



Mechanism of off-color formation in potato chips fried in oil systems containing ascorbic acid as a stabilizer

Lisard Iglesias-Carres^a, Kathryn C. Racine^a, Sydney Chadwick^a, Candace Nunn^a, Sathya B. Kalambur^b, Andrew P. Neilson^{a,*}, Mario G. Ferruzzi^{c, **}

^a Plants for Human Health Institute, Department of Food, Bioprocessing and Nutrition Sciences, North Carolina State University, Kannapolis, NC, USA

^b PepsiCo Global Foods R&D, Plano, TX, USA

^c Arkansas Children's Nutrition Center, U.S. Department of Agriculture and Department of Pediatrics, University of Arkansas for Medical Sciences, Little Rock, AR, USA

ARTICLE INFO

Keywords:

Amino acid
Maillard reaction
BHT
Rosemary
Carnosic acid
Tocopherol
Moisture
Solubility
Citric acid
Canola oil

ABSTRACT

The use of alternative, green antioxidant (AOX) systems is demanded by consumers. Natural AOX systems pose significant challenges. For example, in frying applications, these AOX can negatively alter potato chip color, one of the most important traits in consumer selection. We evaluated the role of natural AOX systems containing ascorbic acid, tocopherols, and other antioxidants in amino acid-related undesirable color formation in fried potato chips. Results indicated that both oil phase AOX and potato factors are critical to generation of off-color formation in fried potato chips through Maillard type reactions. Ascorbic acid solubilization in oil and migration to the chip surface play key roles in observed off-color formation. However, multiple complex reactions may be responsible for color development, which may involve food matrix components. Contributions of AOX other than ascorbic acid appear minimal. Nevertheless, some browning can occur regardless of the presence of ascorbic acid. Color formation through glutamine occurred in the absence of ascorbic acid, but its presence greatly exacerbates color generation, while color generation via asparagine is barely modulated by ascorbic acid. AOX and free amino acid concentrations, temperature, and moisture are critical factors for controlling undesirable color formation during frying with natural oil AOX systems.

1. Introduction

Potato chips are one of the most common snacks consumed worldwide. They are thin slices of potatoes fried in oil (150–190 °C for 3–5 min) (E. Choe & Min, 2007; F. Pedreschi et al., 2016). The general appearance of a potato chip is of great importance to consumer acceptance, and overall color as well as color uniformity (i.e., absence of dark spots and other defects) play a fundamental role in acceptable appearance. Color or other visual traits are the first parameters evaluated by consumers and are key in a product's acceptance, even before consumption (Franco Pedreschi et al., 2006). The golden brown color of potato chips is a result of deep fat frying, resulting in lipid oxidation as well as carbohydrate-protein driven caramelization and Maillard reactions, which depend on reactants including free amino acids, protein, reducing sugars and oil additives that can vary based on potato cultivar and as well as oil composition, stabilization system, frying temperature and time (Marquez & Añon, 1986).

In large-scale commercial frying operations, oil is used at high temperatures for continuous processing, but this process deteriorates oil quality while producing oxidation products with potential to produce off colors, off flavors, and toxic lipid oxidation products (E. Choe & Min, 2007; Hwang et al., 2019). Use of synthetic antioxidant (AOX) ingredients, such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA) and tetryl butyl hydroquinone (TBHQ), has long been a common approach to prolong lipid stability and preserve lipid quality and product quality during frying and shelf life (Hwang et al., 2019; Redondo-Cuevas et al., 2017). However, consumers are increasingly demanding the use of natural ("clean label"), green ingredients, which necessitates exploration of alternatives to synthetic AOXs to prevent lipid oxidation during frying. Some effective natural AOX systems include rosemary extracts, ascorbic acid, α -tocopherol, and their mixtures (Aladedunye et al., 2017; Chammem et al., 2015; Gertz, 2004; Hwang et al., 2019; Lalas & Dourtoglou, 2003; Redondo-Cuevas et al., 2017; Rodriguez-Saona et al., 1997; Rodriguez-Saona & Wrolstad, 1997;

* Corresponding author. 600 Laureate Way, Kannapolis, NC, 28081, USA.

** Corresponding author. 15 Children's Way, Little Rock, AR, 72202, USA.

E-mail addresses: aneilso@ncsu.edu (A.P. Neilson), MFerruzzi@uams.edu (M.G. Ferruzzi).

Urbančič et al., 2014). For example, frying potato chips in oil supplemented with rosemary extract has reported a reduced darkening and rancidity of the oil, as well as a higher acceptability of the potato chips (Lalas & Dourtoglou, 2003). Rosemary extracts as well as carnosic acid have shown to modulate color perception in French fries (P. Li et al., 2021). The addition of antioxidant apple-pomace extracts to fry French fries in mustard oil has shown changes in color parameters, as well as sensory perception of fries (Manzoor et al., 2022). The chemistries of traditional AOX systems are well known (Kurechi et al., 1983; Williams et al., 1999; Yehye et al., 2015), but the impact on product quality of new, green systems remain to be explored across food matrixes (Aziz & Karboune, 2018; Habibie et al., 2019; Mohanan et al., 2018; Rahila et al., 2018). However, the use of green alternatives introduces a new layer of complexity, which is the understanding of potential interactions that alter product quality parameters such as color (Gök et al., 2011; Morales et al., 2014; Rodriguez-Saona et al., 1997; Zhang et al., 2007).

One of the main processes behind color formation in foods is the Maillard reaction, which produces flavors, colors and aromas during food processing. It is usually referred to as non-enzymatic browning due to the brown color formation, and the absence of enzymes required in this process (Manso et al., 2001). Chemically, the Maillard reaction is a series of complex reactions which ultimately lead to the formation of brown nitrogen-containing polymers known as melanoidins (Bastos & Gugliucci, 2015; Manso et al., 2001; Martins et al., 2001). Controlling browning in the food industry can affect the flavor and color of a product, which ultimately affect consumer's consumption and purchase choices (Clark, 1998; Clydesdale, 1993; Fikry et al., 2019). Different factors can affect color formation by the Maillard reaction, including temperature, pH, and levels of free amino acids and reducing sugars (Ajandouz & Puigserver, 1999; Fikry et al., 2019; Kwak & Lim, 2004; Marquez & Añon, 1986; Martins et al., 2001; Rodriguez-Saona et al., 1997; Shang et al., 2020). Off color formation in potato chips has been a quality issue for generations (Jiang & Ooraikul, 1989; Leszkowiak et al., 1990; Serpen & Gökmén, 2007; Shallenberger et al., 1959). Ingredients commonly present in natural antioxidant mixes used to stabilize frying oils (particularly ascorbic acid) are known to be Maillard-reactive (Ağcam, 2022; Liu et al., 2022). Conversely, other common natural ingredients in frying oil, such as rosmarinic and carnosic acids (from rosemary) are known to inhibit the Maillard reaction (Kim et al., 2013; Negroni et al., 2001; Ou et al., 2017). Therefore, the aim of this study was to better understand mechanisms of off color formation in potato chips fried in oil containing natural AOX ingredients that could be used as an alternative to synthetic AOXs, and assess the factors that can be modulated to control undesirable appearance, including off color formation.

2. Materials and methods

2.1. Chemicals and reagents

Hexane and isopropyl alcohol (reagent grade) were purchased from VWR (Suwanee, GA, USA). Acetonitrile, formic acid and water (HPLC grade) were purchased from Avantor (Radnor, PA, USA). L-ascorbic acid, L-dehydroascorbic acid, L-glutamine (GLN), L-asparagine (ASN) and L-arginine (ARG) were purchased from Sigma-Aldrich (Milwaukee, WI, USA). Milli-Q water was obtained from a Super-Q water system (Waters, Milford, MA, USA). Cold swelling tapioca starch (Ultratex 8) was selected as a starch matrix based on results of preliminary trials (not shown). Canola oil was provided by PepsiCo (Plano, TX) and stored at 4 °C until immediately prior to use. Carnosic acid, citric acid, mixed tocopherols (individually and as a mixed AOX system) were provided by Kalsec (Kalamazoo, MI). Individual and mixed AOX ingredients were suspended in canola oil. The profile of the AOX system as well as individual components as provided by Kalsec and can be found in Table 1. AOX system and individual components were aliquoted immediately upon receipt and stored at -20 °C until immediately prior to use. No

Table 1

Characterization of individual components and the mixed AOX system as provided by Kalsec.

Component	g/100 g	Quantification procedure
Individual components^a		
Rosemary extract	0.90 Carnosic acid + carnosol	FCC11 Edition (equivalent)
Mixed tocopherols	3.21 Mixed tocopherols	AOCS Ce 8-89 (modified)
Ascorbic acid	5.34 Ascorbic acid	Titration
Citric acid	0.78 Citric acid	Titration
Antioxidant mixture		
^a	0.95 Carnosic acid + carnosol	FCC11 Edition (equivalent)
	3.59 Mixed tocopherols	AOCS Ce 8-89 (modified)
	5.31 Ascorbic acid	Titration
	0.78 Citric acid	Calculated

^a In canola oil.

emulsifiers or other components were included in the preparation of individual components or AOX mix.

2.2. Preliminary frying experiment

An initial frying experiment was performed to show the generation of off-color produced during the frying of potato chips in the presence of an antioxidant mix containing ascorbic acid. Russet potatoes were obtained from a local supermarket (Kannapolis, NC) and used within 2 d. Potatoes were sliced using a mandolin slicer to a thickness of ~2 mm. Chips (5 raw potato chips/batch) were fried for 6 min in 456.5 g of fresh canola oil at 135 °C containing no additives, 50 mg/kg BHT, or 85 mg/kg ascorbic acid provided via canola oil suspension in 2 distinct forms: ascorbic acid suspension alone in canola oil (5.34 mg ascorbic acid/100g suspension, 1600 mg suspension/Kg frying oil) or through a mixed AOX suspension in canola oil (5.31 g ascorbic acid/100g mixed AOX suspension, 1600 mg mixed AOX suspension/Kg frying oil). Frying was performed in glass beakers with a WILLHI WH 1803B feedback temperature controller coupled to a heating wrap (BriskHeat, Columbus, OH, USA) with constant stirring at 250 rpm.

2.3. Assessment of ascorbic acid solubility and oxidation in canola oil

Ascorbic acid or AOX suspensions (5.34 and 5.31 g ascorbic acid/100 g, respectively) were mixed with fresh canola oil to reach a final ascorbic acid concentration of 85 mg ascorbic acid/Kg frying oil (1600 mg suspension/Kg frying oil) for frying. Samples were then heated from 20 °C to 180 °C in glass beakers as described above with constant stirring at 250 rpm. Two 1.5 mL aliquots were collected when oil temperature reached 20, 45, 70, 95, 120, 145, 170 and 180 °C. These aliquots were immediately centrifuged (17,000×g, 2 min, and 40 °C) to separate "soluble" (remaining in solution during centrifugation) relative to "dispersed" ascorbic acid (insoluble and thus pelleted upon centrifugation). Following centrifugation, a 1.2 mL aliquot of supernatant containing the soluble ascorbic acid fraction was collected and stored at -20 °C until analyses. All conditions were run in triplicates, and each triplicate was analyzed twice with the UPLC-MS/MS system.

2.4. Assessment of ascorbic acid as a browning agent component

Ascorbic acid suspension in fresh canola oil (1600 mg suspension/Kg frying oil; 85 mg ascorbic acid/Kg frying oil) was heated to 135 °C with the above-mentioned apparatus. When temperature was reached, either five dry or five wet cotton balls (immersed in water and gently dabbed to remove excess water) were added and two 1.5 mL oil aliquots were collected 0, 2, 4 and 6 min after cotton ball addition. Oil samples were processed as described for the solubility experiment.

2.5. Extraction and chromatographic analysis of ascorbic acid and dehydroascorbic acid from canola oil

Prior to chromatographic analyses, ascorbic and dehydroascorbic acid were extracted from canola oil samples. Briefly, oil supernatants were thawed, brought to room temperature and vortexed vigorously. A volume of 150 µL of oil supernatant was mixed with 205 µL Milli-Q water, 150 µL hexane and 100 µL isopropyl alcohol. Samples were then mixed in a Disruptor Genie vortex (Scientific Industries, Bohemia, NY, USA) for 2 min at 2500 rpm. Then, samples were centrifuged at 17,000×g for 2 min at 40 °C. A total of 200 µL of the aqueous fraction was collected and mixed with 100 µL of 0.1% formic acid in acetonitrile:water (80:20) at a pH of 4.6.

Immediately following extraction, ascorbic acid and dehydroascorbic acid were analyzed with an Acquity H-class UPLC coupled to a triple quadrupole (TQD) detector (Waters, Milford, MA, USA). Chromatographic separation of both compounds was achieved with an Acquity UPLC BHE Amide 1.7 µm (2.1 × 50 mm) column with an Acquity UPLC BHE Amide 1.7 µm (2.1 × 5 mm) pre-column (Waters). Mobile phase consisted of 0.1% formic acid in acetonitrile:water (80:20) at pH 4.6, and gradient was set to isocratic for 3 min at a flow rate of 0.3 mL/min. Injection volume was 10 µL for all runs. Column temperature was set at 25 °C, and autosampler at 10 °C. Source and capillary temperatures were set at 150 and 400 °C, respectively. Capillary voltage was set at 0.60 kV, and desolvation and cone gas flow (both nitrogen) were set at 800 and 20 L/h, respectively. Electrospray ionization (ESI) was operated in negative mode, and data were acquired using the multiple reaction monitoring (MRM) mode. MRM were optimized to achieve 20 points/s with a detection span of ±0.2 amu. Fragmentation conditions for ascorbic acid and dehydroascorbic acid can be found in [Supplementary Table 1](#).

To quantify ascorbic acid and dehydroascorbic acid in oil, an external standard calibration curve was constructed by spiking 10 different concentrations of both analytes in fresh canola oil. Spiked samples were extracted as previously stated. Ascorbic acid and dehydroascorbic acid from samples were quantified by interpolating the analyte peak abundance in the standard curves. Data acquisition and processing was carried out using the MassLynx Software (Waters). Results are given in mg/L ± SEM ($n = 3$).

2.6. Model potato chip and assessment of browning induced by amino acids

To identify the effects of any single component and interactions among combinations of components of the chip/oil/AOX system, model starch based “test chips” for frying experiments were produced by coating both sides of Grade 1 chromatography paper strips (2 × 3 mm) with a thin layer (~1.0–1.1 g total weight) of 7 g/100 mL aqueous cold swelling tapioca starch solution containing a range of amino acid contents ([Table 2](#)). Starch, amino acid solutions and model chips were prepared fresh daily before frying experiments. Frying experiments were conducted in a 500 mL glass beaker containing 300 g of fresh canola oil.

Table 2

Model chip sample composition for canola oil frying experiments.

Sample code	Paper	Starch	Glutamine	Arginine	Asparagine
1	+	–			
2	+	+			
3	+	+	400 mg/Kg		
4	+	+	2000 mg/Kg		
5	+	+	4000 mg/Kg		
6	+	+		500 mg/Kg	
7	+	+		1000 mg/Kg	
8	+	+			3000 mg/Kg
9	+	+			4500 mg/Kg
10	+	+			6000 mg/Kg

Oil was heated and stirred as described above. Prior to frying experiments, the AOX ingredient or individual components (including ascorbic acid, carnosic acid, citric acid and tocopherols) were added at the concentrations equivalent to those obtained from adding complete AOX to achieve 85 mg/kg ascorbic acid prior to frying, and then heated to desired final temperatures. Model chips were fried for 4 min at a temperature range of 165–175 °C. Chips were removed from fryer and patted with paper towels to remove excess surface oil prior to visual inspection. Following cooling, chips were photographed, and then chip color was determined using a hand-held chromameter CR-400 (Konica Minolta, NJ, USA). Frying experiments were completed in duplicate with triplicate analysis of color and calculation of Browning Index from L*a*b* values obtained by handheld Minolta colorimeter under ambient laboratory lighting.

2.7. Sequential frying experiments

To better understand if the browning processes is modified by continuous frying that may consume reactants in oil over time, experiments using three sequential frying of fresh test chips with the same oil were performed in canola oil spiked with the mixed AOX suspension (1600 mg suspension/Kg frying oil), resulting in a final ascorbic acid concentration of 85 mg/kg frying oil, and model chips coated with GLN 400 mg/kg. The rest of the experimental conditions were equal as to model potato chip experiments (see section 2.5).

2.8. Evaluation of browning by individual components of the AOX system

To explore the potential for individual AOX components to induce browning, experiments were conducted with model chips formulated with highest levels of GLN (4000 mg/kg), ASN (6000 mg/kg) and ARG (1000 mg/kg) and oil plus individual and combinations of AOX ingredients. The rest of the experimental conditions were equal as to model potato chip experiments (see section 2.5).

2.9. Color assessment

The impact of frying and ingredient combination on the surface color of test chips was determined using a hand-held chromameter CR-400 (Konica Minolta, NJ, USA). Color measurements were performed immediately after frying and cooling of the chips. Readings were obtained on a CIELAB scale (L*, a*, b*). A total of three independent measurements were obtained per frying variable and browning index (BI) was calculated as described by Zambrano-Zaragoza et al. ([Zambrano-Zaragoza et al., 2014](#))

2.10. Statistics

Prism 8.0 (GraphPad, La Jolla, CA, USA) was used for statistical analyses and graph creation purposes. The contribution of different antioxidant systems and chip components on browning index were evaluated through Two-way ANOVA. If significant main effects or interactions were detected, Tukey's *post hoc* test was performed to compare individual treatment means. Statistical significance was defined *a priori* as $p < 0.05$.

3. Results and discussion

3.1. Preliminary frying experiment

Our initial frying experiment clearly demonstrated that ascorbic acid and the antioxidant mix promote the generation of brown colors in potato chips. The chips fried in oil with no additives ([Fig. 1A](#)) or 50 mg/kg BHT ([Fig. 1B](#)) had a desirable light golden-brown color with little or no discernible differences. However, the addition of 85 mg ascorbic acid/Kg frying oil, both through an ascorbic acid suspension (5.34 g

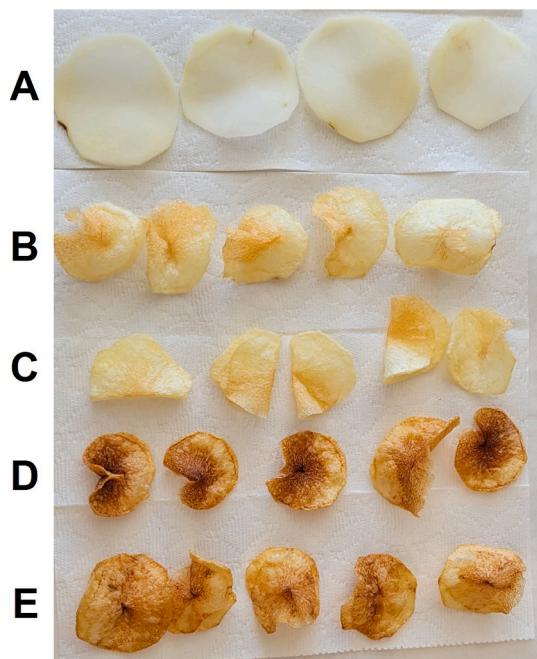


Fig. 1. Appearance of raw potato chips (A) and potato chips fried for 6 min at 135 °C in 456.5 g of fresh canola oil with no additives (B), 50 mg/kg BHT (C), 85 mg/kg ascorbic acid provided through an ascorbic acid suspension (5.34 mg ascorbic acid/100g oil) (D) or through an AOX mixture (5.31 mg ascorbic acid/100g oil) (E) fried for 6 min at 135 °C.

ascorbic/100 g; 1600 mg suspension/Kg frying oil) and AOX (5.31 g ascorbic/100 g; 1600 mg suspension/Kg frying oil), produced chips with an undesirable brown, burned appearance. Therefore, an understanding of the mechanisms responsible for the browning is necessary in order to utilize natural AOX systems while preserving desirable product appearance.

3.2. Solubility and thermal degradation of ascorbic acid in canola oil

Ascorbic acid is a potent water-soluble anti-oxidant component present in or added to various natural AOX systems used to improve lipid performance during frying (Aladedunye et al., 2017; Gertz, 2004; Hwang et al., 2019). Ascorbic acid can serve to regenerate lipophilic antioxidants at the water-oil interface (Eunok Choe & Min, 2009; Dai et al., 2008). Ascorbic acid is insoluble in oil at refrigeration and room temperatures, but solubilizes during heating. Due to poor lipid

solubility, we hypothesized that ascorbic acid would migrate from the oil system to water (on chip surfaces or evolved steam) during frying. The migration and partitioning of ascorbic acid may thus alter local ascorbic acid concentrations and reactivity. In our initial experiments, we evaluated the potential contribution of ascorbic acid in color formation by first studying its solubility in oil across the frying temperature range. Ascorbic acid was found to have poor solubility in canola oil at room temperature regardless of whether it was added as pure ascorbic acid or as a component of the AOX mix (~5 mg/L when added through a pure ascorbic acid suspension, and ~12.5 mg/L when added through AOX mix, both at ~20 °C; Fig. 2). This poor solubility of ascorbic acid in canola oil is in agreement with its water-soluble nature and its low solubility in other oils, fats, fat solvents and organic solvents (i.e., chloroform and benzene (O'Neil, 2006). Solubility of ascorbic acid in canola oil increased with oil temperature with a maximum solubility of ~53 mg/L and ~30 mg/L at ~145 °C for pure ascorbic acid suspension and AOX system, respectively (Fig. 2). It is important to highlight that different precautions were followed to minimize oil temperature drops during aliquoting and centrifugation (fast centrifugation at 2 min and at maximum centrifuge temperature of 40 °C), oil samples must have undergone temperature decreases in this process. This may result in some ascorbic acid falling out of solution, and ascorbic acid solubility may actually be higher than reported.

After the peak of solubility at ~145 °C, a sharp decrease in apparent soluble ascorbic acid concentration was observed with further heating regardless of ascorbic acid origin (pure or mixed AOX). Presumably, this was due to enhanced oxidation observed with an increase in dehydroascorbic acid levels, which peaked at ~175 °C before further decline. Thermal degradation of ascorbic acid into dehydroascorbic acid has been previously observed (Manso et al., 2001). Maximum concentrations of dehydroascorbic acid in our frying system were ~34.6 mg/L when added through the pure ascorbic acid suspension, and ~19.3 mg/L when added through the AOX system (both supplying a final ascorbic acid concentration of 85 mg/kg frying oil). Very little soluble ascorbic acid was observed at maximum frying temperature of 180 °C for pure ascorbic acid (~1.0 mg/L) and mixed AOX system (~1.4 mg/L). This was also true for dehydroascorbic acid for the pure ascorbic acid treatment (~8.5 mg/L) and mixed AOX system (~3.8 mg/L). Our results suggest that, in industrial frying settings, enhanced solubility of ascorbic acid occurs as the fryer reaches operation temperatures (typical oil frying temperatures for chips range between 150 and 190 °C (E. Choe & Min, 2007)), and it is rapidly degraded to dehydroascorbic acid at temperatures >145 °C. Then, dehydroascorbic acid is likely further degraded into other more complex and undetected products. Some of these could include furan derivates and α,β -unsaturated cyclic ketones with a five-member ring (Tatum et al., 1969; Vernin et al., 1997). Of

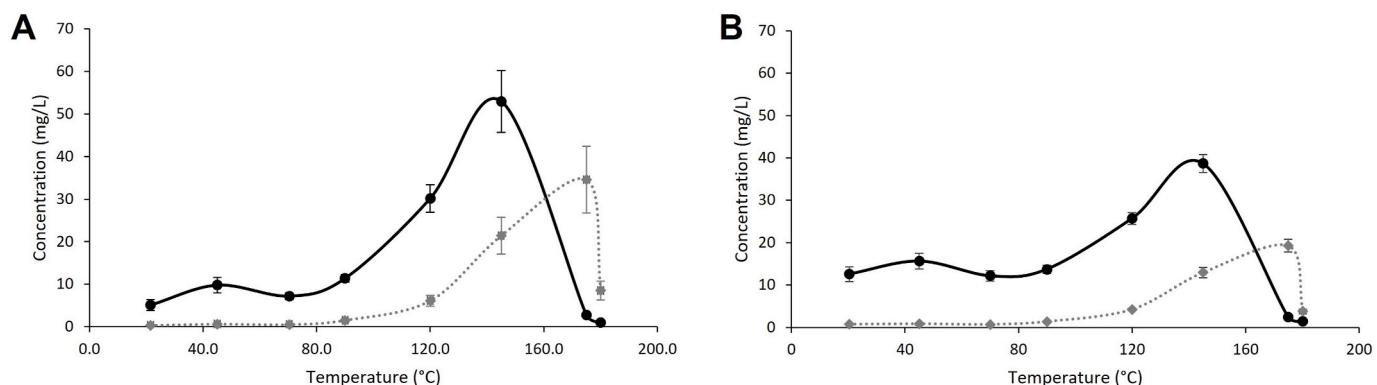


Fig. 2. Effect of oil temperature on apparent soluble ascorbic acid (solid line) and dehydroascorbic acid (dotted line) concentration when ascorbic acid is supplied at a final concentration of 85 mg/kg through a ascorbic acid suspension (5.34 mg/100 g oil) (A). Effect of oil temperature on apparent soluble ascorbic acid (solid line) and dehydroascorbic acid (dotted line) concentration when ascorbic acid is supplied at a final concentration of 85 mg/kg through the AOX mix (5.31 mg ascorbic acid/100 g oil) (B). Results are expressed as mean mg/L ± SEM ($n = 3$).

note, some of these compounds are the same as the ones obtained in the Maillard reaction (Vernin et al., 1997), which could be one of the mechanisms of action involved in color formation.

3.3. Evaluation of ascorbic acid as a browning-triggering component in an inert matrix

To better understand the kinetics of ascorbic acid migration and degradation in a model system, initial experiments were conducted with wet or dry cotton balls as inert absorbent scaffolds for moisture and ascorbic acid collection. Potatoes are ~77 g water/100 g (Zaheer & Akhtar, 2016), and we thus introduced moisture to evaluate the effect of water content in the browning process. Of note, ascorbic acid is a water-soluble compound, and water content in chips play a crucial role. During frying, water from the outer layer of the chip is released into the hot oil, and evaporates quickly. This generates a chip with an outer crust, and an inner moist core (F. Pedreschi et al., 2016). During the frying of potato chips, browning processes predominantly take place on the outer region of the chip (F. Pedreschi et al., 2016), where a water-oil interface is created. Initial results suggested that inclusion of both moisture and ascorbic acid did result in increased brown color formation on the cotton balls when fried at 135 °C (Fig. S1). Note that inclusion of moisture reduced oil uptake by the cotton balls, again suggesting that chip moisture produces a significant oil-water interface. However, the extent of color development was not as extensive or indicative of the extent of color formation observed in chips, strongly suggesting that other components, likely from the chips themselves (i.e., moisture or amino acids) were required for browning formation. This is plausible, as both reducing sugars (or similar compounds providing the necessary

reactivity) and free amino acids are required for Maillard's reaction to start (Manso et al., 2001; Martins et al., 2001).

Subsequent experiments were conducted with both wet and dry cotton balls at reduced frying temperature of 135 °C, where both ascorbic acid and dehydroascorbic acid had been previously detected to have increased solubility and formation (Fig. 2). Dry or wet cotton balls were added when frying oil reached 135 °C. Over the 6 min of frying, oil temperature increased up to ~158 °C for dry cotton balls, and up to ~154 °C for wet cotton balls. While these temperatures are only reflective of the low spectrum of temperatures reached in industrial frying systems (typical between 150 and 190 °C (E. Choe & Min, 2007)), they may be reflective of temperatures at the oil surface of the "wet" side of the fryer where moisture-rich potato chips enter the system, perhaps transiently. This remains to be confirmed. Results show that ascorbic acid is degraded during the 6 min of frying, and dehydroascorbic acid is generated (Fig. 3). For dry cotton balls, soluble ascorbic acid decreases from ~70 mg/L at 0 min, to ~37 mg/L at 6 min, while dehydroascorbic acid increases from ~17 mg/L to ~71 mg/L. For wet cotton balls, soluble ascorbic acid decreases from ~58 mg/L at 0 min, to ~22 mg/L at 6 min, while dehydroascorbic acid increases from ~27 mg/L to ~81 mg/L. When ascorbic acid and dehydroascorbic acid levels are relativized to initial conditions, it was clear that wet cotton balls produce a faster decrease in soluble ascorbic acid levels in the bulk oil (potentially due to both migration out of the bulk oil to the cotton ball surface, and degradation) coupled to a faster increase to dehydroascorbic acid levels. By visually inspecting the cotton balls (Fig. S1), some browning was found the surface of the cotton balls, which was more extensive in wet cotton balls. These results correlated with the higher degradation of ascorbic acid and formation of dehydroascorbic acid.

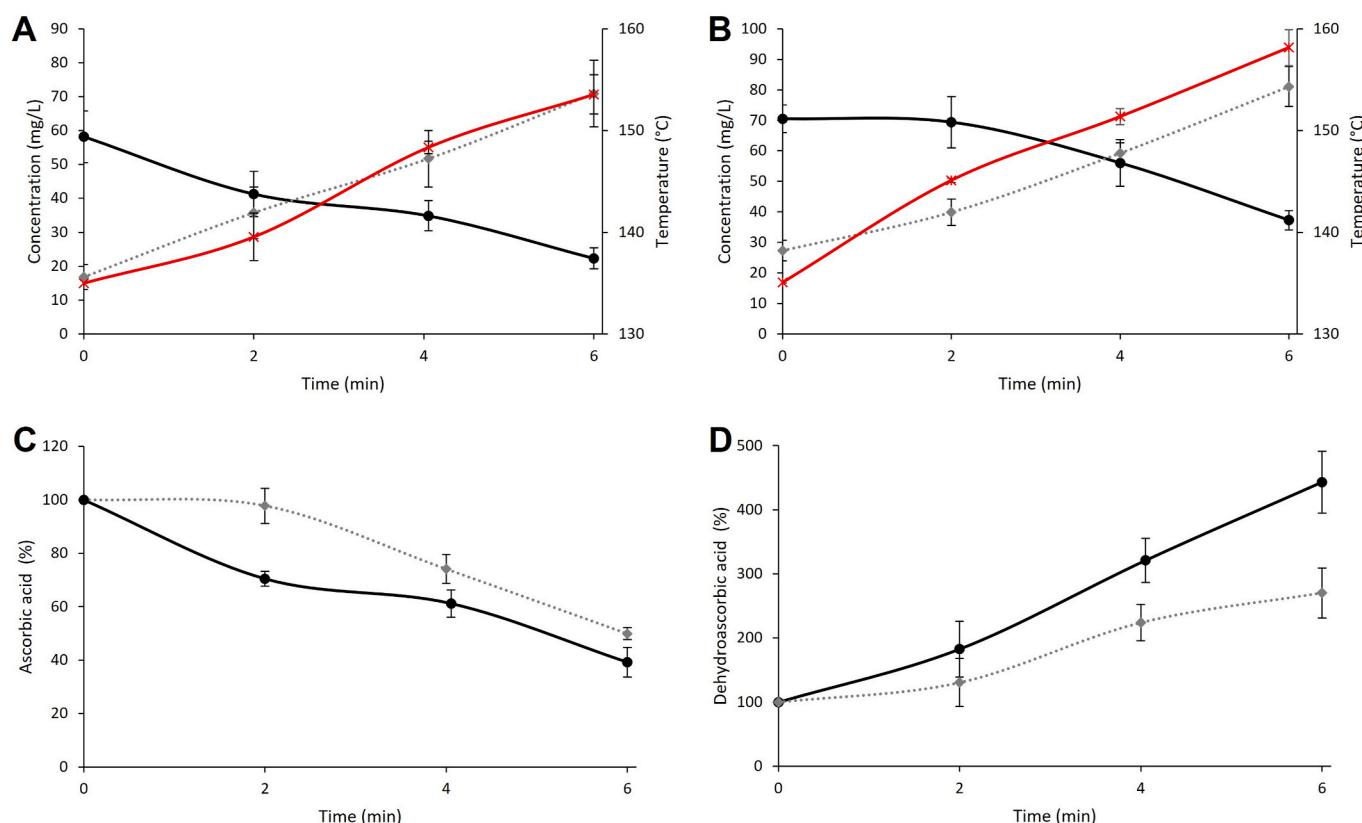


Fig. 3. Canola oil temperature and concentration of soluble ascorbic acid (solid black line) and dehydroascorbic acid (dotted grey line) in canola oils spiked with 85 mg ascorbic acid/Kg frying oil, provided through an ascorbic acid suspension (5.34 mg ascorbic acid/100 g oil; 1600 mg suspension/Kg frying oil) and added 5 wet (A) or dry (B) cotton balls when temperature (solid red line) reached 135 °C. Relative percentage of ascorbic acid (C) and dehydroascorbic acid (D) to initial levels (temperature of 135 °C) in frying systems for wet (solid line) and dry (dotted line) cotton balls. Results are expressed as mean ± SEM ($n = 3$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Overall, the presence of ascorbic acid alone was not sufficient to significantly induce color formation in cotton balls. It thus seems that complex and undetected ascorbic acid degradation products, although similar to some of the intermediate compounds formed during Maillard reaction (Vernin et al., 1997), do not materially contribute to color development in our matrix. This is in line with frying experiments in canola oil with dispersed ascorbic acid (Rodriguez-Saona et al., 1997). However, ascorbic acid could still play a role in color formation by interacting with different components on the surface of the potatoes, as well as with other components in AOX. Considering these observations and the browning observed in cotton balls at slightly lower temperature ranges, it was decided to explore browning in model chip systems using a frying temperature range of 160–170 °C.

3.4. Browning studies in model potato chip system

After observing that ascorbic acid degradation products do not produce a significant change in color in inert matrixes, we evaluated the contribution of other common components present in potato chips and potentially available for reaction. Several components of potato chips have been reported to modulate color generation, including amino acid and reducing sugar content (Rodriguez-Saona et al., 1997). In this sense, free amino acids can significantly contribute to color generation through the Maillard reaction (Kwak & Lim, 2004). Potatoes are rich in free asparagine (ASN), glutamine (GLN) and arginine (ARG) (Ohara-Takada et al., 2005; Peksa et al., 2021), and those could potentially contribute to color generation during frying. For example, free GLN levels have been reported to be exhausted during frying in potato chips, and their initial content significantly affects color generation during frying (Rodriguez-Saona et al., 1997). After preliminary experiments (data not shown), it was determined that the optimal method for generating and introducing the model chips into the frying systems was to rely on freshly prepared experimental “test chips”: chromatography paper coated with ~ 1–1.1 g of starch solution (with or without free amino acids added individually or in combination). Fig. 4 illustrates a range of color formation from representative frying experiments conducted using model chips containing GLN at different levels and fried in oil either ascorbic acid or mixed AOX (85 mg/kg ascorbic acid in both oil systems). Brown color was visually most evident in chips coated with starch +4000 mg/kg of GLN when fried in oil containing either ascorbic acid or mixed AOX ingredient. Modest browning was observed in frying in pure oil; however, browning was not observed in controls (paper and paper + starch) fried in plain oil. These results suggest that interactions between both oil phase AOX systems and free amino acids in potatoes may be primarily responsible for visual brown color formation. For example, it has been shown that the antioxidant properties of amino acids in frying systems are affected by the addition of other AOX, such as rosemary extract or ascorbic acid (Hwang et al., 2019). We then further explored the impact of both amino acid species (GLN, ASN and ARG) and concentration to better understand the impact on frying in both ascorbic acid and AOX oil systems.

Fig. 4B illustrates the dose dependent change in visual brown color with increasing GLN content from 400 to 4000 mg/kg, while Fig. 5 shows the effects of different amino acids on brown color formation (expressed as Browning Index). The experiments with different amino acids and oils systems showed that both the amino acid concentration, the oil system and their interaction statistically affect browning index (Fig. 5C, F and I). The addition of amino acids increased the browning index of “test chips” when no AOX were added when compared to the control, suggesting that there exist browning reactions occurring without the requirement of AOX presence. This can be easily seen in the grey bars from Fig. 5A, D and G. Amongst the three amino acids tested, GLN was the amino acid most responsive to changes in browning index due to changes in its concentration. When antioxidants were included in the frying system, only “test chips” with GLN reported a substantial change in browning index (Fig. 5B, E and H). Browning index was

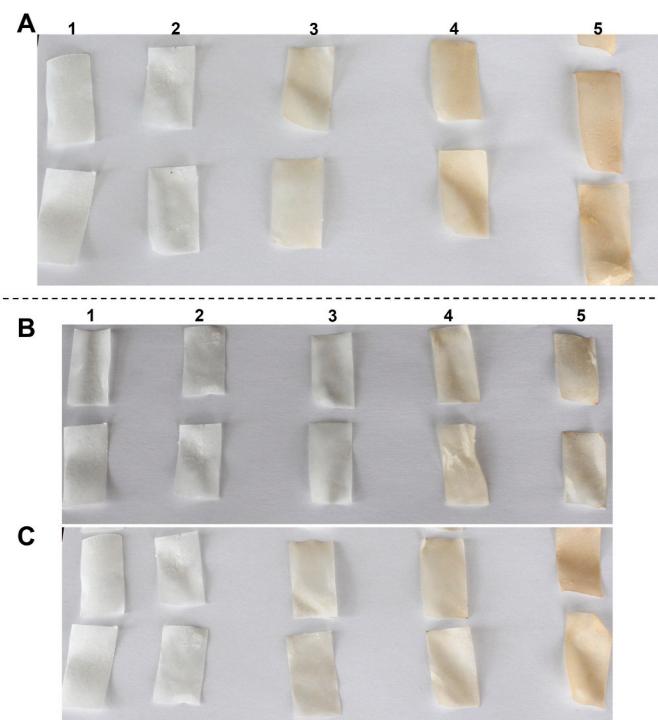


Fig. 4. Images selected from model “test chip” frying experiment to illustrate browning in the presence and absence of glutamine (4 g/kg), and ascorbic acid (85 mg/kg frying oil) provided either by pure ascorbic acid or through the AOX mix (A). A1 – no starch, no glutamine, no ascorbic acid; A2 – starch, no glutamine, no ascorbic acid; A3 – starch, glutamine, no ascorbic acid; A4 – starch, glutamine, ascorbic acid through pure ascorbic acid; and A5 – starch, glutamine, ascorbic acid through AOX. Visual browning increase in dose-dependent fashion relative to glutamine content in “test chips” fired with or without pure ascorbic acid (B). B1 – no starch, no glutamine; B2 – starch, no glutamine; B3 – starch, 0.4 g/kg glutamine; B4 – starch, 2 g/kg glutamine; and B5 – starch, 4 g/kg glutamine. Visual browning increase in dose-dependent fashion relative to glutamine content in “test chips” fired with or without ascorbic acid through AOX (C). C1 – no starch, no glutamine; C2 – starch, no glutamine; C3 – starch, 0.4 g/kg glutamine; C4 – starch, 2 g/kg glutamine; and C5 – starch, 4 g/kg glutamine. Note that all model chips shown were fried.

highest with GLN 4000 mg/kg fried in AOX-containing oil (supplying 85 mg ascorbic acid/Kg oil), followed by 4000 mg/kg fried in ascorbic acid 85 mg/kg (through pure ascorbic acid) and ASN 6000 mg/kg fried in the AOX system. Of note, GLN has been previously described as an important factor in color development in potato chips (Khanbari & Thompson, 1993; Roe & Faulks, 1991). When antioxidants were included in the frying system, the browning index of “test chips” with medium (2000 mg/kg) and high (4000 mg/kg) GLN contents increased significantly, but was not different between AOX or ascorbic acid alone. This suggests that the main component in the AOX system driving color generation is ascorbic acid. Interestingly, browning indices of GLN 2000 mg/kg and 4000 mg/kg samples were similar between oil containing ascorbic acid and that containing AOX ingredients, suggesting that ascorbic acid may in fact be a significant contributor to browning associated with GLN in this model. Of note, this seems to disagree with the browning-inhibition properties of ascorbic acid in other potato models (do Nascimento & Canteri, 2020; Sapers & Miller, 1995; Yildiz, 2019). However, none of those include a frying process, which might be changing the chemistry of these reactions towards a pro-browning one. In contrast, ASN 6000 mg/kg samples had high browning index but only with AOX ingredients. Of note, ASN, along with reducing sugars, has been shown to be involved in the generation of acrylamide, a colorless early product of Millard's reaction, in potato chips, and acrylamide formation has been shown to be reduced through the use of ascorbic acid

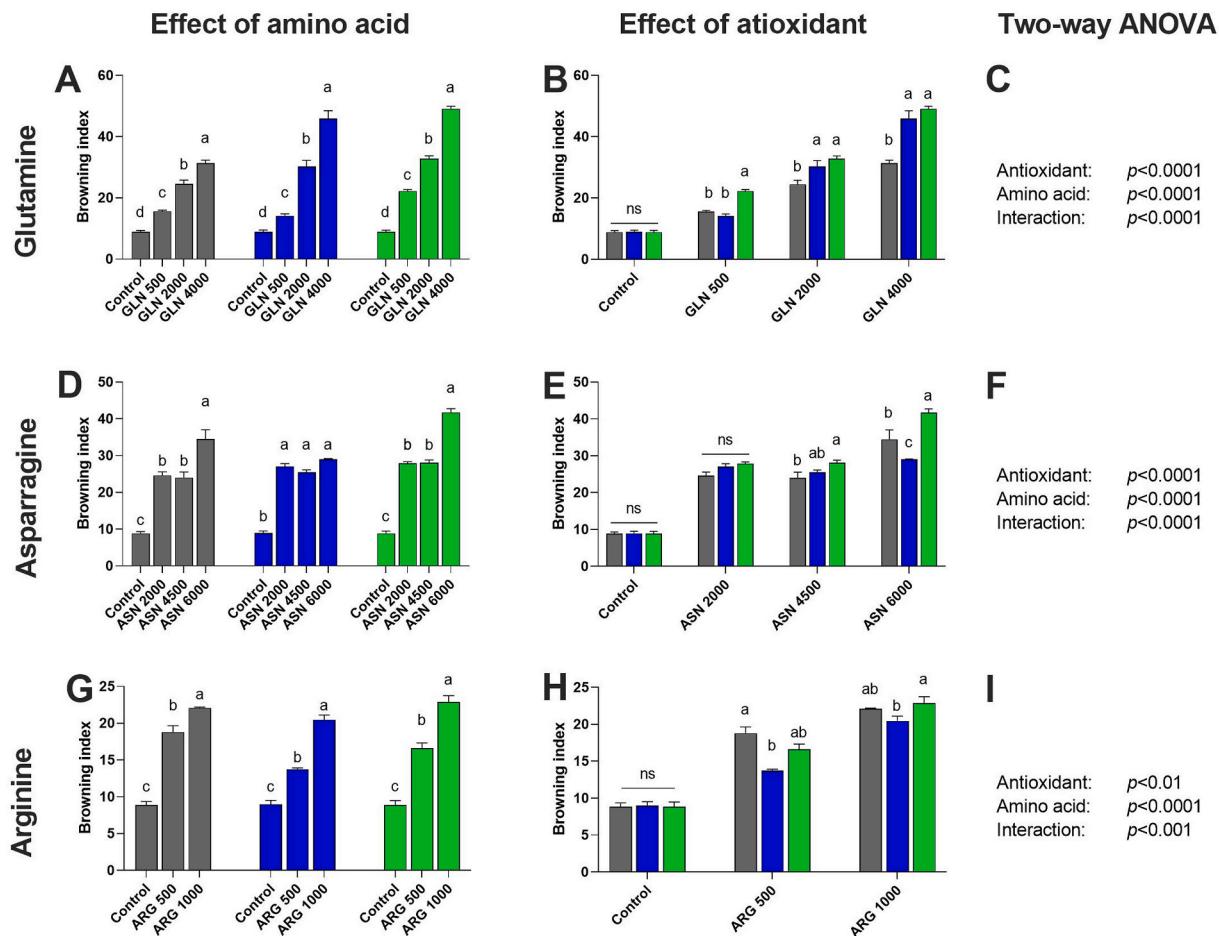


Fig. 5. Browning index of model potato chips at different amino acids and antioxidant systems. Effect of glutamine (GLN, 0–4000 mg/kg; A) asparagine (ASN, 0–6000 mg/kg; D) and Arginine (ARG, 0–1000 mg/kg; G) in different fixed oil systems. Effect of different frying oil systems in different fixed model potato chip amino acid composition (GLN, B; ASN, E; ARG, H). Statistic results of Two-way ANOVA for the individual and interaction effects of different oil systems and amino acids (GLN, C; ASN, F; ARG, I). Control oil system was composed of canola oil alone (grey), while 85 mg ascorbic acid/Kg oil was achieved through a pure ascorbic acid suspension (5.34 mg ascorbic acid/100 g oil; 1600 mg suspension/Kg frying oil; blue) or through an antioxidant (AOX) mix (5.31 mg ascorbic acid/100 g oil; 1600 mg suspension/Kg frying oil; green). Results are expressed as mean \pm SEM ($n = 3$). Superscript letters indicate statistical differences ($p < 0.05$) by Two-way ANOVA (Tukey post hoc test) within bars grouped together. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

0.5% (Liyanage et al., 2021). Of note, ammonia seem to play a relevant role in acrylamide formation in lipid-rich foods, and ammonia can be generated by the degradation of other amino acids (Yasuhsara et al., 2003). This adds another layer of complexity to browning generation by ASN through the inclusion of different chemical reactions, which can be modulated differently by the presence of different antioxidants in the oil system. Combined, our data suggest multiple reactions likely contribute to browning from AOX systems and the potential for unique reactions between other, non-ascorbic acid, AOX ingredients and ASN. It is important to note that browning was also significant with ASN and just plain oil system and ascorbic acid was observed to have a modest protective effect in this case when alone in the oil system. However, presence of amino acid, as would be the case in fresh potatoes appear to be amplifying the browning.

3.5. Sequential frying browning studies in model potato chip

The previous set of experiments in model potato chips acid were conducted to evaluate the behavior of different components in oil to understand their behavior and potential role in off-color formation in chip frying systems. The following set of experiments were conducted to emulate the specific conditions that occur in industrial chip frying systems that reported this off-color formation.

Generally, oil is continuously used for frying at high temperatures (Hwang et al., 2019), with oil added incrementally to offset uptake by chips (as opposed to draining oil and replacing the oil). To further understand the browning processes in a manner more reflective of commercial frying, three sequential frying experiments were conducted in canola oil spiked with 1600 mg AOX/Kg frying oil (providing a final concentration of 85 mg ascorbic acid/Kg frying oil), with fresh model potato chips and GLN 4000 mg/kg but without changing oil in between frying experiments (Fig. 6). The first fry in the system resulted in a browning index of 41.6. The second fry using the same oil resulted in a significant decrease in browning index to 20.9 with a modest increase in the third fry of 29.1. It is likely that the third fry increase was due to the presence of and accumulation of oxidized polymeric material (visible as dark residue/particulates) in the frying oil from the first two experiments. Indeed, increased b^* (measurement of yellowness/blueness) and decrease L^* (measurement of brightness/darkness) values have been shown when soybean oil was repeatedly used to fry potato chips, and content of antioxidants in oil modulated these parameters too (Urbančič et al., 2014). In any case, these results suggest that under conditions of repeated use (as would be the case in commercial frying operations), the reaction likely responsible for the brown color formation is reduced, presumably due to the reduction of chemical factors responsible in the AOX ingredient.

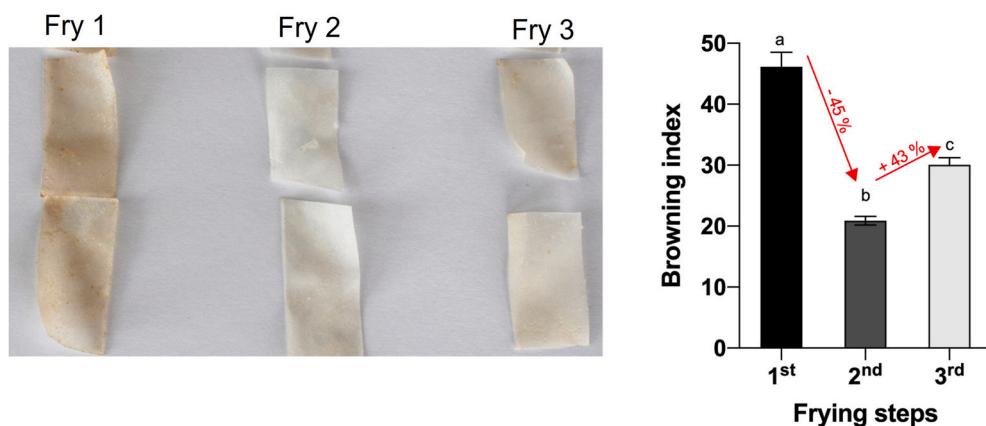


Fig. 6. Visual aspect of model “test chips” coated with glutamine 4000 mg/kg in oil with 1600 mg AOX mix/Kg frying oil (85 mg ascorbic acid/Kg frying oil) in sequential frying experiments (A), and browning index from each chip (B).

3.6. Effect of antioxidant components on browning

To explore the potential for other AOX components to induce browning, experiments were conducted with model chips formulated with highest levels of GLN, ASN and ARG and oil plus individual and combinations of AOX ingredients. Fig. 7C shows the two-way ANOVA results of these experiments, demonstrating that the antioxidant components of the AOX mix, the type of amino acid, as well as their interaction are statistically significant. Experiments with other AOX components suggest that additional AOX ingredients beyond ascorbic acid have minimal to no impact on browning index (Fig. 7). In GLN 4000 mg/kg chips, ascorbic acid appeared to account for almost all the browning observed with AOX ingredient. However, the opposite was observed with ASN 6000 mg/kg chips again suggestive of separate mechanism for browning reactions involving these specific amino acids. Of note, no changes were reported by the addition of AOX components and the whole AOX mix in ARG 1000 mg/kg. It is important to note that as with preliminary experiments, removal of amino acids resulted in almost complete loss of brown color formation. These results are highly suggestive of the direct involvement of both oil phase ascorbic acid and endogenous potato amino acids in the observed phenomena.

Although this manuscript provides relevant information on off color formation in potatoes chips, it has some limitations. Model potato chips do not fully recapitulate the complexity of real potato chips. This could partially explain why model potato chips show a strong effect of ascorbic acid alone in off color formation, which was not as evident in real potatoes. In real potatoes we observed a carbohydrate browning effect, which is not seen in model chips, free of sugars. Moreover, further

research is needed to fully understand the effect of ascorbic acid and amino acids in real potato chips. Nevertheless, this model is useful to isolate and interrogate experimental variables with precision. Future experiments should follow this research by studying the effects of the identified factors affecting off color formation using real potato chips.

4. Conclusion

In conclusion, findings from these series of experiments seem to suggest that both oil phase antioxidants and potato factors are relevant to generation of off-color formation in fried potato chips. Evidence from this work suggest that mechanisms likely involve primarily oil-phase ascorbic acid present in the AOX ingredient which under initial frying conditions may be solubilized prior to oxidation in the oil alone. At temperatures higher than ascorbic acid maximum solubility (145 °C), ascorbic acid is degraded to dehydroascorbic acid. Introduction of fresh potato chips introduces moisture to the system which may facilitate local solubilization and/or precipitation, and likely concentration of oil phase ascorbic acid or oxidation products at the chip surface. At that point, the reactions likely proceed through mechanism established in potato chips previously. While we did not specifically measure Maillard reaction products in this study, we believe that in this system ascorbic acid and free amino acids are likely reacting via Maillard browning reactions, leading to generation of complex Maillard products such as melanoidins (Agcam, 2022; Y. Li et al., 2016; Liu et al., 2022; Pischetsrieder et al., 2005; A.-N. Yu et al., 2011; A. N. Yu et al., 2013). While these reactions have been previously observed in potato chips, it is likely that the undesirable levels observed at the startup phase of

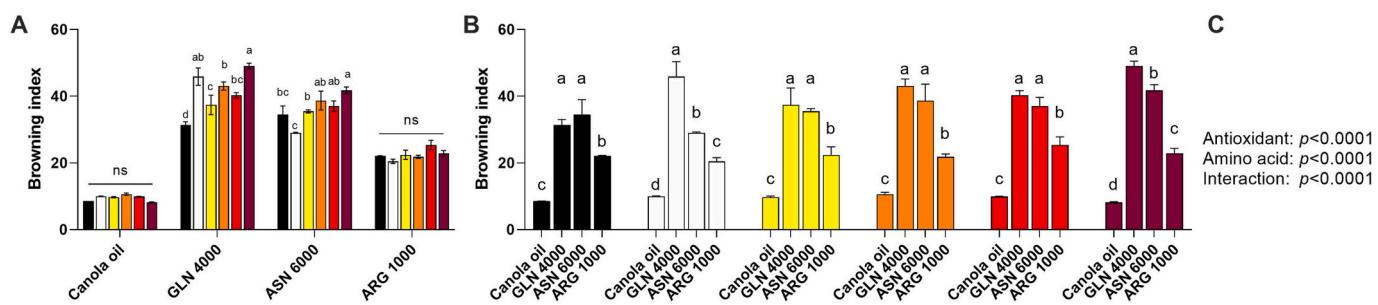


Fig. 7. Contribution of ascorbic acid (AA), mixed tocopherols (TOC), carnosic acid and carnosol (CAR), citric acid (CA), and antioxidant mix (AOX) in browning index in model chips with no added amino acids, glutamine (4000 mg/kg; GLN), asparagine (6000 mg/kg; ASN) arginine (1000 mg/kg; ARG). Concentrations shown are mg/Kg. Panel A shows results grouped per amino acids, while Panel B shows results grouped per antioxidant component. Results of the Two-Way ANOVA can be found in Panel C. Color codes are: control (black); AA (white); AA + TOC (yellow); AA + CAR (orange); AA + CAR + CA (red); and AOX (purple). Results are expressed as mean ± SEM ($n = 3$). Superscript letters indicate statistical differences ($p < 0.05$) by Two-way ANOVA within bars grouped together (Tukey post hoc test). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

frying are related to the elevated ascorbic acid concentrations introduced by the AOX ingredient which exacerbates the color formation until consumption of ascorbic acid in the first minutes of frying.

Funding

This work was supported by PepsiCo, Inc.

CRediT authorship contribution statement

Lisard Iglesias-Carres: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Kathryn C. Racine:** Investigation, Writing – review & editing. **Sydney Chadwick:** Investigation, Writing – review & editing. **Candace Nunn:** Investigation, Writing – review & editing. **Sathyia B. Kalambur:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing. **Andrew P. Neilson:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Mario G. Ferruzzi:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Sathyia B Kalambur is employed by PepsiCo, Inc. The views expressed in this manuscript are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

Data availability

Data will be made available on request.

Acknowledgments

The authors also wish to acknowledge David Raines (Plants for Human Health Institute, Department of Food, Bioprocessing and Nutrition Sciences, North Carolina State University, Kannapolis, NC) for his preliminary assays on this project. The authors thank Rick Dellaporta and Naina Shah at PepsiCo Global Foods R&D for initial project discussions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2023.114682>.

References

- Agcam, E. (2022). A kinetic approach to explain hydroxymethylfurfural and furfural formations induced by maillard, caramelization, and ascorbic acid degradation reactions in fruit juice-based mediums. *Food Analytical Methods*, 15, 1286–1299. <https://doi.org/10.1007/s12161-021-02214-x>
- Ajandouz, E. H., & Puigserver, A. (1999). Nonenzymatic browning reaction of essential amino acids: Effect of pH on caramelization and Maillard reaction kinetics. *Journal of Agricultural and Food Chemistry*, 47, 1786–1793. <https://doi.org/10.1021/jf980928z>
- Aladedunye, F., Przybylski, R., & Matthaus, B. (2017). Performance of antioxidative compounds under frying conditions: A review. *Critical Reviews in Food Science and Nutrition*, 57(8), 1539–1561. <https://doi.org/10.1080/10408398.2013.777686>
- Aziz, M., & Karboune, S. (2018). Natural antimicrobial/antioxidant agents in meat and poultry products as well as fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition*, 58, 486–511. <https://doi.org/10.1080/10408398.2016.1194256>
- Bastos, D. H. M., & Gugliucci, A. (2015). Contemporary and controversial aspects of the Maillard reaction products. *Current Opinion in Food Science*, 1, 13–20. <https://doi.org/10.1016/j.cofs.2014.08.001>
- Chammem, N., Saoudi, S., Sifaoui, I., Sifi, S., de Person, M., Abderraba, M., Moussa, F., & Hamdi, M. (2015). Improvement of vegetable oils quality in frying conditions by adding rosemary extract. *Industrial Crops and Products*, 74, 592–599. <https://doi.org/10.1016/j.indcrop.2015.05.054>
- Choe, E., & Min, D. B. (2007). Chemistry of deep-fat frying oils. *Journal of Food Science*, 72, 77–86. <https://doi.org/10.1111/j.1750-3841.2007.00352.x>
- Choe, E., & Min, D. B. (2009). Mechanisms of antioxidants in the oxidation of foods. *Comprehensive Reviews in Food Science and Food Safety*, 8, 345–358. <https://doi.org/10.1111/j.1541-4337.2009.00085.x>
- Clark, J. E. (1998). Taste and flavour: Their importance in food choice and acceptance. *Proceedings of the Nutrition Society*, 57, 639–643. <https://doi.org/10.1079/pns19980093>
- Clydesdale, F. M. (1993). Color as a factor in food choice. *Critical Reviews in Food Science and Nutrition*, 33, 83–101. <https://doi.org/10.1080/1040839309527614>
- Dai, F., Chen, W. F., & Zhou, B. (2008). Antioxidant synergism of green tea polyphenols with α-tocopherol and l-ascorbic acid in SDS micelles. *Biochimie*, 90, 1499–1505. <https://doi.org/10.1016/j.biichi.2008.05.007>
- Fikry, M., Yusof, Y. A., Al-Awaad, A. M., Rahman, R. A., Chin, N. L., Mousa, E., & Chang, L. S. (2019). Effect of the roasting conditions on the physicochemical, quality and sensory attributes of coffee-like powder and brew from defatted palm date seeds. *Foods*, 8, 61–80. <https://doi.org/10.3390/foods8020061>
- Gertz, C. (2004). Optimising the baking and frying process using oil-improving agents. *European Journal of Lipid Science and Technology*, 106, 736–745. <https://doi.org/10.1002/ejlt.200401015>
- Gök, V., Obuz, E., Şahin, M. E., & Serteser, A. (2011). The effects of some natural antioxidants on the color, chemical and microbiological properties of sucuk (Turkish dry-fermented sausage) during ripening and storage periods. *Journal of Food Processing and Preservation*, 35, 677–690. <https://doi.org/10.1111/j.1745-4549.2011.00517.x>
- Habibie, A., Yazdani, N., Saba, M. K., & Vahdati, K. (2019). Ascorbic acid incorporated with walnut green husk extract for preserving the postharvest quality of cold storage fresh walnut kernels. *Scientia Horticulturae*, 245, 193–199. <https://doi.org/10.1016/j.scientia.2018.10.022>
- Hwang, H. S., Winkler-Moser, J. K., & Liu, S. X. (2019). Study on antioxidant activity of amino acids at frying temperatures and their interaction with rosemary extract, green tea extract, and ascorbic acid. *Journal of Food Science*, 84, 3614–3623. <https://doi.org/10.1111/1750-3841.14963>
- Jiang, Z., & Ooraikul, B. (1989). Reduction of nonenzymatic browning in potato chips and French fries with glucose oxidase. *Journal of Food Processing and Preservation*, 13, 175–186. <https://doi.org/10.1111/j.1745-4549.1989.tb00099.x>
- Khanbari, O. S., & Thompson, A. K. (1993). Effects of amino acids and glucose on the fry colour of potato crisps. *Potato Research*, 36, 359–364. <https://doi.org/10.1007/BF02361803>
- Kim, H., Cadwallader, K. R., Kido, H., & Watanabe, Y. (2013). Effect of addition of commercial rosemary extracts on potent odorants in cooked beef. *Meat Science*, 94, 170–176. <https://doi.org/10.1016/j.meatsci.2013.01.005>
- Kurechi, T., Aizawa, M., & Kunugi, A. (1983). Studies on the antioxidants XVIII: Oxidation product of tertiary butyl hydroquinone (TBHQ) (I). *Journal of the American Oil Chemists' Society*, 60, 1878–1882. <https://doi.org/10.1007/BF02901542>
- Kwak, E. J., & Lim, S. I. (2004). The effect of sugar, amino acid, metal ion, and NaCl on model Maillard reaction under pH control. *Amino Acids*, 27, 85–90. <https://doi.org/10.1007/s00726-004-0067-7>
- Lalas, S., & Dourtoglou, V. (2003). Use of rosemary extract in preventing oxidation during deep-fat frying of potato chips. *JAOCs, Journal of the American Oil Chemists' Society*, 80, 579–583. <https://doi.org/10.1007/s11746-003-0741-x>
- Leszkowiat, M. J., Barichello, V., Yada, R. Y., Coffin, R. H., Lougheed, E. C., & Stanley, D. W. (1990). Contribution of sucrose to nonenzymatic potato chips: A research note. *Journal of Food Science*, 55, 383–389.
- Liu, L., Liu, L., Xie, J., & Shen, M. (2022). Formation mechanism of AGEs in Maillard reaction model systems containing ascorbic acid. *Food Chemistry*, 378, Article 132108. <https://doi.org/10.1016/j.foodchem.2022.132108>
- Liyanage, D. W. K. K., Yevtushenko, D. P., Konschuh, M., Bizimungu, B., & Lu, Z.-X. (2021). Processing strategies to decrease acrylamide formation, reducing sugars and free asparagine content in potato chips from three commercial cultivars. *Food Control*, 119, Article 107452. <https://doi.org/10.1016/j.foodcont.2020.107452>
- Li, P., Yang, X., Lee, W. J., Huang, F., Wang, Y., & Li, Y. (2021). Comparison between synthetic and rosemary-based antioxidants for the deep frying of French fries in refined soybean oils evaluated by chemical and non-destructive rapid methods. *Food Chemistry*, 335, Article 127638. <https://doi.org/10.1016/j.foodchem.2020.127638>
- Li, Y., Yang, Y., & Yu, A. N. (2016). Effects of reaction parameters on generation of volatile compounds from the Maillard reaction between L-ascorbic acid and glycine. *International Journal of Food Science and Technology*, 51, 1349–1359. <https://doi.org/10.1111/ijfs.13106>
- Manso, M. C., Oliveira, F. A. R., Oliveira, J. C., & Frías, J. M. (2001). Modelling ascorbic acid thermal degradation and browning in orange juice under aerobic conditions. *International Journal of Food Science and Technology*, 36(3), 303–312. <https://doi.org/10.1046/j.1365-2621.2001.t01-1-00460.x>
- Manzoor, S., Masoodi, F. A., Rashid, R., & Dar, M. M. (2022). Effect of apple pomace-based antioxidants on the stability of mustard oil during deep frying of French fries. *Lebensmittel-Wissenschaft & Technologie*, 163, Article 113576. <https://doi.org/10.1016/j.lwt.2022.113576>
- Marquez, G., & Añon, M. C. (1986). Influence of reducing sugars and amino acids in the color development of fried potatoes. *Journal of Food Science*, 51, 157–160. <https://doi.org/10.1111/j.1365-2621.1986.tb10859.x>
- Martins, S., Jongen, W., Boekel, V., & Martinus, A. (2001). A review of Maillard reaction in food and implications to kinetic modelling. *Trends in Food Science & Technology*, 11, 364–373.

- Mohanam, A., Nickerson, M. T., & Ghosh, S. (2018). Oxidative stability of flaxseed oil: Effect of hydrophilic, hydrophobic and intermediate polarity antioxidants. *Food Chemistry*, 266, 524–533. <https://doi.org/10.1016/j.foodchem.2018.05.117>
- Morales, G., Jimenez, M., Garcia, O., Mendoza, M. R., & Beristain, C. I. (2014). Effect of natural extracts on the formation of acrylamide in fried potatoes. *LWT - Food Science and Technology*, 58, 587–593. <https://doi.org/10.1016/j.lwt.2014.03.034>
- do Nascimento, R. F., & Canteri, M. H. G. (2020). Use of sodium metabisulfite and ascorbic acid as anti-browning agents in processed potatoes. *British Food Journal*, 122, 380–389. <https://doi.org/10.1108/BFJ-05-2019-0322>
- Negrón, M., D'Agostina, A., & Arnoldi, A. (2001). Effects of olive, canola, and sunflower oils on the formation of volatiles from the maillard reaction of lysine with xylose and glucose. *Journal of Agricultural and Food Chemistry*, 49, 439–445. <https://doi.org/10.1021/jf0003653>
- Ohara-Takada, A., Matsuura-Endo, C., Chuda, Y., Ono, H., Yada, H., Yoshida, M., Kobayashi, A., Tsuda, S., Takigawa, S., Noda, T., Yamauchi, H., & Mori, M. (2005). Change in content of sugars and free amino acids in potato tubers under short-term storage at low temperature and the effect on acrylamide level after frying. *Bioscience Biotechnology and Biochemistry*, 69, 1232–1238. <https://doi.org/10.1271/bbb.69.1232>
- O'Neil, M. J. (Ed.). (2006). *The merck index - an encyclopedia of chemicals, drugs, and biologicals*. Merck and Co., Inc.
- Ou, J., Huang, J., Wang, M., & Ou, S. (2017). Effect of rosmarinic acid and carnosic acid on AGEs formation in vitro. *Food Chemistry*, 221, 1057–1061. <https://doi.org/10.1016/j.foodchem.2016.11.056>
- Pedreschi, F., León, J., Mery, D., & Moyano, P. (2006). Development of a computer vision system to measure the color of potato chips. *Food Research International*, 39, 1092–1098. <https://doi.org/10.1016/j.foodres.2006.03.009>
- Pedreschi, F., Mery, D., & Mariquie, T. (2016). Quality evaluation and control of potato chips. In *Computer vision technology for food quality evaluation* (2nd ed., pp. 591–613). <https://doi.org/10.1016/B978-0-12-802232-0.00022-0>
- Pęksa, A., Miedzianka, J., Nemš, A., & Rytel, E. (2021). The free-amino-acid content in six potato cultivars through storage. *Molecules*, 26, 1322–1337. <https://doi.org/10.3390/molecules26051322>
- Pischetsrieder, M., Larisch, B., & Severin, T. (2005). The maillard reaction of ascorbic acid with amino acids and proteins - identification of products. In *The maillard reaction in foods and medicine*. <https://doi.org/10.1533/9781845698447.2.107>
- Rahila, M. P., Surendra Nath, B., Laxmana Naik, N., Pushpadass, H. A., Manjunatha, M., & Franklin, M. E. E. (2018). Rosemary (rosmarinus officinalis linn.) extract: A source of natural antioxidants for imparting autoxidative and thermal stability to ghee. *Journal of Food Processing and Preservation*, 42, 1–10. <https://doi.org/10.1111/jfpp.13443>
- Redondo-Cuevas, L., Castellano, G., & Raikos, V. (2017). Natural antioxidants from herbs and spices improve the oxidative stability and frying performance of vegetable oils. *International Journal of Food Science and Technology*, 52, 2422–2428. <https://doi.org/10.1111/ijfs.13526>
- Rodríguez-Saona, L. E., & Wrolstad, R. E. (1997). Influence on potato composition on chip color quality. *American Potato Journal*, 14, 121–128.
- Rodríguez-Saona, L. E., Wrolstad, R. E., & Pereira, C. (1997). Modeling the contribution of sugars, ascorbic acid, chlorogenic acid and amine acids to non-enzymatic browning of potato chips. *Journal of Food Science*, 74, 1001–1010. <https://doi.org/10.1111/j.1365-2621.1997.tb15024.x>
- Roe, M. A., & Faulks, R. M. (1991). Color development in a model system during frying: Role of individual amino acids and sugars. *Journal of Food Science*, 56(6), 1711–1713. <https://doi.org/10.1111/j.1365-2621.1991.tb08677.x>
- Sapers, G. M., & Miller, R. L. (1995). Heated ascorbic/citric acid solution as browning inhibitor for pre-peeled potatoes. *Journal of Food Science*, 60(4), 762–766. <https://doi.org/10.1111/j.1365-2621.1995.tb06223.x>
- Serpen, A., & Gökmén, V. (2007). Modeling of acrylamide formation and browning ratio in potato chips by artificial neural network. *Molecular Nutrition & Food Research*, 51, 383–389. <https://doi.org/10.1002/mnfr.200600121>
- Shallenberger, R. S., Smith, O., & Treadway, R. H. (1959). Role of the sugars in the browning reaction in potato chips. *Journal of Agricultural and Food Chemistry*, 7, 274–277. <https://doi.org/10.1021/jf60098a010>
- Shang, Y. F., Cao, H., Wei, C. K., Thakur, K., Liao, A. M., Huang, J. H., & Wei, Z. J. (2020). Effect of sugar types on structural and flavor properties of peony seed derived Maillard reaction products. *Journal of Food Processing and Preservation*, 44, 1–12. <https://doi.org/10.1111/jfpp.14341>
- Tatum, J. H., Shaw, P. E., & Berry, R. E. (1969). Degradation products from ascorbic acid. *Journal of Agricultural and Food Chemistry*, 17, 38–40. <https://doi.org/10.1021/jf60161a008>
- Urbanić, S., Kolar, M. H., Dimitrijević, D., Demšar, L., & Vidrih, R. (2014). Stabilisation of sunflower oil and reduction of acrylamide formation of potato with rosemary extract during deep-fat frying. *LWT - Food Science and Technology*, 57, 671–678. <https://doi.org/10.1016/j.lwt.2013.11.002>
- Vernin, G., Chakib, S., Rogacheva, S. M., Obretenov, T. D., & Pärkányi, C. (1997). Thermal decomposition of ascorbic acid. *Carbohydrate Research*, 305, 1–15. [https://doi.org/10.1016/S0008-6215\(97\)00234-6](https://doi.org/10.1016/S0008-6215(97)00234-6)
- Williams, G. M., Iatropoulos, M. J., & Whysner, J. (1999). Safety assessment of butylated hydroxyanisole and butylated hydroxytoluene as antioxidant food additives. *Food and Chemical Toxicology*, 37(9–10), 1027–1038. [https://doi.org/10.1016/S0278-6915\(99\)00085-X](https://doi.org/10.1016/S0278-6915(99)00085-X)
- Yasuhara, A., Tanaka, Y., Hengel, M., & Shibamoto, T. (2003). Gas chromatographic investigation of acrylamide formation in browning model systems. *Journal of Agricultural and Food Chemistry*, 51, 3999–4003. <https://doi.org/10.1021/jf0300947>
- Yehye, W. A., Rahman, N. A., Ariffin, A., Abd Hamid, S. B., Alhadi, A. A., Kadir, F. A., & Yaehoobi, M. (2015). Understanding the chemistry behind the antioxidant activities of butylated hydroxytoluene (BHT): A review. *European Journal of Medicinal Chemistry*, 101, 295–312. <https://doi.org/10.1016/j.ejmech.2015.06.026>
- Yıldız, G. (2019). Control of enzymatic browning in potato with calcium chloride and ascorbic acid coatings. *Food and Health*, 5, 121–127. <https://doi.org/10.3153/fh19013>
- Yu, A.-N., Tan, Z.-W., & Shi, B.-A. (2011). Influence of the pH on the formation of pyrazine compounds by the Maillard reaction of L-ascorbic acid with acidic, basic and neutral amino acids. *Asia-Pacific Journal of Chemical Engineering*, 7, 455–462. <https://doi.org/10.1002/apj.594>
- Yu, A. N., Tan, Z. W., & Wang, F. S. (2013). Mechanistic studies on the formation of pyrazines by Maillard reaction between L-ascorbic acid and L-glutamic acid. *Lebensmittel-Wissenschaft & Technologie*, 50, 64–71. <https://doi.org/10.1016/j.lwt.2012.07.001>
- Zaheer, K., & Akhtar, M. H. (2016). Potato production, usage, and nutrition—a review. *Critical Reviews in Food Science and Nutrition*, 56, 711–721. <https://doi.org/10.1080/10408398.2012.724479>
- Zambrano-Zaragoza, M. L., Mercado-Silva, E., Del Real, L. A., Gutiérrez-Cortez, E., Cornejo-Villegas, M. A., & Quintanar-Guerrero, D. (2014). The effect of nano-coatings with α-tocopherol and xanthan gum on shelf-life and browning index of fresh-cut “red Delicious” apples. *Innovative Food Science & Emerging Technologies*, 22, 188–196. <https://doi.org/10.1016/j;ifset.2013.09.008>
- Zhang, Y., Chen, J., Zhang, X., Wu, X., & Zhang, Y. (2007). Addition of Antioxidant of Bamboo leaves (AOB) effectively reduces acrylamide formation in potato crisps and French fries. *Journal of Agricultural and Food Chemistry*, 55, 523–528. <https://doi.org/10.1021/jf062568i>