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Ascorbic Acid: Rationale and Applications in Inhibiting Enzymatic Browning of Fruits and Vegetables– A Comprehensive Review

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Abstract

Enzymatic browning mostly happens in fresh fruits and vegetables and is critical in determining the product's shelf life. A class of enzymes known as polyphenol oxidases are responsible for this color alteration. Polyphenol oxidase is the main enzyme that catalyzes the oxidation of phenolic compounds in the presence of oxygen, forming brown pigment. Therefore, several methods are required to prevent these reactions. Natural ascorbic acid is considered among the highly effective chemicals in stopping this reaction and preventing browning. It is a non-toxic and effective alternative to synthetic chemicals. It is also characterized by having powerful antioxidant and free radical scavenging properties. This review offers a focused and novel contribution to the scientific literature by exclusively investigating AA as an anti-browning agent (ABA), enabling a detailed understanding of its specific mechanisms, efficacy, and practical applications. Unlike broader reviews that cover many inhibitors, this work provides a comparative analysis of the performance of AA in various foods, highlighting its strengths and limitations in different contexts. By integrating research from past years, we highlight different approaches, such as the combination with synergists and integration with edible coatings and packaging. Importantly, we not only describe its optimal conditions and benefits, but also assess its limitations, such as its instability and susceptibility. Finally, the evidence and future directions are organized in a way that helps food technologists identify promising protocols, design preservation strategies, and avoid previously documented limitations of future research.

Keywords: Ascorbic acid, Browning control, Enzymatic browning, Fruits, Vegetables

Introduction

Browning in fruits and vegetables (FV) is a major challenge to the food manufacturing industry due to the influence on appearance, nutritional value, and safety of the food product (Tinello & Lante, 2018). Consumers most often rely on visual cues to assess food quality and make informed decisions about freshness. The discoloration of the product contributes to decreased market viability and greater consumer rejection (Dias *et al.*, 2020). In addition to the visual impact of discoloration, browning also negatively impacts the utilization of produce and losses of production resources across the entire agricultural supply chain, from producers to retailers (Moon, Kwon, Lee, & Kim, 2020). Two major types of biochemical reactions cause this undesirable

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discoloration: non-enzymatic browning and enzymatic browning. Non-enzymatic browning which is similar to the Maillard reaction, is more common in heat processing and less relevant for fresh produce. On the other hand, enzymatic browning (EB) dominates in fresh and minimally processed fruits and vegetables, where it causes tissue damage and rapid exposure to oxygen (Alrushdi, Mohammed *et al*., 2025; Paravisini & Peterson, 2019). The effects of EB on quality are particularly significant during postharvest handling, storage, and minimal processing. These operations result in significant quality loss and economic cost (Moon *et al*., 2020). EB is associated with three enzymes: phenylalanine ammonia-lyase (PAL), peroxidase (POD) and polyphenol oxidase (PPO) (Arnold & Gramza-Michałowska, 2022). PPO (EC 1.10.3.1) catalyzes the EB reaction in plants, fungi, and bacteria. It is a copper-dependent cofactor protein, which can be activated as tyrosinase (monophenolase) or catechol-oxidase (diphenolase) (Sommano, Chanasut, & Kumpoun, 2020).

This enzyme converts phenols to quinones, which combine with other substances to produce melanoid, a brown pigment (Lim & Wong, 2018; Singh *et al*., 2018). EB affects color retention and leads to nutritional and sensory losses, weakening marketability and reducing consumer acceptance. Therefore, it may be responsible for food waste (Shrestha *et al*., 2020). To mitigate the effects of EB, the fresh produce industry has traditionally relied on chemical inhibitors, but the rising concerns regarding the safety and regulatory status of synthetic additives, due to their possible health risks (e. g. allergic reactions), have increased focus on natural, food-safe alternatives (Bobo-García, Arroqui, Merino, & Vírseda, 2020; Favre, Dos Santos, López-Fernández, Mazzobre, & del Pilar Buera, 2018). Considering this, exploring novel natural additives for food without negative side effects that have anti-browning abilities is critically desirable for food-processors (Al-Abbasy, Ali, Rashan, & Al-Bajari, 2021). Ascorbic acid (AA), is a crucial natural substance found in abundance in plant sources. It can replace artificial additives to preserve FV, avoid costly losses, and extend shelf life. The use of AA in this field is due to its non-toxicity and lack of reported adverse effects in typical food applications (Dias *et al*., 2020; Paudel *et al*., 2020). AA has been selectively applied to various fresh foods (e.g, apples, potatoes, mushrooms, etc) and its potential use as a preservative. This review provides a comprehensive summary by collecting and analyzing data exclusively on AA applications as an anti-browning agent in fresh products. Thus, it offers a scientific basis for food technologists to develop safe and effective anti-browning strategies.

Search Criteria

Approximately 220 articles have been surveyed for this review. These articles were selected by a search process based on keywords such as ascorbic acid, browning, enzymatic browning, polyphenol oxidase, peroxidase, and browning control on electronic database systems such as PubMed, John Thompson, Scopus, Science Direct, and Google Scholar. After analyzing all the articles, many were excluded, and the research papers that were useful for this study were identified.

Browning

The Browning phenomenon is widely considered a major problem facing the global economy. It is a biological process that often occurs in food and under different circumstances, which can have beneficial and harmful effects. For fruits, vegetables, and nuts, browning is considered undesirable. These foods lose their nutritional value and produce undesirable color, flavor, and taste. However, this process can be advantageous in processing other products such as chocolate, coffee, black tea (Debelo, Li, & Ferruzzi, 2020), bread, and soy sauce (Nooshkam, Varidi, & Bashash, 2019). It is necessary to create a distinctive color and flavor in these foods. The EB reaction (Fig. 1) is mainly caused by PPO (Arnold &

Gramza-Michałowska, 2022). PPO oxidizes diphenol to quinone, a highly sensitive active molecule subsequently polymerize into brown pigments by reacting with other phenolics, sugars, amino acids, or soluble proteins.

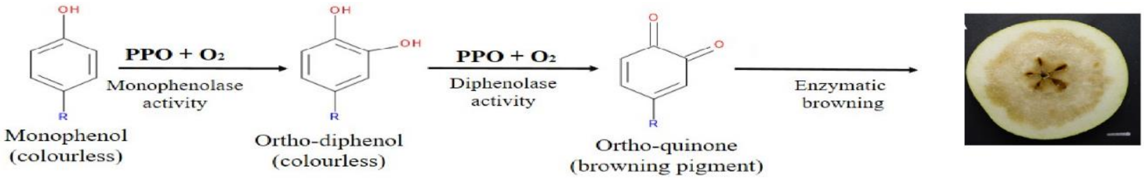

Fig. 1. The schematic of the enzymatic browning process (Moon *et al.*, 2020) (modified)

It mostly happens in products during harvesting, storage, and processing (Queiroz, Mendes Lopes, Fialho, & Valente-Mesquita, 2008). The presence of EB degrades color, flavor, and nutritional content, resulting in reduced shelf life (Rashan & Al-abbasy, 2021). The rate of EB depends on the phenolic substrate contents, pH, oxygen accessibility, temperature, concentration, and source of an enzyme (Lante, Tinello, & Nicoletto, 2016).

Ascorbic Acid

AA, commonly known as vitamin C, is a vital nutrient that can be acquired from various sources like fruits, vegetables, and multivitamin supplements (Ali *et al*., 2024; Murererehe, Uwitonze, Nikuze, Patel, & Razzaque, 2022). It plays a crucial role in numerous physiological functions within human health. AA is a six-carbon lactone naturally produced from glucose and other sugars (Kükürt & Gelen, 2024; Mittu *et al*., 2022). Chemically, AA is a weak organic acid with an enediol structure conjugated with the carbonyl group in the lactone ring (Al-burgus, Ali, & Al-abbasy, 2024; Atta, Mohamed, & Abdelgawad, 2017). The compound's acidity and antioxidant properties are attributed to the two enolic hydrogen atoms supplying the electrons. Dehydroascorbic acid, which has the same vitamin activity as AA, is created when oxygen is present (Fig. 2) (Li, Guo, & Wang, 2008; Rico, Martin-Diana, Barat, & Barry-Ryan, 2007).

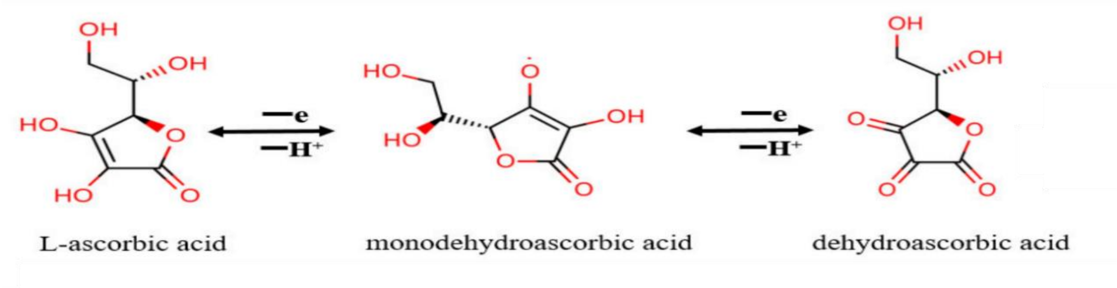

Fig. 2. Degradation of L-ascorbic acid to dehydroascorbic acid (Yin *et al.*, 2022)

It is a natural component and broadly spread in FV (Kabasakalis, Siopidou, & Moshatou, 2000; Pernice *et al*., 2009), such as citrus fruits, strawberries, potatoes, tomato, broccoli, gooseberry, cabbage, turnip, red peppers, green peppers, and many green veggies. So, plants are becoming important sources of vitamin C (Malo & Wilson, 2000). It plays a role in numerous mono and dioxygenases to conserve metals in a reduced state. For example, mono and dioxygenases commonly comprise copper or iron as redox cofactors. The food sector uses AA extensively because of its conservatory benefits, namely as the most potent and non-toxic antioxidant and a free-radical scavenger (Santos *et al*., 2022; Tu, Njus, & Schlegel, 2017). Since humans can not synthesize AA, it must be obtained through diet; it is considered an important nutrient. However, during food storage, AA is quickly oxidized, which causes considerable losses (Hassan, Haddad, & Sultan, 2020). It is also acknowledged as the most important hydrophilic antioxidant for different types of enzymatic reactions (Bratovcic, 2020; Telang, 2013). This atypical antioxidant produces monodehydro ascorbate, a radical that combines preferentially with radicals rather than non-radical substances, and it gives a single reducing equivalent. This occurs because monodehydro ascorbate would form an energetically undesirable tricarbonyl structure if an electron were removed. AA oxidizes exclusively to monodehydroascorbate rather than producing this structure, and when monodehydroascorbate combines with other radicals, it oxidizes through processes that might prevent the creation of this undesirable structure (Du, Cullen, & Buettner, 2012). Reactive nitrogen and oxygen species, including hydroperoxyl radicals and superoxide, aqueous peroxyl radicals, and singlet oxygen, are easily scavenged by AA. (Yates, Schlicker, & Suitor, 1998).

Browning Control

Browning control has always been a challenge for the food industry. Since phenols, oxygen, and enzymes are the three primary components contributing to browning processes, the primary goal of anti-browning agent treatments is to eliminate one of these variables and thus control browning (Younus, Mahdi, Al-Abbasy, & Sheej Ahmad, 2025). This control will extend the shelf life, improve customer acceptance of the food, and reduce economic losses (Bobo-García *et al.*, 2020). To attenuate this undesirable process, industries employ chemical, physical, or biological techniques and treatments (Feng, Liu, Liu, Shi, & Wang, 2020; Zhang, He, & Simpson, 2018). These techniques have drawbacks, including changes in the sensory and nutritional qualities of the final products and potential health risks (Levaj *et al.*, 2023). An efficient and widely used method for managing the EB of various fresh-cut FV is chemical treatment with anti-browning agents. These agents can be classified based on their mechanisms of action into several categories as chelating agents, reducing agents, acidulants, complexing agents, and enzyme inhibitors (Altunkaya & Gökmen, 2008, 2009). Successful browning inhibition by reducing agents, such as AA, erythorbic acid, ascorbyl-2-phosphate, ascorbyl-triphosphate, and cystein was observed (Farouk *et al.*, 2020; Sikora & Świeca, 2018).

Anti-browning Mechanism of AA

Color is the key factor in appraising the consumer's quality of FV. Many natural and synthetic chemical compounds are commonly used to obstruct the browning rate of fresh FV through various mechanisms (Rodrigues, Asquieri, & Orsi, 2014). This treatment thus provides temporary protection to preserve these products from damage (Eleni & Theodoros, 2011). One of these important and extensively used compounds for this purpose is AA. Due to its safety and nutritional value, it is frequently employed as an anti-browning agent in dipping solutions (Pizzocaro, Torreggiani, & Gilardi, 1993; Veltman, Kho, Van Schaik, Sanders, & Oosterhaven, 2000). It has been investigated both alone and in conjunction with other antioxidants or preservatives, such as some phenols that function as competitive inhibitors like resorcinols (Yoruk & Marshall, 2003). This status is generally recognized as safe (GRAS). The Thailand Food and Drug Administration claims that there hasn't been any restriction for the upper limit of AA consumption (Suttirak & Manurakchinakorn, 2010). Understanding the kinetic and mechanistic pathways through which AA inhibits enzymatic browning is crucial for optimizing its application in food preservation. Kinetics studies on the rate of PPO inhibition by AA have shown that AA interacts with the enzyme’s active site, preventing the oxidation of phenolic compounds (Ndakidemi, Mneney, & Ndakidemi, 2014; Yoruk & Marshall, 2003). The inhibitory action is concentration-dependent, with higher AA concentrations leading to more significant inhibition of PPO activity. Several studies have focused on elucidating these mechanisms:

1. Reduction of o-quinones back to phenolic substrates: As a strong reducing agent, AA converts the reactive o-quinones, the intermediate compounds produced during the PPO, back into their original phenolic forms before they can polymerize. This reaction prevents the accumulation of pigmented compounds and effectively halts browning at an early stage (Lee & Whitaker, 1995; Tang, Guo, & Zhu, 2023).
2. Reduction of Cu^{2+} to mononuclear copper Cu+ at the PPO active site (Suttirak & Manurakchinakorn, 2010).
3. Consumption of oxygen: AA can also react non-enzymatically with O_2, reducing the oxygen availability required for PPO activity. This secondary mechanism further slows down quinone production and subsequently browning progression (Sapers & Miller, 1998).
4. AA acts as a competitive inhibitor of PPO by binding to the active center of the enzyme and competing with its natural substrates (Gao, Li, & Li, 2013).

On the other hand, AA may decrease the pH of crushed food products and thus inhibits the activities of POD and PPO or activates phenylpropanoid metabolism to raise total phenolic content (Landi, Degl'Innocenti, Guglielminetti, & Guidi, 2013; Li, Ding, Li, & Yan, 2023; Zhou *et al*., 2021). The efficiency of AA derivatives, containing dehydroascorbic acid, ascorbic acid-2-phosphate, isoascorbic acid, and ascorbic acid-2-sulfate, was associated with that of AA (Hsu, Shieh, Bills, & White, 1988). Based on kinetic studies, AA and isoascorbic acid are the utmost effective inhibitors of mushroom PPO, followed by dehydroascorbic acid. According to (Özoğlu & Bayındırlı, 2002), AA is more effective than its isomer isoascorbic acid.

Essential Motives for Using AA as an Anti-browning Agent

Brown pigment on food products decreases consumer tolerability and affects their taste and nutritional status. Healthcare awareness has led to an increased focus on finding solutions to food browning (Singh *et al*., 2018). Consumers evaluate food products based on color, appearance, taste, and nutritional value (Peanparkdee & Iwamoto, 2019). Chemical-based techniques were employed to prevent FV from browning. However, the application of this technique may pose health risks because some chemicals may include hazardous residues (Moon *et al*., 2020). Therefore, researchers resorted to using AA as an effective inhibitor of various PPOs (Arslan, Erzengin, Sinan, & Ozensoy, 2004; Chazarra, García-Carmona, & Cabanes, 2001). AA is a natural, abundantly available, and non-toxic material. Because of its great browning-inhibiting efficiency and the lack of deleterious effects in the foods to which it is introduced, AA is used as a reference or comparison to natural and synthetic chemicals, as well as natural extracts.

Effect of AA on Individual Commodities

AA has been widely studied for its antioxidant effect against enzymatic browning in fruits and vegetables. This process is important for the maintenance of quality, color, and nutrient value of the commodity. AA efficacy on different commodities varies significantly with commodity type, processing type, and concentration of AA used. Literature has proven the effectiveness of AA in affecting the quality of apples and preventing fresh apples from turning brown. Granny Smith was less susceptible to browning upon immersion in (3% w/v) compared to other types (Yi *et al*., 2017). Similarly, another study on fresh apples (*Malus pumila*) concluded that PPO was inhibited by a large amount of AA (Wen *et al*., 2021). The impact of added AA stored at 4C° was investigated on POD and PPO reaction in light pretreated watermelon (*Cucumis melo L. reticulatus Naud*), and POD activity declined with time (And & Watson, 2001). The inhibitory efficacy of potatoes' PPO by chili pepper and lemon extracts was 70% and 54%, respectively. Anti-browning activity could be attributed to its high content of AA (Mercimek *et al.*, 2015). In addition, the AA application to freshly harvested potatoes can postpone browning by inhibiting PAL (Zhou *et al.*, 2021). AA is a potent competitive inhibitor of PPO's active site with catechol as a substrate to reduce the intensity of browning. This has been demonstrated in certain plants such as lettuce (*Lactuca sativa*) (Altunkaya & Gökmen, 2008), Peppermint (*Mentha piperita*) (Kavrayan & Aydemir, 2001), and tea leaves (*Camellia sinensis*) (Öztürk, Aksoy, & Küfrevioğlu, 2020). Table 1 summarizes the inhibition of PPO activity in different vegetables and fruits using AA.

Table 1- Inhibitory effect of AA treatments on PPO activity in fruits and vegetables (*(w/v) and **mmol/L)

Fruit/Vegetable	AA Concentration	% PPO inhibition	References
Abiu	0.176% *	80%	(Susanto, Arif, Widayanti, & Matra, 2023)
Apple (Red Delicious)	0.4 *	45%	(Arnold & Gramza-Michałowska, 2022)
Apple puree	0.35% *	100	(Vercammen *et al.*, 2012)
Apple slices (Golden Delicious)	1% *	~25%	(Watada, Izumi, Luo, & Rodov, 2005)
Apple slices (Newton Pippin)	1% *	~59%	(Watada *et al.*, 2005)
Apricot	2 **	100%	(Derardja, Pretzler, Kampatsikas, Barkat, & Rompel, 2019)
Apricot	10 **	99%	(Morsy & Rayan, 2019)
Banana	1% *	~85%	(Danyen, Boodia, & Ruggoo, 2009)
Banana	0.5% *	~60%	(Moline, Buta, & Newman, 1999)
Blackberry	0.1 **	100%	(Schwartz, Olgin, & Klinman, 2001)
Blueberry	Varied	99.7%	(Siddiq & Dolan, 2017)
Eggplant	0.5–1% *	15–25%	(Barbagallo, Chisarib, & Patanèc, 2012)
Guava puree	1% *	~72%	(Khedr & Ali, 2017)
Lettuce	5 **	~90%	(Landi *et al.*, 2013)
Lotus Rhizome	0.08**	86.21%	(Li, Li, Yan, & Wang, 2022)
Mango	0.1% *	60%	(Arafat, 2009)
Mango	1%*	75%	(Prasad, Sharma, & Srivastav, 2016)
Mango	2% *	85-90%	(Marín *et al.*, 2021)
Mango Puree	Varied	91.1% - 95.5%	(Guerrero-Beltrán, Swanson, & Barbosa-Cánovas, 2005)
Mung Bean	2–20**	51–60%	(Sikora & Świeca, 2018)
Mushroom	0.04 **	50%	(Hsu *et al.*, 1988)
Peach	1**	95.4%	(Jia, Jiang, Chen, Wei, & Shao, 2022)
Pear slices	1%*	75%	(Kader, Zagory, Kerbel, & Wang, 1989)
Pineapple	0.05**	70%	(Auon-Reyna *et al.*, 2019)
Pineapple slices	0.8% *	~50%	(Pérez-Gago, González-Aguilar, & Olivas, 2010)
Pomegranate	150 **	100%	(Patil, Dhande, Thigale, & Rajput, 2011)
Potato	1%*	65%	(Li *et al.*, 2023)
Potato slices	0.5%*	~65%	(AL-abbasy *et al.*, 2025)
Strawberry	2% *	~88%	(Nazoori, Poraziz, Mirdehghan, Esmailizadeh, & Zamani Bahramabadi, 2020)

Synergistic Treatments

There have been various reports on the AA combination with other factors having a synergistic effect in inhibiting the action of the PPO and thus enhancing the control of the browning of fresh foods. These synergists may be plant extracts, chemical compounds, or physical treatments. For instance, a synergistic influence of AA (0.05% w/v) and cinnamon essential oil nanoemulsion (0.1–0.4% w/v) was found to completely inactivate PPO at 4 ◦C after two days of storage (Xu *et al*., 2020). AA with sodium dihydrogen phosphate controls the browning of yellow noodles by slightly reducing the PPO activity but significantly decreasing the free quinone content (Tang *et al*., 2023). The mango fruits were immersed in calcium nanoparticles with different concentrations of AA and stored for 35 days at 6 °C. The browning in kiwifruit segments can be effectively prevented by adding 0.3 g/L polyvinylpyrrolidone to the medium, which is followed by 0.2 mg/L AA. A mixture of 1.2% yerba mate leaf extract and 1% AA was proven to optimally suppress EB in fresh-cut Granny Smith apples (Rodríguez-Arzuaga & Piagentini, 2018). Another study indicated that *Rosa roxburghii* extract, rich in AA and coumaric acid, inhibits the activity of PPO in Red Fuji cloudy juice (Yu *et al*., 2021). According to (Abdelwahd, Hakam, Labhilili, & Udupa, 2008; Babaei, Abdullah, Saleh, & Abdullah, 2013), the most effective method for managing EB was to pre-treat the tip of Faba bean seeds and Curculigo latifolia using polyvinylpyrrolidone and AA for nine hours. The PPO and POD activities responsible for browning of sugarcane juice were entirely inhibited when AA was combined with bentonite (Hithamani, Medappa, Chakkaravarthi, Ramalakshmi, & Raghavarao, 2018). AA and its isomer, erythorbic acid, were found to be equally effective in preventing browning in pineapple slices. The EB inhibition in apricots was investigated by inactivating their PPO using plant proteases and AA. Apricot PPO activity significantly declined to 66 and 55 % when treated with (0.1 and 0.2 mM mmol/L) of AA, respectively, compared to the untreated samples (Derardja *et al*., 2019). A combination of AA and citric acid has been shown to significantly reduce the browning of fresh fruits such as Chinese Yam (*Dioscorea polystachya* Turczaninow). Citric acid can lower the pH of food products, hence increasing the efficacy of AA (Yang, Song, Wang, Wang, & Zhao, 2024). Alternatively, the combination of AA with chitosan (a natural polymer derived from chitin) has increased the ability to inhibit browning of plums and fresh-cut apples. Chitosan acts as a protective environmental barrier, allowing AA to work more effectively, protecting the food from external air (Liu, Yuan, Chen, Li, & Liu, 2014; Özdemir & Gökmen, 2019). The ultrasound and AA showed a synergistic inhibitory effect on fresh-cut apple PPO activity during storage (Jang & Moon, 2011). The combination of AA (2g/L) with modified atmosphere packing inhibited the PPO activity and browning intensity of fresh-cut eggplant treated for four days (Sarengaowa *et al*., 2022). (Almeida & Nogueira, 1995) reported that PPO activity in banana, pear, and peach fruits was controlled using AA and heat treatment at 70°C for 2 minutes. The researchers highlighted the applicability of this method to substitute for the use of sulfur dioxide to control PPO activity.

Application in Juices

The juice industry faces significant challenges with EB during the storage of fresh fruit juices. AA is one of the most extensively used natural preservatives to combat this issue. It has been shown through many studies that AA is effective in preventing this phenomenon that occurs in fruit juices. These effects are summarized in Table 2.

Table 2- Inhibitory effect of AA on different fruit juices

Fruit juice	AA concentration or combination	References
Banana	(1000 – 1200 ppm)	(Tapre & Jain, 2016)
Banana	(470 mg/L)	(Koffi, Sims, & Bates, 1991)
Apple	(1.8 mmol/L)	(Hope, 1961)
Apple	ascorbic and cyclodextrins	(Hicks, Sapers, & Seib, 1990)
Apple	ascorbic acid and acidic polyphosphate	(Sapers *et al*., 1989)
Apple	0.2% w/v	(Komthong, Igura, & Shimoda, 2007)

Apple	-	(Ribárszki *et al*., 2022)
Cloudy apple	-	(Özoğlu & Bayındırlı, 2002)
Pear	-	(Montogomery & Petropakis, 1980)
Pear	0.24% (w/v)	(Jiang, Kim, Nam, Yim, & Eun, 2016)

Common Trends, Optimal Conditions, and Knowledge Gaps

In compiling recent applications and developments of AA preservation, certain trends are common. First among these is the strong focus on multifunctional natural preservation techniques that accommodate consumer demand for sustainable and clean solutions. Synergistic mixtures and their use in edible or active packaging systems reflect a broader trend towards comprehensive antioxidant protection, combining physical barriers and biochemical activity to maintain freshness and prevent spoilage (Chua, Chan, Tay, & Soo, 2023; Oliveira *et al*., 2025). Optimum conditions for the efficacy of AA vary across commodities, but certain factors are universal in their implication. The concentration of AA tends to be in the range of 0.1-1%, being more potent for the brownhng controlling (Rasane *et al*., 2024). The pH of the processed product is a crucial factor, with the optimum value being slightly acidic (4-6), which is the most suitable environment for AA action (Nicolas, Richard-Forget, Goupy, Amiot, & Aubert, 1994). Moreover, the exposure to the light and temperature may affect AA stability, with studies showing that it is most effective when used at low storage temperature (0-10°C), thereby inhibiting rapid degradation and maintaining its anti-browning activity (Oms-Oliu *et al*., 2010, Paull, 1999). However, gaps in knowledge must be filled by conducting further research on long-term stability under conditions of fluctuating storage, compatibility with other natural preservatives, and scalability of smart packaging and packaging technologies. Although genetic approaches to increasing endogenous AA levels in crops hold much promise. However, regulatory concerns and public acceptability remain significant barriers (Oms-Oliu *et al*., 2010; Paull, 1999).

A Comparative Study

AA is widely recognized as one of the most effective natural anti-browning agents due to its strong reducing ability and non-toxicity. However, its effectiveness varies when compared to other chemical and natural inhibitors (Table 3), particularly in terms of mechanism of action, stability, cost, and sensory impact (Kim *et al*., 2019) . For example, citric acid acts as a metal chelator in preventing EB, through binding to the copper in PPO or pH-lowering, as mentioned by (Altunkaya & Gökmen, 2008). This applies to most carboxylic acids. However, the amino acid L-cysteine can inhibit the browning process principally by reducing POD and PPO activities via forming a stable complex with copper (Li *et al*., 2023; Sadoon & Ahmad, 2020).

Toxicologically, certain compounds, such as sulfites, especially in some sensitive persons, like asthmatics, are recognized to cause adverse health effects. Among this extremely sensitive group, many deaths have occurred as a result of consuming sulfur-containing foods. On the other hand, sulfates can also release SO_2 gas in some foods, which harms the flavor of the product being treated (Taylor *et al*., 1988). These effects were not observed when using AA. Natural extracts are highly concentration-dependent in inhibiting enzymatic browning, which limits their use due to their strong taste or color (Gómez-López, 2002). In contrast, ascorbic acid is used at lower concentrations, is colorless and tasteless, and is consistently effective in a wide range of products (Rico *et al*., 2007).

Table 3- Comparison of anti-browning agents with ascorbic acid

ABA	Mechanism of action	Effectiveness	Side effects/ Limitations
Ascorbic acid	Reduces quinones back to phenols, acts as an antioxidant, and an oxygen scavenger	High short-term effectiveness, often combined with other agents for stability	Unstable, rapidly oxidizes, leading to browning rebound (re-browning)
Citric acid	Lowers pH, reducing PPO activity, and chelates copper at the active site of PPO	Moderate, best when combined with other agents	Alters flavor due to acidity, limited by pH tolerance of the product
Sodium metabisulfite	Reduces quinones, a strong PPO inhibitor, and reacts with o-quinones to form colorless products	Very high	Can cause allergic reactions (sulfite sensitivity), banned or limited in some countries
Calcium ascorbate	Combining ascorbic acid's reduction with calcium's firming effect	Better than pure ascorbic acid in maintaining texture and color	Costly, limited by calcium-induced hardness in some products
EDTA	Chelates copper ions from PPO, inhibiting enzyme activity	Moderate	Not approved for all food uses; may require labeling, synthetic additives
Hexylresorcinol	Directly inhibits PPO; prevents formation of melanins	Very high	More expensive, limited regulatory approval in some regions
Honey	Natural antioxidant, mild antimicrobial, and PPO inhibition	Low to moderate	May impart unwanted flavor/sweetness, variable composition
L- Cysteine	Reacts with o-quinones to form colorless products; an antioxidant	High	May cause off-odors (sulfurous), allergen concerns
Acetylated monoglycerides	Form coatings that limit oxygen contact, a physical barrier	Moderate (indirect)	Less effective alone, usually used with other agents

Future Trends in the Use of Ascorbic Acid as an Anti-Browning Agent

Changes in technology have expanded the potential uses of AA in food preservation, particularly when combined with other antioxidants or antimicrobials to produce blends with enhanced efficacy (Baghi, Gharsallaoui, Dumas, & Ghnimi, 2022). To increase its stability and extend its functional life, packaging systems such as nanoemulsions, biopolymer coatings, edible films, and biodegradable coatings are being developed. This feature has oxygen-binding capabilities and provides continuous antioxidant protection, enhancing food quality and sustainability (Aziz, Ali, Haddad, & Abdullah, 2024; Kuai *et al*., 2021). On the processing front, treatments such as ultrasound-assisted dipping, vacuum impregnation, and spraying are being optimized to improve AA delivery and minimize waste (Díaz-Montes & Castro-Muñoz, 2021). In the long term, plant breeding and genetic engineering methods seek to improve the natural growth or retention of AA in crops, reducing the need for external additives (Zhu, Wu, & Sun, 2019). Finally, with growing consumer demand for organic products with clean labels, AA's natural and safe properties are gaining popularity, and future applications are expected to focus on regulatory compliance and clear labeling.

Limitation

AA is also frequently used in food applications but faces limitations due to its instability and high susceptibility to oxidation, especially when exposed to air, light, and temperature (Comunian, Abbaspourrad, Favaro-Trindade, & Weitz, 2014; Wagner & Buettner, 2023). It may reduce its effectiveness over time and cause temporary effect. It can affect flavor and pH to become sour or tart, which is undesirable in fruits with delicate or low-acid flavors. This change in sensory properties requires maximum dosage adjustment to be made carefully, especially in sensitive juice products where flavor balance is of the highest priority. These limitations underscore the importance of considering AA's chemical stability and sensory effect in well-designed systems (Taqi, AL-shahery, & Al-Abbasy, 2024; Yin *et al.*, 2022).

Conclusion

The global food consumption landscape is rapidly transforming. Consumer preferences are driving a swift evolution in food choices worldwide. Color is one of the most important factors influencing consumer purchasing decisions. However, repeat purchases depend on the consumer's satisfaction with the product's texture, flavor, and nutritional value. EB is one of the serious problems to the food industry and represents the second most vital reason for the negative impact on color, which leads to deterioration. EB's progress has been related to PPO activity. Therefore, inhibiting this enzyme will certainly limit the development of this phenomenon. Applying anti-browning agents is considered the best effective way to control the EB reaction in fresh FV. In this regard, it is preferable to have natural agents such as AA. The widespread use of AA is due to its generally abundant, non-toxic, safe, and healthy properties compared to other chemicals. The capability of AA to prevent EB is represented by: reducing o-quinones to diphenols or Cu^{2+} to Cu+ at the PPO active site, while also decreasing crushed food pH. Based on the research considered, we conclude that AA was a good inhibitor for PPO and could prevent EB of FV. The anti-browning efficiency of AA is related to two main factors: the types and cultivars of produce, and its concentration when it is alone or the concentrations of its synergetic factors. But often elevated concentrations had a greater effect than low ones. Also, the low pH at which AA works has a better effect in preventing the formation of brown pigmentation. After conducting this review and evaluating the general nutritional situation, we recommend using AA to prevent this phenomenon from forming on its own without combining it with other substances. This is to avoid the side effects of the combined substances on human health after consuming food products.

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Authors Contribution

O.Y.A: Conceptualization, Writing– review and editing, Supervision. **Z.H.A:** Data curation, Writing– original draft, Investigation. **N.M.M:** Formal analysisn, Writing– original draft. **A.S.A:** Validation, Data analysis, Software.

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Abbreviation

Anti-browning agent (ABA); Ascorbic acid (AA); Enzymatic browning (EB); fruits and vegetables (FV); Peroxidase (POD); Phenylalanine ammonia-lyase (PAL), Polyphenol oxidase (PPO).

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مقاله مروری

جلد ۲۱، شماره ٦، بهمن- اسفند ١٤٠٤، ص.

اسید اسکوربیک: ضرورت‌ها و کاربردها در مهار قهوه‌ای شدن آنزیمی میوه‌ها و سبزیجات- یک بررسی جامع

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چکیده

قهوه‌ای شدن آنزیمی بیشتر در میوه‌ها و سبزیجات تازه اتفاق می‌افتد و در تعیین ماندگاری محصول بسیار مهم است. دسته‌ای از آنزیم‌ها که به‌عنوان پلی‌فنول اکسیداز شناخته می‌شوند، مسئول این تغییر رنگ هستند. پلی‌فنول اکسیداز آنزیم اصلی است که اکسیداسیون ترکیبات فنلی را در حضور اکسیژن کاتالیز می‌کند و رنگدانه قهوه‌ای تشکیل می‌دهد. بنابراین، روش‌های مختلفی برای جلوگیری از این واکنش‌ها مورد نیاز است. اسید اسکوربیک طبیعی از جمله مهمترین مواد شیمیایی در متوقف کردن این واکنش و جلوگیری از قهوه‌ای شدن است. این ماده یک جایگزین غیرسمی و مؤثر برای مواد شیمیایی مصنوعی است. همچنین با داشتن خواص آنتی‌اکسیدانی قوی و مهار رادیکال‌های آزاد مشخص می‌شود. این مقاله مروری، مطالعات انجام شده در مورد استفاده از اسید اسکوربیک به‌عنوان یک عامل ضد قهوه‌ای شدن در منابع غذایی مختلف را خلاصه می‌کند. این مقاله ممکن است بینشی در مورد پتانسیل توسعه استفاده از اسید اسکوربیک در عملیات قهوه‌ای شدن مواد غذایی و کاهش ضررهای اقتصادی در بخش مواد غذایی ارائه دهد.

واژه‌های کلیدی: اسید اسکوربیک، سبزیجات، کنترل قهوه‌ای شدن، قهوه‌ای شدن آنزیمی، میوه‌ها

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