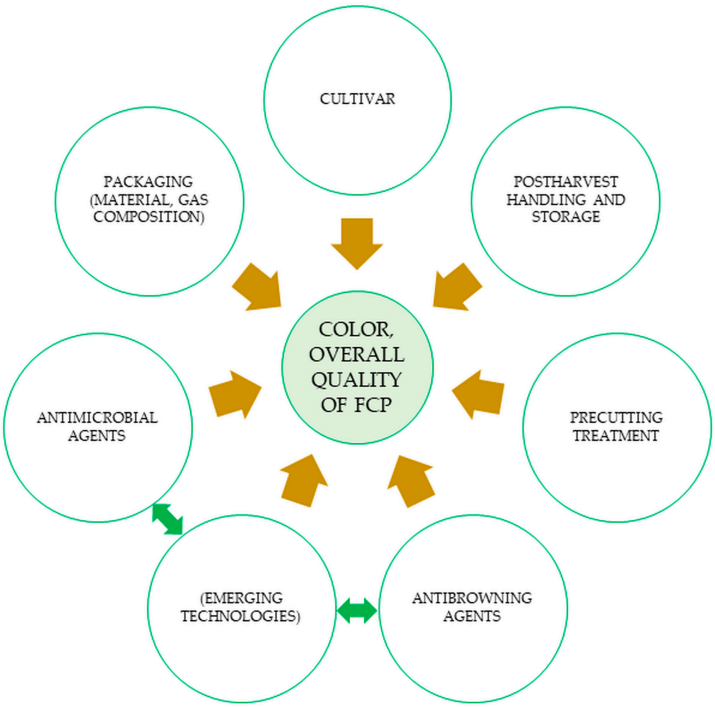

Figure 1. Overview of the factors that affect the quality of fresh-cut potatoes.

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].

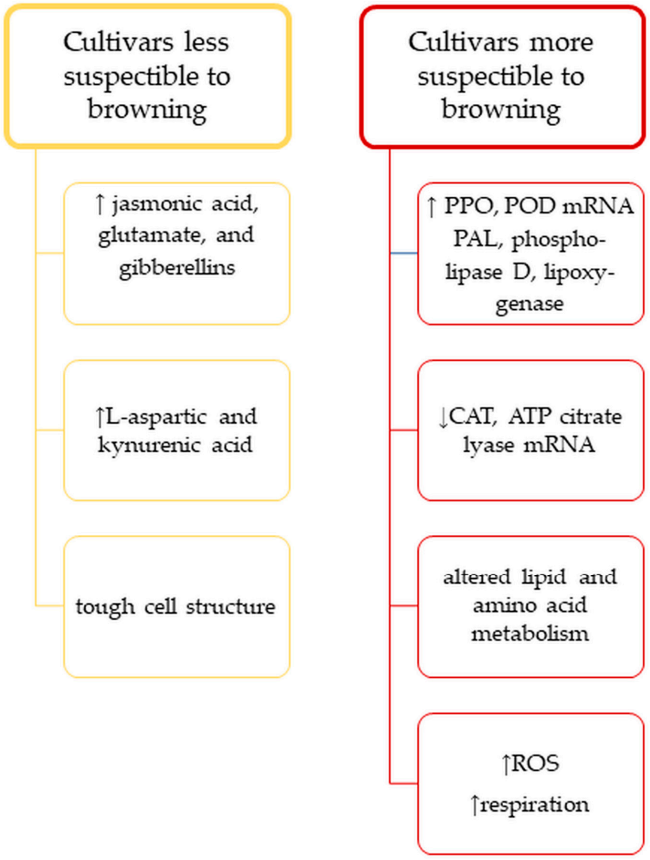

Figure 2. Differences between cultivars in terms of brown sensitivity (↑ = increase, ↓ = decrease) [56,57].

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.

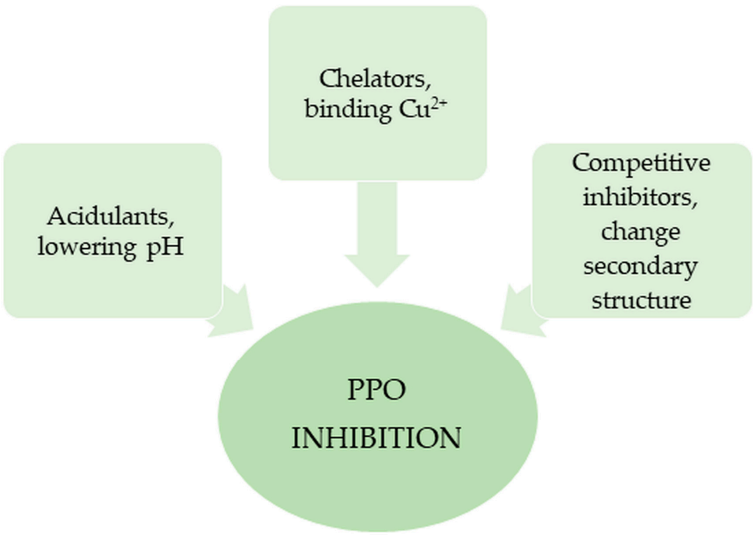

Figure 3. Influence of anti-browning agents on polyphenol oxidase (PPO) inhibition.

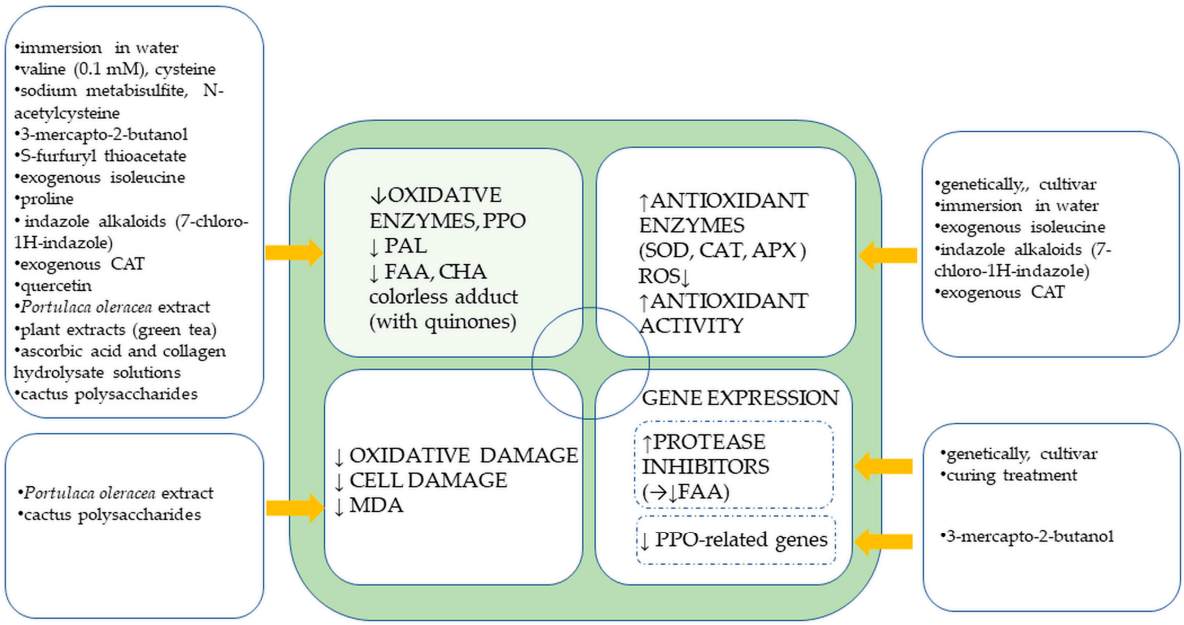

Figure 4. Overview of changes in plant cells of fresh-cut potatoes responsible for resistance to browning due to use of the latest anti-browning agents or due to cultivar characteristics (↑ = increase, ↓ = decrease) [11,12,72,76–88].

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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Chapter 3

General discussion

- Effect of UV-C irradiation and storage time on microbiological, physical and sensory properties of raw FCP, and on their sensory properties after boiling and frying

- Effect of UV-C irradiation, storage time and subsequent cooking on phenolics, sugar and acrylamide content of FCP

- Effect of HHP on the quality and shelf-life of FCP

- Effect of UV-C irradiation, HPP treatment and storage time on microbiological, physical and chemical properties of raw FCP, and on acrylamide and PAH in fried FCP

1. Effect of UV-C irradiation and storage time on microbiological, physical and sensory properties of raw FCP, and their sensory properties after boiling and frying

The aim of the research presented in ***Publication No. 1*** was to investigate which UV-C dose can contribute the most to preserve the safety and quality of FCP, thus extending its shelf-life, and maintaining its suitability for boiling and frying. The results obtained are discussed in this section. The table potato *Solanum tuberosum* L. cv. Birgit was used in this case, as well as for other studies in this dissertation. The tubers were peeled, cut into 0.4 cm thick slices, treated with 2% SA solution for 3 min and vacuum packaged in a single layer in PA/PE vacuum bags. The samples thus prepared were irradiated with UV-C for 0, 3, 5 and 10 min (control, 3-UV-C, 5-UV-C and 10-UVC) to obtain irradiation doses of 0, 1.62, 2.70 and 5.40 kJ m^{-2}. The FCP prepared in this way were also used for the continuation of the research *(Publication No. 2*). All samples were stored at 6 °C and analyzed on the 0^{th}, 8^{th}, 11^{th}, 15^{th} and 23^{rd} day of storage. On the same days, some of these samples were set aside for boiling (100 °C, 15 min) and frying (180 °C, 5 min) and for sensory analysis. The microbial activity, total solids content (TS), total soluble solids content (TSS), pH value, firmness and color of the raw FCP, as well as the sensory properties of the raw, boiled and fried potatoes were analyzed. In addition, the effect of the UV-C treatment on the permeability of packaging material was examined.

5- and 10-UV-C treatments slowed the growth of aerobic mesophilic bacteria during 15 days of storage ***(Publication No. 1 - Figure 1)***. From 11^{th} to 23^{rd} day of storage, a reduction of about 2 log CFU g^{-1} was observed in samples treated with these treatments. However, there was no significant difference in efficiency between them, probably due to the rough surface of the material cut in this way, which can lead to the shading of microorganisms and thus to a partial reduction in the effectiveness of the irradiation (Fonseca and Rushing, 2006; Manzocco et al., 2011). Therefore, with regard to saving energy, a 5-UV-C treatment can be considered as optimal for minimizing and decelerating the proliferation of microorganisms under the conditions of this experiment. The EC Regulations (EC, 2005, EC, 2007) do not provide information on the permitted TAMBC in products such as FCP, i.e., raw potatoes intended for subsequent cooking. However, the borderline limit for aerobic bacteria count levels in VP 'ready for eat' refrigerated vegetables is $10^6 - < 10^8$ CFU g^{-1} (Guidelines for assessing the microbiological safety of ready-to-eat foods). Since FCP treated with 5-UV-C had 8.36 log CFU g^{-1} of TAMBC on the 15^{th} day of storage, it can be considered as microbiologically correct in terms of further cooking.

All treatments resulted in a slightly increase in TS and a decrease in TSS and pH *(Publication No. 1 - Table 1)*. Firmness was lower in all UV-C treated samples than in the control samples, but it increased with increasing irradiation time. The color parameter *L** was higher in 5- and 10-UV-C treated samples, while the parameters *a** and *b** were not significantly affected by UV-C irradiation. Increased *L** values confirm that 5- and 10-UV-C treated samples were less prone to browning, which is a desirable characteristic of FCP (Tudela and Gil, 2020).

The sensory properties of raw, boiled and fried potatoes were analyzed. Raw UV-C irradiated FCP were less susceptible to browning, especially 5- and 10-UV-C *(Publication No. 1 - Table 2)*, which is consistent with the *L** values previously discussed *(Publication No. 1 - Table 1)*. The aforementioned samples also had a more pronounced characteristic odor and less pronounced off-odor. A similar observation was reported by Manzocco et al. (2011) who found that UV-C treated samples of fresh-cut melons had better flavor. Furthermore, in this research, firmness was slightly lower in UV-C treated samples. The influence of UV-C was also reflected in the sensory properties of boiled and fried potatoes *(Publication No. 1 - Tables 3 and 4)*. The samples treated with 5- and 10-UV-C had a more pronounced odor, taste, sweetness and saltiness. In addition, these samples had significantly lower firmness and pronounced creaminess after cooking and were less prone to browning compared to the control samples. Furthermore, these desirable changes were more pronounced with increasing UV-C dose. Overall, the 5- and 10-UV-C treatment did not deteriorate the sensory properties of FCP, although some of them were more pronounced.

During the 23-day storage, TAMBC grew as expected in all samples, but significantly slower in the 5- and 10-UV-C samples as a result of germicidal effect of UV-C *(Publication No. 1 - Figure 1)*. In addition, growth was rapid during 8 days, and slowed down after the11th day of storage, which can be attributed to reduced oxygen content in VP, which inhibits the growth of aerobic mesophilic, and to decreased pH. Storage time also affected TSS and pH, which decreased during storage, but increased at 23rd day *(Publication No. 1 - Table 2)*. The decrease of pH during storage could be related to the metabolism of microorganisms, as Li et al. (2022) found in VP peeled potatoes or respiration rate (increased CO_2 content) (Dite Hunjek et al. 2020a). Storage time also had a significant effect on some sensory properties of raw FCP *(Publication No. 1 - Table 2)*. The samples tended to brown more with increasing storage time, while the characteristic odor was less pronounced and off-odor was more pronounced, especially on the 23rd day. However, Principal Component Analysis (PCA) showed that these changes were mainly related to the control samples

(Publication No. 1 - Figure 2). The storage time also had an influence on the sensory properties of boiled and fried potatoes. Most noticeable was the increased browning *(Publication No. 1 - Table 3 and 4)* during the storage time, which was mainly related to the control and 3-UV-C samples *(Publication No. 1 - Figure 3 and 4)*. Regardless of the storage time, the 10-UV-C samples had more pronounced sweetness, saltiness, taste and creaminess, followed by the 5-UV-C treated samples *(Publication No. 1 - Figure 3 and 4)*.

In addition, the effect of UV-C treatment on the permeability of packaging material was investigated and a slight increase in the permeability of PA/PE packaging material was observed for the 5-UV-C and 10-UV-C samples. However, the difference with control was not significant. Tarek et al. (2015) also found that the UV-C doses used (46.7–746 mJ cm^{-2}/0.5 to 8 min) did not induce alterations of the PE films surface properties.

Finally, it can be assumed that 5-UV-C treatment is optimal, in conditions of this experiment, for treating FCP with UV-C radiation; these samples can be stored for 15 days and retain their safety, quality and sensory properties.

2. Effect of UV-C irradiation, storage time and subsequent cooking on the phenolics, sugars and acrylamide content of FCP

Continuing the research, the influence of UV-C irradiation, storage time and subsequent cooking on the chemical composition of FCP was examined *(Publication No. 2)*. The content of phenolics and sugars (fructose, glucose and sucrose) in raw, boiled and fried FCP, and the content of acrylamide in fried FCP were analyzed. The tested FCP was prepared in the experiment described in *Publication No. 1*. During storage, samples were taken on the 0^{th}, 8^{th}, 11^{th}, 15^{th} and 23^{rd} day, frozen at -60 °C and then freeze dried. The samples prepared in this way were analyzed. Phenolics and acrylamide were analyzed by UPLC MS^2 and sugars (fructose, glucose and sucrose) by HPLC. Since the analyzed phenolic components such as caffeic acid, rutin or catechin were not detected or were detected in concentrations below the LOQ, the analysis was continued with the most abundant phenolic component, chlorogenic acid (Deußer et al., 2012). The results are presented in *Publication No. 2* as mean values across different sources of variation, which include all processed data.

The grand mean of chlorogenic acid content in FCP was 9.67 mg 100 g^{-1} DW *(Publication No. 2 – Table 1)*. All applied UV-C treatments caused a decrease in chlorogenic acid content, but this was more pronounced in treatments with higher doses. Although the chlorogenic acid content was not tested, a decrease in total phenolic content with increasing UV-C dose was observed in UV-C irradiated fresh-cut spinach (Artés-Hernández et al., 2009). However, according to one of the few studies on the effect of UV-C light on FCP, by Teoh et al. (2016), total phenolics increased when FCP was irradiated before packaging and storage in permeable plastic boxes. Chlorogenic acid has various health benefits (Akyol et al., 2016; Manach et al.; 2004, Plazas et al., 2014), therefore its higher retention is favorable, but in terms of browning processes, a lower content is preferable, as it acts as a substrate in enzymatic browning processes (Li et al., 2018; Amaki et al., 2011; Narváez-Cuenca et al., 2013).

During 23 days of storage the content of chlorogenic in the raw FCP (control and UV-C) slightly decreased, but it still remained at about 80% of the initial content at the end of storage *(Publication No. 2 – Table 1)*. This could potentially be clarified by the involvement of chlorogenic acid as a substrate for PPO in oxidation reactions leading to browning of the tissue (Amaki et al., 2011).

Cooking caused a significant reduction in chlorogenic acid content (source of variation: cooking method *vs.* UV-C treatment) *(Publication No. 2 – Table 1)*. The loss was slightly more pronounced in boiled samples than in fried samples. As reported by Tudela et al. (2002), cooked (boiled, steam boiled, fried, and microwaved) FCP of cv. Mona Lisa had significantly lower levels of caffeic acid derivates, but higher contents were found in boiled potatoes compared with fried potatoes. Cooking conditions, oxidative enzyme activity, solubility, degradation and other factors can influence the content of phenolics in cooked potatoes (Azizi et al., 2020; Blessington et al., 2010; Tian et al., 2016a). When heated, the cells are degraded, resulting in easier release of phenolics and their extractability and bio-accessibility (Tian et al., 2016a), and in addition, they can participate in the Maillard reaction, which causes further loss. According to the statistical results no obvious effect of UV-C irradiation on chlorogenic acid content in boiled or fried FCP was observed (source of variation: cooking method *vs.* UV-C treatment) *(Publication No. 2 – Table 1)*.

The grand mean content of glucose was 0.292 g 100 g^{-1} DW and fructose 0.212 g 100 g^{-1} DW, respectively. Although all applied UV-C treatments caused an increase of sugar content, this

was significantly pronounced with 5-UV-C (source of variation: cooking method *vs*. UV-C treatment) *(Publication No. 2 – Table 1 and Figure 2a)*. These changes may be due to the possible effect of UV-C radiation on enzymes involved in sugar metabolism, which alters the sugar content in fruits and vegetables (Lin et al., 2017; Zhou et al., 2020). These results highlight the importance of selecting the most appropriate dose of irradiation that will result in a lower increase in sugar levels, thereby reducing the potential for acrylamide formation during frying.

During storage, sugar content increased in raw samples (source of variation: storage days; UV-C treatment *vs.* storage days and cooking method *vs.* storage days) *(Publication No. 2 – Table 1)*, but this was most evident in raw and 5-UV-C treated FCP samples. The fructose and glucose content in the raw samples increased until the end of storage, while the sucrose content increased until the 15th day of storage. An accumulation of sugar may occur after stress caused by minimal potato processing (peeling, cutting, etc.) and subsequent breakdown of starch, but also due to sucrose hydrolysis catalyzed by the enzyme invertase. A similar rise in glucose and fructose contents was observed in UV-C treated peaches during the final days (6-8) of storage (Zhou et al., 2020).

The sugar content decreased after cooking, but no significant difference was found between boiled and fried samples *(Publication No. 2 – Table 1, Figure 1b and 2 b, c)*. Although the sugar content was initially the highest in the raw 5-UV-C samples, the content after cooking was similar to the other FCP samples (source of variation: cooking method *vs.* UV-C treatment). Similarly, no particular trend of change was observed in the cooked samples with regard to the days of storage of the samples. According to literature data, the sugar content in boiled potatoes may vary depending on the cooking method and conditions (Lin et al., 2017; Singh et al., 2020). The likely cause of reduction in their content during boiling is the solubility of sugars in water and leakage (Zhang et al., 2018), while during frying, RS may be involved in the formation of colors, aromas and acrylamide through Maillard reactions (Dresow and Böhm, 2009; EFSA, 2015; Marquez and Añon, 2006).

All fried (UV-C treated) FCP samples showed higher acrylamide content compared to the control, but it was significantly increased with 5-UV-C treatment *(Publication No. 2 – Table 1)*. Compared to the control samples, the 5-UV-C samples had about 1.5-fold higher acrylamide amount. The 5-UV-C treatment also led to an increase in the RS content in raw potatoes, which is significant because of their important role in the formation of acrylamide. A strong correlation

between acrylamide content in fried samples and reducing sugar content in raw samples was confirmed by the Spearman correlation coefficient (r = 0.74), which is consistent with previous observations (Dite Hunjek et al., 2021; Elmore et al., 2015). However, regardless of the observed increase in acrylamide content, it was in all cases below the assumed limit of 750 μg kg^{-1} of product (EU, 2017). Sobol et al. (2020) also found an increase in acrylamide content in fried potatoes produced from irradiated potato tubers.

Although statistical analysis of all results showed that there was no significant influence of storage time on the increase of acrylamide content in fried potatoes (source of variation: storage time), the source of variation UV-C treatment *vs.* storage days nevertheless showed an increase in content during 23 days for all samples except 3-UV-C *(Publication No. 2 – Table 2)*. A strong negative correlation (r = − 0.77) was found between acrylamide content in fried FCP and chlorogenic acid in raw samples. A negative correlation between the amount of acrylamide and total phenolics, and between acrylamide and chlorogenic acid was also observed by Dite Hunjek et al. (2021), Zhu et al. (2010) and Kalita et al. (2013).

3. Effect of HHP on the quality and shelf-life of FCP

In this research *(Publication No. 3)* the effect of HHP treatment on the microbial stability, quality and sensory properties of FCP was examined during 15-day storage. The peeled tubers were sliced and the slices were immersed in plastic jars filled with 2% SA solution, tightly sealed and HHP treated. After previously conducted preliminary research on the effects of HHP of 300 and 400 MPa, the research was continued with 400 MPa due to better antimicrobial efficiency. Therefore, in this study, the prepared FCP samples were subjected to a pressure of 400 MPa at ambient temperature for a duration of 0, 3, 5 and 10 min (control, 3-HHP, 5-HHP and 10-HHP). After treatment, the slices were drained, vacuum packaged in PA/PE bags and stored at 6 °C for 15 days. After 8, 11 and 15 days of storage, samples were analyzed for color (CIELAB), firmness (texture analyzer) and TAMBC. The slices were also boiled and fried, and all samples were sensory evaluated. Samples that were not treated with HHP served as control samples.

All treatments applied resulted in a reduction in TAMBC, with the greatest reduction observed in the 10-HHP samples (reduction of 1 log CFU g^{-1}) compared to the control samples *(Publication No. 3 – Figure 1)*. Eshtiaghi and Knorr (1993) reported a 4-log cycles reduction also achieved at 400 MPa, but during 15 min treatment. Furthermore, only a slight difference in the

effectiveness of 3-HHP and 5-HHP was observed. At the same time, however, the samples were thermally treated (boiled and fried) and sensory analyzed, and it was found that the texture of fried 5-HHP and 10-HHP samples was completely destroyed. Therefore, in the further part of the experiment, only the control and 3-HHP samples were examined during storage.

During storage, TAMBC increased in the control and 3-HHP samples, but much slower in 3-HHP, which had TAMBC about 3.5 log CFU g^{-1} at the end of the storage, while the control samples had about 7.5 log CFU g^{-1}. On day 15, the TAMBC of 3-HHP samples was below the set limit (Guidelines for assessing the microbiological safety of ready-to-eat foods) for aerobic colony count level in VP 'ready for eat' refrigerated vegetables, while there are no prescribed standards for FCP requiring subsequent heat treatment.

HHP affect the cell structure leading to softening of the tissue. However, it is possible that cell disruption allow contact between pectinmethylesterase and high methytated-pectin, leading to its de-esterification, followed by gel-formation by low methoxy-pectin with divalent ions, which is responsible for increased firmness (Oey et al., 2008). Dourado et al. (2020) documented a decrease in firmness when a higher HHP (200 and 400 MPa for 5 min) was applied to potato sticks immersed in water or asparaginase solution. The results of this study show that HHP treatments had no significant effect on instrumentally measured firmness *(Publication No. 3 – Table 1)*, although the firmness values of the HHP treated samples were higher (8.06 –9.17 N) than those of the control (7.32 N). However, in sensory evaluation, the firmness of the HHP samples was significantly lower than the control *(Publication No. 3 – Table 1)*.

The 5-HHP and 10-HHP treatments caused a significant increase in the brightness (L^*) of FCP *(Publication No. 3 – Table 1)*, with the highest value measured for 5-HHP samples. No browning was observed in the sensory evaluation of color *(Publication No. 3 – Figure 2)*. Similarly, Sánchez-Moreno et al. (2006) reported an increase in L^* in tomato purée treated with HHP. Since the texture changes due to HHP could affect the distribution of surface reflectance (Oey et al., 2008), this could be the reason for brighter slices rather than pigment loss (Macdougall, 2002).

The thermally treated samples were sensory evaluated (firmness, color, characteristic potato taste and off-taste) at the beginning of storage *(Publication No. 3 – Table 1 and Figure 3)*. The HHP treatment of FCP had no effect on the color of boiled (as browning) and fried slices (as characteristic color). However, 5-HHP and 10-HHP treatments had significant negative effects on

potato taste and influenced the formation of off-taste of boiled and fried FCP, which was more pronounced with longer HHP treatment times. This is probably due to the effect of HHP on enzymatic and chemical reactions, which can consequently affect taste (Oey et al., 2008). Moreover, HHP treatment had no effect on the firmness of boiled and fried FCP, however, the 5-HHP and 10-HHP samples showed significant mechanical damage during frying *(Publication No. 3 – Figure 4)*, with a concomitant heavy splashing of the oil, which may also be a consequence of possible damage to the internal tissue and infusion of the solution (Sopanangkul et al., 2002). Therefore, only the control and 3-HHP samples were further analyzed during storage.

The storage time had no significant influence on the instrumentally and sensory measured firmness of the raw FCP, but it increased the brightness of the samples *(Publication No. 3 – Table 2 and Figures 5 and 6)*. Moreover, no browning was observed during storage, which is consistent with the resistance to browning of cv. Birgit (The European Cultivated Potato Database, 2022). After sensory evaluation, more pronounced changes were observed in boiled and fried potatoes at 15^{th} day of storage, in the form of reduced potato taste, formation of off-odor, observed browning in boiled FCP, and loss of characteristic color in fried FCP. Dite Hunjek (2021) also reported a negative influence of storage on potato taste, which was even more pronounced in boiled potatoes than in fried potatoes. Furthermore, the deterioration of sensory properties during storage was more pronounced in 3-HHP samples than in the control *(Publication No. 3 –Figure 6)*.

It can be concluded that despite the significant effect of HHP (400 MPa/3 min) on the TAMBC, the samples prepared and treated in this way had poor sensory properties. Moreover, longer HHP treatments (5-HHP and 10-HHP) completely destroyed the texture of the fried FCP. Since all samples were treated with HHP while immersed in liquid, water diffusion into the potato tissue occurred, which affected sensory properties during storage, but also disabled frying. Considering all these factors, in the continuation of the research the HHP treatment (400 MPa/3 min) of VP FCP (without liquid) was applied.

4. Effect of UV-C irradiation, HPP and storage time on microbiological, physical and chemical properties of raw FCP, and on acrylamide and PAH in fried FCP

The aim of the research presented in the *Publication No. 4* was to investigate which of the treatments applied UV-C irradiation, HHP or combined UV-C/HHP can achieve the desired quality and safety, and preserve these properties of FCP during storage. The preparation of the

FCP samples for HHP treatment differs from the previous study. In this study, the samples were first VP and then treated with HHP, in contrast to the previous study in which the samples were treated with HHP while immersed in liquid and then VP. In order to obtain comparable results, the best previously selected UV-C treatments were therefore carried out again and compared with HHP and the combined UV-C/HHP treatment. For this purpose, potato tubers of the cv. Birgit were peeled, sliced and treated with 2% SA solution, VP and subjected to the treatment: UV-C irradiation (2.70 kJ m^{-2}) or HHP (400 MPa/3min) (selected on the basis of the results of previous research (*Publications No. 1, No. 2 and No. 3)*) or both treatments UV-C/HHP (first UV-C irradiation (2.70 kJ m^{-2}) and then HHP (400 MPa/3min)). The untreated samples represented the control samples. All samples were stored at 6 °C and analyzed on the 0^{th}, 8^{th}, 11^{th} and 15^{th} day of storage. On the same days, the raw FCP were analyzed for TAMBC, TS, TSS, pH, firmness, color, chlorogenic acid and RS content, and a sensory evaluation (odor, color - as browning, firmness, moistness and off-odor) was carried out. On the aforementioned days, some of the samples were fried (180 °C, 5 min) for sensory analysis and acrylamide and PAH analysis. The acrylamide and PAH analysis were carried out on freeze dried fried samples. A total of 15 PAHs were identified and quantified by GC–MS, which were separated for clarification purposes into the major light fraction (up to four aromatic rings - naphthalene, acenaphtylene, acenaphtene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, and chrysene) and heavy fraction (five or six aromatic rings - benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, and indeno(1,2,3,-c,d)pyrene).

The TAMBC of the control samples was 2.6 log $CFUg^{-1}$ at the beginning of storage and increased to 9.5 log CFU g^{-1} by day 15 *(Publication No. 4 – Figure 1)*. The observed reductions due to the effect of the treatments on day 0 were 1.0, 1.1 and 1.4 log CFU g^{-1} for UV-C, HHP and UV-C/HHP, respectively. However, the samples treated with HHP and UV-C/HHP showed the slowest bacterial growth, with TAMBC of 4.5 and 3.9 log CFU g^{-1}, respectively, after 15 days of storage. The higher increase in TAMBC during storage in UV-C treated samples than in HHP or UV-C/HHP treated samples, could probably be due to a repair mechanism (photoreactivation) as well as replication of bacteria that remained functional after treatment (Allende and Artés; 2003, Gardner and Shama, 1998). Indeed, since UV-C only acts on the surface of the material, some microorganisms may remain in the shade due to the rough topography of the FCP, and proliferate during storage. HHP treatment damages the structural organization of the cells, leading to leakage

of the cell contents and consequent cell death (Guerrero-Beltrán et al., 2005), which is why HHP is effective in inactivating microorganisms. This germicidal effect of UV-C radiation and HHP on FCP has also been confirmed in several recent studies (Manzocco et al., 2011; Tsikrika et al., 2021). All samples tested in this study, with the exception of the control sample on day 15, were below the borderline level of aerobic colony count for VP ready-to-eat refrigerated vegetables (6 − < 8 log CFU g^{-1}) (Guidelines for assessing the microbiological safety of ready-to-eat foods).

TS slightly increased by the influence of UV-C *(Publication No. 4 – Table 1)*, similar to what was reported in our previous research *(Publication No. 1 – Table 1).* However, the TS content increased significantly when HHP and UV-C/HHP were applied. Namely, due to the effect of HHP, there may be an increase in the cell membrane permeability, improvement in diffusion and an increase in mass transfer, which ultimately leads to water loss (Janowicz and Lenart, 2018; Sopanangkul et al., 2002). According to previous studies, the same or lower percentage of moisture was observed in potato samples with pressure up to 400 MPa/5 min (Dourado et al., 2020) or 600 MPa/3 min (Tsikrika et al., 2019). According to Tsikrika et al. (2019), the effect also depended on the potato cultivar used. In addition, the TS content did not change significantly during storage.

All treatments caused an increase in TSS, with the highest values recorded for HHP (4.66 °Bx) and UV-C/HHP (4.45 °Bx) *(Publication No. 4 – Table 1)*. The HHP included in these treatments may damage the cells, allowing the release of sugars and other soluble solids from the cells (Oliveira et al., 2015, Rastogi and Niranjan, 2008). Dourado et al. (2020) found up to 5-fold increase in TSS in external potato water when potatoes were exposed to 400 MPa. In previous research *(Publication No. 1 – Table 1)*, a slight decrease in TSS content was found when UV-C was considered. It was also found that the content of TSS increased at 15th day, which could be due to the starch breakdown in soluble solids or the hydrolysis of cell wall (Iturralde-García et al., 2022).

The mean value of the pH of control samples was 5.60 *(Publication No. 4 – Table 1)*. Similar to previous study *(Publication No. 1 – Table 1)*, UV-C caused a slight decrease of pH, while HHP and UV-C/HHP slightly increased pH. During storage, the pH decreased as it was observed in previous research *(Publication No. 1 – Table 1)*.

Firmness of the samples did not change under the influence of the treatments, nor under the influence of the storage days *(Publication No. 4 – Table 1)*. Although a slight decrease in firmness due to UV-C was reported in previous research *(Publication No. 1 – Table 1)*, this was

not the case here. Firmness was not affected by the influence of HHP, similar to what was reported in *Publication No. 3.* According to Dourado et al. (2020), a decrease in firmness was found when HHP of 200 and 400 MPa was applied on potato slices immersed in liquid.

The mean values of *L**, *a** and *b** for the control samples *(Publication No. 4 – Table 2)* were slightly lower compared to the results of previous research *(Publication No. 1 – Table 1)* and the research by Dite Hunjek et al. (2020b) on the same potato variety. This is probably a consequence of different growing conditions and the age of the potatoes themselves. All treatments applied caused a significant increase in the *L** value, a decrease in *a** and had no influence on the *b** values. The increase of *L** values (brightness) under the influence of UV-C irradiation was already reported in previous study *(Publication No. 1 – Table 1)*. The brightest samples were those treated with UV-C/HHP. According to some other studies on different vegetables treated with HHP (Sánchez-Moreno et al., 2006; Zhou et al., 2014), an increase in *L** value was observed in tomato puree and pumpkin slices. The action of HHP can damage cells, allowing better contact between PPO and phenolic substrates, i.e., creating conditions that favor the browning process. However, HHP could also affect the distribution of surface reflectance due to texture changes, resulting in brighter slices (Macdougall, 2002). During storage, the brightness increased on day 8 and remained stable until the end of storage *(Publication No. 4 – Table 2)*. Parameter *a**, which describes redness as a positive value and greenness as negative value, changed although no specific trend was detected, and values remained below 1. These results indicate that no browning occurred during storage. Tsikrika et al. (2021), who treated the peeled potato tubers with a pressure of 600 MPa/3 min, reported a decrease in *L** and *b** values (yellowness) during storage. The characteristic color of the potato tissue of the cv. Birgit is yellow (The European Cultivated Potato Database). The *b** values were statistically highest on the 8th day of storage, but no trend toward change was observed. It can be concluded that all treatments applied can maintain the natural color of the potato tissue during the 15-day storage period.

The mean value of chlorogenic acid content in the control samples was 15.0 mg 100 g^{-1} DW *(Publication No. 4 – Table 3)*. All treatments applied influenced chlorogenic acid content. UV-C reduced the chlorogenic acid content by 30.7%. Although less significant, the reduction in content due to the effect of UV-C was observed earlier *(Publication No. 2 – Table 1)*. However, treatment with HHP and UV-C/HHP reduced the content by 58.0 and 72.7%, respectively. Similar

results were published by Tsikrika et al. (2019) and Tsikrika et al. (2021). They observed a significant decrease in chlorogenic acid content due to the effect of HHP (600 MPa/3 min) on the VP tubers, depending on the cultivar used. At the same time, they observed an increase in caffeic acid content, and suspected that this might be a consequence of the degradation of chlorogenic acid in free form to its constituents, such as caffeic acid (Tsikrika et al., 2019). During the 15-day storage, the chlorogenic acid content increased *(Publication No. 4 – Table 3)*, the smallest increase in the HHP and UV-C/HHP samples *(Publication No. 4 – Figure 2)* was observed. A lower increase could be due to a lower activity of enzymes involved in biosynthesis of chlorogenic acid, due to the effect of HHP involved in both treatments. The reduced chlorogenic acid is beneficial in preventing the browning process, which was not observed in the treated samples during storage, according to the color analysis *(Publication No. 3 – Table 2)*.

The mean value of RS content of the control samples was 0.79 g 100 g^{-1} DW *(Publication No. 4 – Table 3)*, which was slightly higher than in previous research *(Publication No. 2)*. All treatments applied had a significant effect on increasing the RS content. The increase in sugar content under the influence of 5-UV-C has already been discussed (Chapter 6, Subchapter 2). Although HHP itself increased the content of RS, the highest increase was under the influence of a combined UV-C/HHP treatment, which caused about a doubling of the content. One possible reason for the increase in sugar content under the influence of HHP is its effect on cell structure, which facilitates the release and availability of sugars. Similar to the results of this study, an increase in RS content was observed when red ginseng was treated with HHP (400-600 MPa/1 min) (Ghafoor et al., 2012), while no changes in RS content were observed in other study (Shigematsu et al., 2017) on HHP treated (100-600 MPa/10 min/ambient temperature) FC VP sweet potatoes. However, the influence of combined treatments should be studied in more detail. The content of RS increased during 15 days of storage *(Publication No. 4 – Table 3)*, regardless of the treatment. However, it was the most pronounce in the UV-C treated samples on the 8th and 15th day *(Publication No. 4 – Figure 3)*. Similar changes during storage of raw untreated potatoes were observed in previous research *(Publication No. 2 −Table 1)*.

The mean value of acrylamide content in the fried control FCP was 598 µg kg^{-1} DW *(Publication No. 4 – Table 3)*. All treatments applied led to an increase in the acrylamide content. The mean value of acrylamide content in UV-C and HHP treated samples was 750 µg kg^{-1} DW and 767 µg kg^{-1} DW, respectively, and all values were much below the limit of 750 µg kg^{-1} of

product (EU, 2017/2158). The acrylamide values in this study are expressed in DW and are about three times higher than the values expressed in the mass of the fried samples. Regarding the effect of HHP on potatoes, Dourado et al. (2020) observed no significant changes in acrylamide content when raw potato sticks immersed in water were treated with HHP (100, 200, or 400 MPa/5 min). In this research, the combined UV-C/HHP treatment resulted in a 3-fold higher content *(Publication No. 4 – Figure 4)*. Acrylamide is formed through Maillard reactions in which RS and the free amino acid asparagine serve as precursors. In this research an increase in RS was found under the effect of UV-C, HHP and UV-C/HHP treatment *(Publication No. 4 – Table 3)*, as well as a strong correlation between RS and acrylamide in *Publication No. 2*. However, this disproportionate increase (considering the increase in RS) with combined UV-C/HHP treatment should be further investigated. According to Ghafoor et al. (2012) the application of HHP (400–600 MPa) to red ginseng roots resulted in an increase in the content of RS and amino acids, including asparagine. It could be assumed that this combined treatment may possibly affect some of the precursors or the reaction process itself. During storage, a slight increase in acrylamide content was observed in the control, UV-C and HHP treated samples, while a significant increase was observed in the UV-C/HHP samples after 8 days of storage, which remained stable thereafter *(Publication No. 4 – Figure 4)*. The samples treated with UV-C and HHP under the conditions of our experiment were safe in terms of acrylamide content.

Following the analysis of acrylamide in the fried samples, the inadequacy of the combined UV-C/HHP treatment was identified, and therefore the analysis of PAH was carried out only for the single UV-C and HHP treatment *(Publication No. 4 – Figure 5)*. 15 PAH were identified, and the content of benzo(g,h,i)perylene was found to be below the detection limit of the method in all analyzed samples. The dominant molecule in the light fraction was phenanthrene (4.90–28.63 µg kg^{-1}), and in the heavy fraction benzo(k)fluoranthene (0.70–6.21 µg kg^{-1}), which is somewhat different from the results published by Balbino et al. (2020), where naphthalene dominated in the light fraction, and benzo(g,h,i)perylene in the heavy fraction. In all tested samples, the content of benzo(a)pyrene and PAH4 was below the limits specified in EU Regulation 835/2011 (EU, 2011a). Furthermore, in the samples treated with UV-C, the contents of the heavy PAH and PAH4 fractions were significantly lower, while the contents of the light fraction were higher compared to the control. According to previous studies on the effect of UV-C light (of different wavelengths) on the degradation of PAH in soils, water and wastewater, UV-C radiation causes photocatalytic

degradation of PAH to varying degrees, depending on the chemical composition of the matrix (Eldos et al., 2020, Salihoglu et al., 2012, Liu et al., 2016). Therefore, it could be possible that the UV-C treatment in this study caused the degradation of heavy PAH to lower molecular weight PAH. After 15 days of storage, there was an increase in light PAH, which could be related to the partial destruction of the cells and the loss of water content after the applied treatments.

PCA was performed on the collected sensory data for raw, boiled and fried FCP *(Publication No. 4 – Figures 6, 7 and 8)*. In this way, the relationship between the analyzed parameters was visualized, and a possible grouping of the samples according to the applied treatment (UV-C, HHP and UV-C/HHP) and the storage days was also monitored.

In the analysis of raw FCP samples, PC1 and PC2 *(Publication No. 4 – Figure 6a and 6b)* accounted 84.24% of the total data variance. UV-C treated raw samples stood out on the positive PC1 as they had higher firmness and odor scores and lower off-odor scores. In contrast, almost all HHP and UV-C/HHP treated samples were in positive PC2 as they were rated with the highest moistness. In terms of storage, most samples stored for 0 and 8 days were in the positive PC1 range, due to the higher firmness and odor scores. Samples stored for 11 and 15 days were in the negative part of PC1, mainly due to the increased moistness and color (as browning) scores.

The sensory properties of boiled FCP as a function of treatment applied and storage time are shown in *Publication No. 4 – Figure 7a and 7b*, where PC1 and PC2 accounted 83.86% of the total data variance. In the upper left quadrant where the UV-C treated samples with higher creaminess and odor scores. The control samples were characterized by higher scores for creaminess and color (as browning), while the HHP and UV-C/HHP treated samples had pronounced firmness. Samples stored for 0 and 8 days showed correlation with higher scores for odor, firmness, creaminess, and characteristic taste, while most samples stored for 15 days were related with increased scores for color (browning).

PCA analysis revealed the sensory properties of fried FCP as a function of the treatment applied and the storage days *(Publication No. 4 – Figure 6a and 6b)*, with PC1 and PC2 describing 79.86% of the total data variance. Control samples were grouped on negative PC2 and showed a high correlation with color and oiliness. Samples treated with UV-C were highly correlated with odor. HHP and UV-C/HHP treated samples were placed on the positive PC2, which can be related to the lower color and oiliness scores, as well as the higher firmness scores. Samples which were stored for 0 and 8 days had more pronounced positive characteristics such as color, odor, crispness,

and taste, while in contrast, all samples stored for 15 days had lower scores, but still satisfactory pronounced positive attributes. Finally, some negative changes in sensory properties were observed on the 15^{th} day, especially in the control samples. Regardless of the treatment applied (UV-C, HHP and UV-C/HHP), sensory properties of the samples treated in this way seem to have been satisfactorily maintained during the 15-days storage period.

Chapter 4

Conclusions and prospect

- In the experiment investigating the effect of 3-min UV-C (3-UV-C), 5-min UV-C (5-UV-C) and 10-min UV-C (10-UV-C) treatments, the results showed that the efficacy of 5-UV-C and 10-UV-C treatments in slowing the growth of aerobic mesophilic bacteria during storage was significant and equal in this sense. These samples were microbiologically acceptable at least until the 15th day of storage. In the control samples, the TAMBC level already exceeded the recommended upper limit, for VP ready-to-eat fruits and vegetables on the 11th day of storage (Guidelines for assessing the microbiological safety of ready-to-eat foods), which was accompanied by increasing off-odor and browning of the samples.
- 5- and 10-UV-C treatments of raw samples resulted in a more pronounced odor and less pronounced browning of FCP during 15 days. Furthermore, these treatments also had the effect of increasing the brightness (increased *L**) of raw FCP. 5- and 10-UV-C treated and subsequently boiled and fried samples had a more pronounced odor, taste, sweetness and saltiness.
- All applied UV-C treatments led to a reduction of the chlorogenic acid content in the raw FCP, but most significantly 10-UV-C. The content decreased in the raw samples during storage, but a large amount (about 79%) was retained until the 15th day.
- The highest increase in RS and acrylamide content was observed in the samples treated with 5-UV-C. Their content increased during storage, but acrylamide levels in all samples were significantly below the EU specified levels of 750 µg kg^{-1} (EU, 2017/2158). A strong positive correlation was found between RS and acrylamide content.
- The effects of UV-C treatments and storage time resulted in a slight change in pH, TS, TSS and firmness.
- Boiling and frying led to a reduction of the content of chlorogenic acid and RS, regardless of the treatment. In addition, a slight increase in the permeability of the PA/PE packaging material was observed when the 5- and 10-UV-C treatment were applied, but it was not significantly different from the control. Considering the overall quite similar effects of the 5- and 10-UV-C treatments, the 5-UV-C was chosen for further research because of the time and energy savings.
- The effect of HHP (400 MPa/ 0, 3, 5 and 10 min) on FCP placed in plastic container with SA solution showed that 10-min HHP resulted in the highest reduction of TAMBC, while 3- and 5-min treatments were similarly effective. During storage, the effect of the 3-min treatment was particularly pronounced, as it slowed bacterial growth. The applied HHP treatments led to

an increase in brightness (L^*) and a slight increase in the instrumentally measured firmness of the raw FCP. However, the texture of the samples treated with HHP for 5- and 10-min was completely destroyed during frying. 3-min treatment of FCP had no effect on the sensory firmness of the raw FCP during the 15-day storage period, and browning was not observed. However, the sensory properties of boiled and fried samples were significantly degraded, especially after the 11th day of storage. These results are thought to be due to the effect of HHP treatment on the FCP while it was immersed in a liquid (sodium ascorbate solution). Therefore, the treatment of FCP should be carried out in the following order: immersion in SA solution, drainage, VP and then HHP treatment.

- To select the best (optimal) treatment, a comparison of the efficacy of UV-C (5 min) and HHP (400 MPa/3 min) determined in the previous experiments and combined UV-C/HHP treatment were performed on VP FCP. The UV-C/HHP treatment proved to be the most efficient in reducing TAMBC, while the HHP and UV-C/HHP treatments showed the best efficacy in slowing down the growth of microorganisms during storage. All treated samples were microbiologically acceptable after 15 days of storage, while the control samples exceed the recommended levels for ready-to-eat fresh-cut fruits and vegetables (Guidelines for assessing the microbiological safety of ready-to-eat foods) on the 11th day. These changes in TAMBC in the control samples were accompanied by a more pronounced tendency to browning and the development of off-odor.
- Although treatments and/or storage affected pH, TS and TSS content and color of raw FCP, these changes were mostly negligible. In addition, all treatments applied resulted in a decrease in chlorogenic acid content and an increase in RS content in raw FCP. The highest effect in this case had UV-C/HHP treatment. Under the influence of all treatments, the acrylamide content in fried potatoes increased, but most strongly when the UV-C/HHP treatment was applied. With the exception of the UV-C/HHP samples, the other samples can be regarded as harmless to health with regard to the specified levels (EU, 2017/2158).
- In view of the safety aspect, the effect of UV-C and HHP treatments on the PAH content was also examined. UV-C increased the content of light PAH, and the content of benzo(a)pyrene and PAH4 was always below the limits set by EU Regulation 835/2011.
- During storage, the content of chlorogenic acid and RS increased with the intensity of changes depending on the treatment applied. Light PAH levels also increased during storage. The

acrylamide content increased slightly during storage, but significantly in the UV-C/HHP samples on day 8.

- Despite some changes in sensory properties, the raw, boiled and fried samples were acceptable during 15-day storage. The sensory results also showed that HHP is more effective when applied to VP FCP compared to HHP treatment of FCP immersed in SA solution.

- These results proved stated hypothesis that UV-C irradiation and HHP can reduce the TAMBC and slow their growth during FCP storage, thereby maintaining product quality and extending shelf-life up to the 15th day of storage. The effectiveness of the treatments depended on the conditions applied. The 5-UV-C (2.70 kJ m^{-2}) and HHP (400 MPa/3 min) treatments proved to be effective in terms of antimicrobial activity and had a mostly minor effect on the physical properties of raw FCP and maintained sensory properties of raw FCP and subsequently thermally treated FCP. Their application resulted in a decrease in chlorogenic acid content and an increase in sugar content in raw FCP. They also led to an increase in the acrylamide content in the fried FCP, but these changes had no effect on the safety of the product, as the levels were under the limits according to the official regulation.
- In general, the application of 5-UV-C (2.70 kJ m^{-2}) and HHP (400 MPa/3 min) treatments to FCP pretreated with a 2% solution of SA and VP has the potential to maintain the quality and safety of raw FCP during a 15-day storage at 6 °C. These relatively short processes can be used as final operations of FCP production. These findings can serve as a basis for further scientific research in the field of processing and preparation of FCP intended for storage at refrigerator temperatures as well as for FCP production at the industrial level.

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Autobiography

Autobiography

Zdenka Pelaić is completing her Ph.D. study „Biotechnology and Bioprocess engineering, Food technology and Nutrition" at the University of Zagreb, Faculty of Food Technology and Biotechnology, in the field of Food Technology. From 2018-2022 she was working at the University of Zagreb, Faculty of Food Technology and Biotechnology as a research assistant, on the project "Innovative techniques in potato minimal processing (*Solanum tuberosum*) and its safety after preparation - IMPROvePOTATO" funded by the Croatian Science Foundation. From 2019 till now, she works as an associate, title assistant at the Department of Ecology, Agronomy and Aquaculture, at the University of Zadar. In 2016, she participated as a technical assistant-analyst in the project "Beekeeping promotion / BEE promoted" as part of the IPA cross-border cooperation Croatia - Bosnia and Herzegovina, and from 2014 - 2016, she worked as a technical associate on the EU project "Application of innovative technologies in the isolation of bioactive compounds from organic waste in wine production" at the University of Zagreb, Faculty of Food Technology and Biotechnology. Before that (2001-2014), she worked as a chemistry teacher at the Zadar Private Gymnasium, the "Nova" Private Primary School and Gračac High School. She completed additional pedagogical-psychological, didactic and methodical education at the Faculty of Philosophy of the University of Zadar (2001). In 1997/1998, she did an internship at Adria d.d. factory, Zadar. She graduated in 1996 in the field of food engineering at Faculty of Food Technology and Biotechnology, University of Zagreb, on the topic "The influence of olive oil storage on sustainability and phenolic compounds in oil". Her current research area is the influence of innovative technologies on the quality, safety and shelf life of fresh-cut potato. Until now, she was author or co-author at 9 scientific papers in journals indexed in Web of Science/Current Contents Connect and 6 papers in other Journals and Proceedings. She presented her results at many international and national congresses, and was awarded for the best poster presentation at the international congress.

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