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Potato Enzymatic Browning, Mitigation and Prevention: Current Overview of Approaches and Findings

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ABSTRACT

The phenomenon of enzymatic browning that affects foods is considered one of the most common problems that the world suffers from and one of the biggest challenges in the food industry. This browning chemical reaction typically occurs postharvest, during food processing, storage, or after mechanical peeling and cutting. Potatoes, which form the basis of many meals for the world's population, are among the foods most susceptible to this problem, leading to changes in color and flavor and exposing them to spoilage and a decrease in nutritional quality. The main factor in the occurrence of this phenomenon is polyphenol oxidase, which works to oxidize the phenolic compounds to form corresponding quinones, which in turn polymerize with other compounds, using sugars, amino acids, as well as amino or sulfhydryl groups of protein, generating melanoid pigments. In general, various physical, chemical, and biological treatments have the potential to control or inhibit browning.

1-Introduction

Potatoes (*Solanum tuberosum L.*) are the staple food of most people in the world and have a major impact on health. Because of their high dietary fiber content, low energy, and abundance of nutrients, potatoes are becoming more and more popular among customers. There are many different items made from fresh-cut potatoes (FCP)(Komlaga, Oduro, Ellis, & Dziedzoave, 2021). However, potato tubers lose their skin protection after being peeled and chopped mechanically, injuring the cells and causing the release of their contents and an acceleration of browning. Browning is a highly complicated process involving multiple enzymes and types of chemicals, and it is one of the main issues with the shelf life of FCP. One of the negative effects of chopping potatoes and other fruits and vegetables is enzymatic browning (EB). When tissue integrity is compromised during cutting, phenolic compounds (the substrate for browning) come into interaction with oxidative enzymes(G. Li *et al*., 2023; M. Wang *et al*., 2021). This interaction occurs when endogenous phenolics are oxidized to quinones in the presence of oxygen and enzymes, which can then polymerize with other phenolics, sugars, or amino or sulfhydryl groups of soluble proteins (Aya I Rashan & Al-abbasy,

2021; Sui, Meng, Dong, Fan, & Wang, 2023). *Polyphenol oxidase* (PPO) and *peroxidase* (POD) are the primary enzymes implicated in this process. Nevertheless, *phenylalanine lyase* (PAL), an essential enzyme in the production of polyphenols, is damage-induced(Organization, 2023; Zaheer & Akhtar, 2016). Browning usually causes enormous quantities of waste and financial loss for the FCP sector in addition to causing quality deterioration and reducing the shelf life of fresh potatoes. It presented a challenge to numerous scientists who attempted to reduce the occurrence and preserve food from spoiling and undesirable flavor and color by creating multiple methodologies and effective procedures using different anti-browning substances.

The basic idea of anti-browning treatments is to eliminate one of the three primary causes of browning reactions, which are oxygen, phenolics, and the enzymes PPO and POD(Zaheer & Akhtar, 2016). There are numerous physical, chemical, and biological techniques for regulating how browning occurs in FCP. Low temperature, heat treatment, and ultrasonic treatment are examples of physical technology. They are being aware that there could be some unfavorable side effects from these technologies(Feng, Liu, Liu, Shi, & Wang, 2020). FCP browning could be efficiently inhibited by chemical methods like sulfites, chelating agents, antioxidants, and natural extracts; however, there are concerns about food safety. Genetic engineering methods have good browning-inhibiting effects on FCP. However, these technologies are not suitable for commercial use, and most consumers do not approve of transgenic foods(Chantada–Vázquez *et al., 2018)*. The central objective of this review is to focus on significant information that has been used, particularly for preventing enzymatic browning in fresh and processed potatoes to avoid undesirable properties.

2.POTATO

Potato serves as one of the principal crops grown for staple meals worldwide because of its high nutritional value, economic significance, ability to ensure food security, and adaptability in processing(Organization, 2023). Because of their excellent nutritious fiber content and abundance of nutrients, potatoes are attracting more and more attention from people(Organization, 2023; Zhou *et al*., 2019). It has been regarded as the most significant food plant and one of the greatest suppliers of human nourishment for centuries(Zaheer & Akhtar, 2016). In addition, potatoes are a crop that can be grown all year round(Figure 1)(Silveira, Oyarzún, Sepúlveda, & Escalona, 2017). The quality of potatoes is becoming more and more in demand and the internal deterioration brought due by the impact on tubers during mechanical harvesting and storage may result in significant losses(Ojha, Karki, & Ali).

Figure 1: Photograph of a potato plant

Potato tubers are an excellent source of vitamins, minerals, carbs, and protein-rich in essential amino acids. It also has a lot of flavonoids, which have medical benefits. (Beals, 2019; Muller, Pretorius, & Schönfeldt, 2022). Potato tubers have a powerful prebiotic impact, lower the gut environment's pH, and regulate lipid metabolism-related diseases by decreasing cholesterol levels. The pharmacological properties of potatoes include antibacterial, anti-inflammatory, and antioxidant(Rasheed, Ahmad, & Bao, 2022). Potato tubers lose their skin defense when they are mechanically peeled and chopped, injuring the cells and causing the release of their contents and accelerating EB(A. Ali, Yeoh, Forney, & Siddiqui, 2018; Zhu *et al*., 2021). There are differences in potato cultivars' susceptibilities to EB.

3.BROWNING:

Browning is a significant chemical reaction that occurs when food is processed and stored. Vegetables and fruits lose their nutritional value and sensory appeal due to browning, and consumers may even be discouraged from buying fresh produce. Some food develops extremely desired color and flavor during browning, which is also linked to delicious, widely accepted, and high-quality products, for example, bread, chips, and roasted nuts(Gupta, Sood, Gupta, Bandral, & Langeh, 2022). Unlike other foods become undesirable due to browning as potatoes. Particularly, browning can be divided into two primary categories: Non-Enzymic Browning (NEB) and EB(Omar Y Al-Abbasy, Younus, Rashan, & Ahmad, 2024; Corzo-Martínez, Corzo, Villamiel, & Del Castillo, 2012), which will be covered in more depth a little later.

4.ENZYMATIC BROWNING:

The oxidative process known as EB causes fruits and vegetables to turn brown and is mostly caused by the enzymes present (Figure 2). There are three main enzymes involved in EB reactions of freshly chopped foods: PPO, POD, and PAL(Arnold & Gramza-Michałowska, 2022). PAL (EC 4.3.1.24) controls the phenylpropanoid pathway, which is responsible for the production of flavonoid and phenol compounds. An indirect source of the browning products could be the increased PAL activity, which could speed up the manufacture of phenolic compounds(M. Wang *et al*., 2021). Oxidative browning by POD (*EC1.11.1.7*) happens by oxidizing a wide range of chemicals only when H_2O_2 is present, which will result in EB reactions(Shrestha *et al*., 2020). The main enzyme is naturally PPO (), which has binuclear copper at its active site and is each linked by three histidine residues. It was originally identified in mushrooms and, subsequently, in some bacteria, fungi, arthropods, plants, and animals(Sae-leaw & Benjakul, 2019).

PPO inserts oxygen in an aromatic ring via an ortho-position to a pre-existing hydroxyl group, oxidizing the diphenol to the corresponding quinone(Mayer, 2006). These quinones can then polymerize with other phenolics, sugars, and amino acids as well as with sulfhydryl groups of soluble protein, and generate polymeric melanoid brown pigments(Bobo-García, Arroqui, Merino, &

Vírseda, 2020). The presence of EB typically degrades color, flavor, and nutritional content, resulting in a shorter shelf life and quicker deterioration of quality. Various factors, including PPO level, phenolic compound level, pH, temperature, and the tissue's accessibility to oxygen, influence the pace of EB in fruits and vegetables(Ioannou, 2013).

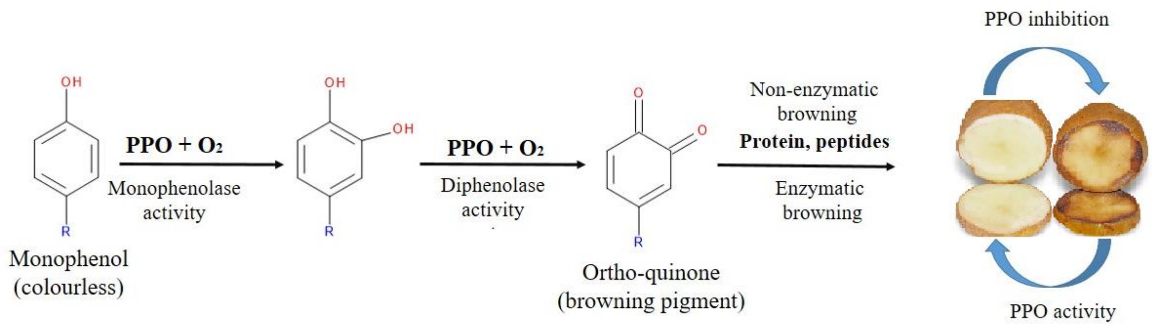

Figure 2: PPO reaction in potato

5.PPO IN POTATO

Proteins and enzymes are just two of the several vital biochemical substances found in potatoes. PPO is the most important of these enzymes in the current investigation. In potatoes, PPO activity was low in leaves and stems but strong in stolons, tubers, roots, and flowers.

PPO activity per tuber increased during tuber growth, peaking in growing tubers based on fresh weight (Hasan Ali AL-Jammaas, 2023). Potato PPO has been isolated and characterized using an essential stage of chromatography. Sepharose 4B-l-tyrosine-p- amino benzoic acid affinity column has been used to purify potato PPO. The optimum pH and temperature of potato PPO activity were 6.6 and 35 °C, respectively, when using o-dihydroxy benzene as substrate(Y. Wang *et al*., 2011).

PPO has two molecular weights, 40 and 60 kDa. The 60 kDa of PPO, which exhibits poor activity, is transformed into the 40 kDa form with high activity (F. Liu, Zhao, Zhu, Gan, & Ni, 2015).

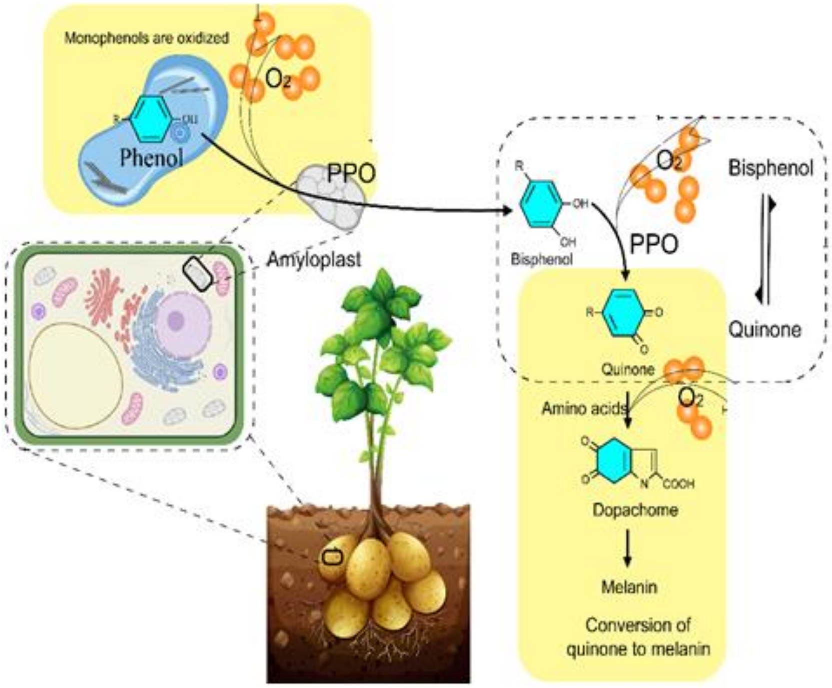

Figure 3P: PPO in potato tubers is located in the amyloplasts, and phenols are present in the vesicles.

Many potato PPO genes have been identified and separated. These genes have distinct temporal and geographical expression patterns. Potato tubers express a minimum of five distinct PPO genes(Chi *et al*., 2014).

6.POTATO BROWNING

FCP's browning is primarily caused by EB(Rashid *et al*., 2021). When tissue is sliced, oxidative enzymes come into contact with phenolic compounds due to the disruption of structural integrity(Bobo-García *et al*., 2020). EB poses a significant risk to growers and the industry because it can contaminate tubers during harvest and postharvest processes such as blanching, shipping, and storing (Aya Ihsan Rashan, Altaee, Salh, Al-Abbasy, & Al-Lehebe, 2023). In addition to degrading FCP's quality and shortening its shelf life, EB causes enormous waste and financial losses (Feng *et al*., 2020). According to several reports, millions of dollars are lost annually as a result of the discoloration, and 50% of customers would completely toss the meal if the browning was evident. Owing to the intricacy of the browning process, it has long been difficult for scientists to comprehend the mechanism underlying all of these reactions in potatoes. Their main objective is to create an effective ABA treatment or strategy while maintaining the potato's real color and product quality (Jaeger *et al*., 2018; Weerawardana, Thiripuranathar, & Paranagama, 2020).

7.BROWNING CONTROL

Controlling browning is still a problem in the food trade. Since phenolic, O_2, and enzymes are the three primary components that contribute to browning processes, the primary goal of ABA handling is to eliminate one of these variables and then control the browning. Thus, the color will be retained, which will extend the shelf life and improve customer acceptance of processed raw potato goods(Bobo-García *et al*., 2020). ABA techniques sometimes involve the use of heat or newly developed technology to inactivate enzymes, as well as specific chemicals or natural extracts. Because of their established synergistic benefits, these techniques can be applied singly or in combination (Levaj et al., 2023; Taqi & et al., 2024). In industry, physical and /or chemical treatments are used to inhibit this undesirable process(Zhang *et al*., 2018). These techniques do, however, have significant drawbacks, such as changes to the finished products' organoleptic and nutritive qualities, and some of them may even pose a risk to human health. Thus, the safest and most promising way to prevent unwanted browning chemicals in newly harvested and processed potato-derived products is to develop innovative technologies to control PPO activity in plants(Tinello & Lante, 2018). Below, however, is an overview of the physical, chemical, natural extracts, and biological strategies that can be used to alter or prevent the brown color of potatoes.

8.PHYSICAL METHODS

The browning of FCP has been managed by a variety of physical techniques (Shrestha *et al*., 2020). Although thermal treatments are generally safe, there are still certain issues that need to be resolved. For instance, heat treatment may cause the FCP to soften(Ellis, Knowles, & Knowles, 2019). Much research has been conducted, including that using heat shock and ultrasounds, to preserve the storage quality of FCP. While heat can quickly deactivate PPO, it can also have a detrimental effect on the nutritional value, texture, and look of goods(Park, Moon, Park, Lee, & Kim, 2020). By raising CO_2 and lowering O_2 levels, a controlled environment is frequently employed to partially suppress EB. Nowadays, it's applied to vegetables like potatoes(D. Li *et al*., 2020). In a different study, potatoes treated with 80% oxygen pretreatment had a strong AB impact by delaying the rise in PPO activity*(X. Liu et al.*, 2019). To maximize the ABA impact, it was suggested to use ascorbic acid (AA) in conjunction with a physical approach. For instance, compared with either AA or ultrasound healing alone, the combination of both significantly reduced PPO activity in FCP(Xu *et al*., 2022). For eight days, FCP was stored at 4 °C to examine the impact of ultrasonic coupling of purslane extract on the browning resistance. A 10 min. The ultrasonic period and 0.02% w/w of extract produced a superior effect(Zhu *et al*., 2021). French fries generated by steam blanching and glucose oxidase treatment for 15 min. at 35°C exhibited a brighter and more consistent color than those that were not treated (Younus, Mahdi, Al-Abbasy, & Sheej Ahmad, 2025) . Physical approaches can be more cost-efficient and provide higher security, but they are not as effective at inhibiting EB because they cannot directly inactivate the enzymes involved in browning. More significantly, many physical treatments cause undesirable alterations to texture, flavor, and color(Moon, Kwon, Lee, & Kim, 2020).

9.CHEMICAL METHODS

The chemical methods used to control the browning of potatoes are:

1- Antioxidants

Antioxidants (AO) are compounds that can shield lipids, proteins, and other biomolecules from oxidation. This helps keep potatoes fresher longer by reducing the development of bad tastes(Franco & Martínez-Pinilla, 2017). In the food industry, several AOs are used as additives. They prevent the onset of the browning process when they react with oxygen(Dias *et al*., 2020; Park *et al*., 2020). Moreover, AO prevents melanin from forming and tampers with the intermediate products of subsequent processes. AA is an AO whose ABA characteristics are also being researched (Tsikrika, Tzima, & Rai, 2022). Through the reduction of oxidized substrates, AA acid inhibits EB even in the absence of direct contact with PPO(Arias, González, Oria, & Lopez-Buesa, 2007). The FCP slices were kept at 4°C after being submerged in AA (0.3 mmol L^{-1}) for 10 min. It was found to have less browning than the control group*(*G. Li *et al*., 2023). When phenolic molecules get oxidized, AA acid lowers pH, which reduces PPO and POD activities and restores oxidized phenolic compounds to their natural form(Tang, Guo, & Zhu, 2023; Zhou *et al.*, 2021). Another AO that can suppress FCP browning is L-cysteine(A. Ali *et al*., 2018). PPO activity of FCP was reduced when L-cysteine concentration increased because of a reaction that produced a colorless adduct(H. M. Ali, El-Gizawy, El-Bassiouny, & Saleh, 2016). Understanding that L-cysteine and AA are better forms of ABA and have a high level of safety for human health(L. Li, Wu, Zhao, Guo, & Liu, 2018). Several AOs, including 4-hexylresorcinol, N-acetylcysteine, erythorbic acid, and glutathione, are being investigated for their ABA characteristics (Tsikrika et al., 2022). Finally, curcumin and quercetin inhibited the purified potato PPO using catechol as a substrate, and IC_{50} values were found to be 0.018 and 0.029 mM, respectively(Aksoy, 2020).

2- Natural Extracts

Many chemical approaches have been investigated in the last few decades to lessen quinone browning. Nevertheless, certain approaches are rather restricted because of their high expense and possible safety issues(Moon *et al*., 2020). To address this, it's critical to look for novel, inexpensive, and safe food additives with ABA qualities that come from natural sources in the food processing sector. An encouraging substitute for chemicals in preservative formulations is the use of naturally occurring materials. Herbs, seeds, leaves, bark, and roots are possible sources of natural preservatives and their extracts (Omar Y Al-Abbasy, Ali, & Younis, 2020; Alrushdi et al., 2025). Unquestionably, using natural sources is necessary to increase customer acceptance of these products, avoid financial losses, produce high-quality meals and the market for active components in natural preservatives is growing due to two important causes(Omar Younis Al-Abbasy, Ali, Rashan, & Al-Bajari, 2021; Kerdudo *et al*., 2016). First is the desire for a healthy lifestyle and consumer knowledge of environmental issues. Second, natural preservatives have antibacterial, AO, and even ABA properties(Al-burgus, Ali, & Al-abbasy, 2024).

Several natural extracts have been carried out to control the browning of potato tubers. Liu and colleagues (2019) discovered that treatment with 0.05% purslane aqueous extract reduced the intensity of browning by inhibiting PPO, POD, and PAL activities in FCP*(X. Liu et al*., 2019). This extract is edible and rich in alkaloids and polyphenols. The browning of freshly cut sweet potatoes was considerably prevented by citrus peel extract (2 g. L^{-1}), which is a perfect natural AO and is characterized for use as a food additive to enhance the potato quality. Browning reactions in pretreatment sweet potato (Ipomoea batatas) slices were reported to be well controlled by 10% aqueous extracts of *Aframomum danielli* (Adegoke, Odebade, Afolabi, & Univetrsity, 2017). According to Yapi *et al*., (2015), onions and garlic extracts have an inhibitory effect on the edible yam EB, and a significant inhibition was observed upon the addition of hot onion extract. Additionally, it was discovered that the potato PPO is inhibited ideally by aqueous rice bran extract at 40 °C (Boonsiripiphat & Theerakulkait, 2009). it was found that chili pepper extracts have a 70% inhibition of potato PPO, possibly due to their high ascorbic acid content (Mercimek *et a*l., 2015). Numerous plant extracts can successfully stop browning owing to their potent AO activity (Liu et al. 2019). Other extracts that are known to inhibit the potato PPO are shown in Table 1 below:

Table 1: Extracts that can inhibit the potato PPO

Extract	Potato product	Reference
Honey, Pineapple, chili pepper	Sweet potatoes	(Lim, Cheun, & Wong, 2019)
Rice bran protein	Potato puree	(Legcharoen, Kubglomsong, & Theerakulkait, 2020)
Green tea, wheat bran, Clove, marjoram	Fresh–cut potato	(Bobo-García et al., 2020)

Mango peel	Potato puree	(Jirasuteeruk & Theerakulkait, 2020)
Tartary buckwheat seedlings	Potato	(D. Li *et al.*, 2020)
Lemon, red beet	Potato	(Mercimek *et al.*, 2015)
Rosemary essential	Sliced potatoes	(Rizzo *et al.*, 2018)
Hawthorn leaf	Fresh–cut potato	(Qiao *et al.*, 2021)

10.Acidification:

To keep food products at the proper pH, food additives such as acidifying agents and acidity regulators are frequently utilized. This is why ABA is also derived from acidulants. Song *et al.*, (2023) demonstrated that applying an optimal concentration of 15 g/L of glutamic acid (Glu) for 4 minutes considerably decreased the browning of potato pulp and shreds and extended the shelf life to 5 days(G. Li *et al.*, 2023). In addition, aspartic acid (Asp) solution treatments can also reduce PPO activity and prevent potato pulp from discoloring(Feng *et al.*, 2020). EB of FCP may also be inhibited by oxalic acid, citric acid, malic acid, and sodium acid pyrophosphate. These acids may be due to lower pH levels, which suppress PPO activity and limit the amount of total phenols(Mosneaguta, Alvarez, & Barringer, 2012).

11.Chelating agents:

PPO activity depends on copper to operate properly; hence, substances that chelate copper limit it. Sorbic acid, polycarboxylic acids, polyphosphates, and EDTA are only a few of the chelating agents that are employed in the food business (Moon et al. 2020, Brody et al. 2001). The method of ABA action, such as citric acid, oxalic acid, and isoleucine involves potentially inhibiting PPO activity by chelating the active-site copper (Cu^{2+}) from it(Feng et al., 2020; J. Song et al., 2022). About 60% of the PPO activity in FCP treated with 0.02% EDTA was inhibited(H. M. Ali et al., 2016).

12.Sulfites:

Although they are governed by regulations because of their harmful effects on health, many sulfiting agents, including sulfur dioxide, sodium and potassium bisulfites, and metabisulfites, have been added to food since ancient times to prevent EB because they are very beneficial in controlling browning (Jen *et al.*, 1989). Sulfites and sulfur dioxide are examples of chemical technology that could efficiently prevent FCP browning(Shrestha *et al.*, 2020). Using $NaHSO_3$ fully suppressed the PPO activity of FCP(H. M. Ali *et al.*, 2016). Regretfully, $NaHSO_3$ decomposes to form SO_2, which is hazardous to human health(L. Li *et al.*, 2018). By soaking potato slices in 3% sodium acid sulfate, the maximum EB inhibitory effect was noted(Mosneaguta *et al.*, 2012).

13.Others:

There are many chemical compounds observed to inhibit the potato PPO that were not mentioned above, for example, It was noted that low concentrations of xanthosine were able to reduce the production of brown color, while at a high concentration (5g L^{-1}) it completely prevented in the potato mash by reducing the activities of PPO and POD(Tao *et al.*, 2021). Precooked potatoes that have been exposed to EB may not develop complexing agents such as β-cyclodextrin (Sadoon & Ahmad, 2020; Singh, Pundhir, & Ghosh, 2015). Additionally, proline, methionine, valine, and glycine can considerably lower the browning FCP. FCP treated with 0.02% NaCl showed a 60% inhibition in PPO activity(A. Ali *et al.*, 2018; H. M. Ali *et al.*, 2016; Ma *et al.*, 2021). Every approach, though, has benefits and drawbacks depending on how it is used. It has been discovered that 3-mercapto-2-butanol can successfully prevent FCP browning by competitively inhibiting PPO activity(Huang *et al.*, 2021). The best solution for preventing the EB of Burbank and Norkotah potato slices was sodium erythorbate(Mosneaguta *et al.*, 2012). Other chemicals that are known to inhibit the potato PPO are shown in Table 2 below:

Table 2: Chemical compounds inhibited potato PPO

Compounds	Potato product type	Reference
Chlorogenic acid	Fresh-cut potatoes	(Cheng *et al.*, 2020)
S-Ethyl thioacetate	Fresh-cut potatoes	(Feng *et al.*, 2022)
S-furfuryl thioacetate	Fresh-cut potatoes	(Feng *et al.*, 2022)
Phloridzin, Phloretin, Benzentiol	Potato	(Aksoy, 2020)
p-alkylbenzoic acids	Potato	(Lin *et al.*, 2010)
p-Coumaric	Potato	(Jiang & Penner, 2022)
Sodium nitroprusside	Fresh-cut potatoes	(Z. Song *et al.*, 2023)

14.BIOLOGICAL METHODS

Despite genetic engineering and other biological techniques having good inhibitory effects on FCP browning, most biological technologies are not suitable for commercial usage, and most consumers do not approve of transgenic foods(Alsaayigh & Al-Azzawi, 2025; Wu, 2019). Hence, more study is required to create novel ABA inhibitors and techniques that are secure, practical, and efficient. In any case, applying genetic engineering techniques to produce potato tubers with increased

resistance to EB without compromising their beneficial features is a quick and accurate process. Antisense RNA derived from a potato PPO cDNA was shown by (Aya Ihsan Rashan et al., 2023) to suppress EB and reduce PPO activity in European potatoes. Further research revealed that the main commercial potato cultivar in the US has its PPO activity and EB levels controlled using sense and antisense RNA from a heterologous tomato PPO gene(Coetzer, Corsini, Love, Pavek, & Tumer, 2001).

In 2020, González and colleagues altered the StPPO2 gene in the tetraploid cultivar Desiree using the CRISPR/Cas9 technology. They hypothesized that by carefully modifying this target gene, the tuber's PPO activity would decrease and the EB would decrease(Chantada–Vázquez *et al*., 2018). The mRNA level of snakin-2 (StSN2) increased when FCP was stored for longer periods, and the EB of FCP was reduced when StSN2 was overexpressed in comparison to the wild type. This effect could be brought about by modifications in key kinase and other protein phosphorylation levels, as well as by an increase in AO enzyme activity and a decrease in phenolic contents*(G. Li et al*., 2023). Dong and his colleagues (2021) hypothesized that a novel aspartic protease inhibitor gene (StASPI) contributes significantly to the browning resistance of potatoes following cutting(Ma *et al*., 2021).

15.CONCLUSION

Browning is undesirable in some products, as it reduces sensory properties such as color, flavor, and nutritional properties. Potato is a typical food with easy browning and then deterioration, and the PPO is responsible for this problem, which leads to reduced nutritional value and economic losses. As is known, consumers around the world have become more concerned about making the food they eat acceptable to them. For this reason, preventing browning through PPO control is an important key to enhancing product value, reducing postharvest losses, and maintaining food quality. Accordingly, many physical, chemical, and biological treatments have been used to control or prevent the browning.

We concluded in this review that, compared to physical treatments, chemical agents have been widely used but may cause some adverse effects on human health. As for genetically modified foods, they are considered a hope for the food industry to control PPO activity postharvest process. The development of natural browning inhibitors with health benefits is of interest to researchers in this field because they can gain consumer trust. However, their use without negatively affecting their color and sensory properties remains a challenge for food technologists. Therefore, we recommend further research to discover new natural anti-tanning agents and to develop mixtures with advanced preservation properties for food applications through which negative effects can be avoided.

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