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Reaction pathways and factors influencing nonenzymatic browning in shelf-stable fruit juices during storage

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Abstract

The occurrence of nonenzymaticbrowning in fruit juices during storage is a major quality defect. It negatively affects consumer acceptance and consumption behavior and determines the shelf-life of these products. Although nonenzymatic browning of fruit juices has been the subject of research for a long time, the exact mechanism of the nonenzymatic browning reactions is not yet completely understood. This review paper aims to give an overview of the compounds and reactions playing a key role in nonenzymatic browning during the storage of fruit juices. The chemistry of the plausible reactions and their relative importance will be discussed. To better understand nonenzymatic browning, factors affecting these reactions will be reviewed and several strategies and methods to evaluate color changes and browning will be discussed. Nonenzymatic browning involves three main reactions: ascorbic acid degradation, acid-catalyzed sugar degradation, and Maillard-associated reactions. The most important NEB pathway depends on the matrix. Nonenzymatic browning is affected by many factors, such as the juice composition, the pH, the oxygen availability (packaging material), and the storage conditions. Nonenzymatic browning can thus be considered as a complex problem. To characterize color changes and browning and obtain insight into the browning mechanism of fruit juices, food scientists applied several approaches and strategies. These included the use of model systems with/without the addition of labeled compound and real systems as well as advanced analytical methods.

Abbreviations: 3OH2P, 3-Hydroxy-2-pyrone; a^*, Measure of greenness/redness of a sample; AA, Ascorbic acid; ASLT, Accelerated shelf-life test; b^*, Measure of blueness/yellowness of a sample; BI, Browning index; C^*_{ab}, Chroma; DHAA, Dehydroascorbic acid; DKG, 2,3-Diketogulonic acid; E_a, Activation energy; h_{ab}, Hue angle (°); HMF, 5-Hydroxymethylfurfural; L^*, Measure of lightness of a sample; NEB, Nonenzymatic browning; ΔE^*, Total color difference between two samples

1 | INTRODUCTION

Consumers appreciate fruit and fruit-based products (e.g., juices, smoothies, jams, purees) because of their sensorial characteristics such as their attractive color and pleasant flavor. Besides, the consumption of fruit-based products can contribute substantially to nutritional compounds' recommended daily needs. Despite their popularity, high consumption and ease of production, shelf-stable fruit-based products such as juices and purees are sensitive toward quality changes during storage at room temperature. The major quality defect of these fruit-based products is their change in color, which is expressed by the formation of brown-colored pigments (Berk, 2016; Bharate & Bharate, 2014). These color changes negatively affect consumption behavior and consumer acceptance and limit the shelf-life of these products (Buvé, Van Bedts, et al., 2018). Moreover, browning will lead to increased food waste and brand damage.

Browning of fruit-based products has been studied for many years in a wide variety of products. Despite the large number of studies focusing on this topic (Burdurlu & Karadeniz, 2003; Buvé, Kebede, et al., 2018; Paravisini & Peterson, 2016, 2019; Pham et al., 2019; Pham et al., 2020a, 2020b; Wibowo et al., 2015a–2015d), the mechanisms behind the browning phenomenon are not yet understood fully. Browning of fruit-based products can result from two types of reactions: enzymatic and nonenzymatic reactions. Enzymatic browning reactions are mainly attributed to the activity of polyphenol oxidase and peroxidase and can be controlled by the application of thermal treatment (e.g., a pasteurization) whether or not in combination with the use of additives (Martinez & Whitaker, 1995; Teribia et al., 2021; Vámos-Vigyázó, 1981). It is generally agreed that nonenzymatic browning (NEB) in fruit juices is due to an interplay of reactions involving ascorbic acid (AA), sugars, and amino acids (Bharate & Bharate, 2014; Corzo-Martínez et al., 2012; Handwerk & Coleman, 1988). Three mechanisms, being AA degradation, acid-catalyzed sugar degradation, and Maillard (-associated) reactions, have been identified as the main reaction pathways responsible for NEB of fruit juices (Bharate & Bharate, 2014). Nevertheless, the exact mechanism of the NEB reactions is unknown (Berk, 2016; Bharate & Bharate, 2014; Paravisini & Peterson, 2016). Depending on the juice matrix, one mechanism may be dominant compared to the others. For instance, the degradation of AA has been reported to be the major color deterioration reaction occurring during storage of shelf-stable orange juice (Kennedy et al., 1990; Roig et al., 1999; Roig et al., 1996). However, as all fruit-based products are complex systems that contain relatively high amounts of AA and sugars (e.g., glucose, fructose, and sucrose) and a mixture of amino acids, multiple pathways linked to NEB can occur simultaneously in these products. Controlling of NEB is therefore not straightforward.

This review aims to give an overview of the work carried out to understand and characterize the browning problem in shelf-stable fruit juices during storage. Although it is known that enzymatic reactions can result in the formation of brown color, this review will only focus on NEB reactions as endogenous enzymes are assumed to be inactivated in shelf-stable fruit-based products. The main NEB reactions will be described and their contribution to the formation of brown-colored compounds during storage of different types of fruit juices will be revised. Related to this, the impact of product- and process-related factors influencing the rate of browning will be reviewed as they are the scientific basis to develop possible strategies to control the rate of browning. In a last part of this review, an overview of possible methods to evaluate browning in fruit juices will be presented/discussed.

In the context of color changes during storage, it should be noted that fruit-based products have a particular color due to the presence of natural pigments such as carotenoids, anthocyanins, betalains, or chlorophylls. Upon storage, these pigments can be sensitive toward degradation, resulting in the fading of the natural color and the appearance of a brown color due to the reactions described above (Buvé, Kebede, et al., 2018). Studying the stability of these pigments along the food chain is of great interest for researchers and food industries, but will not be included in this review.

2 | NONENZYMATIC BROWNING REACTIONS: CHEMISTRY AND RELATIVE IMPORTANCE

The reaction pathways and importance of the three main NEB reactions, being AA degradation, acid-catalyzed sugar degradation, and Maillard (-associated) reactions, will be discussed. The reaction schemes are included if deemed relevant for the reader.

2.1 | Ascorbic acid degradation

AA, also referred to as vitamin C, is one of the most important nutrients in fruit juices (Kabasakalis et al., 2000). It is a water-soluble and strongly reducing molecule. AA is relatively thermolabile and sensitive to different processing and storage conditions due to the presence of an enolic structure (Berk, 2016). The degradation of AA during storage of fruit juices has been proposed to occur simultaneously (but at a different rate) through

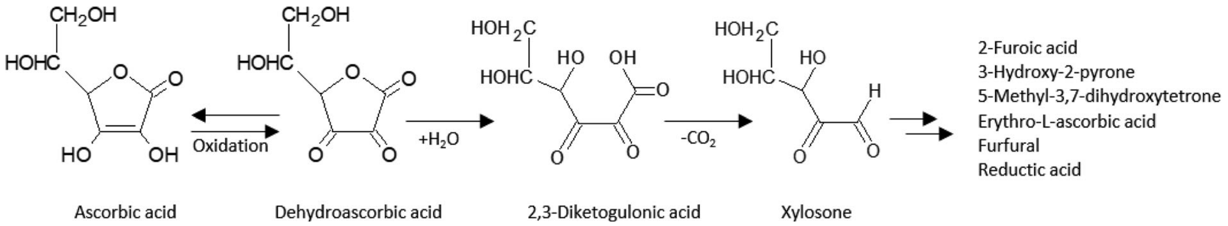

FIGURE 1 Possible degradation pathway of ascorbic acid under aerobic conditions with an indication of the most important reaction intermediates and possible end products (based on Kimoto et al., 1993; Shinoda et al., 2005; Yuan & Chen, 1998)

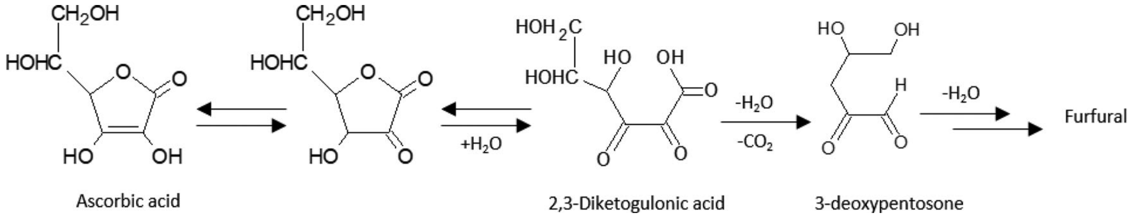

FIGURE 2 Possible degradation pathway of ascorbic acid under anaerobic/low oxygen conditions (based on Kurata & Sakurai, 1967)

an aerobic and anaerobic pathway (Bharate & Bharate, 2014; Corzo-Martínez et al., 2012; Kennedy et al., 1992; Rojas & Gerschenson, 2001). The aerobic degradation pathway (Figure 1) starts with the reversible oxidation of AA to dehydroascorbic acid (DHAA). DHAA is unstable and spontaneously undergoes an irreversible cleavage to 2,3-diketogulonic acid (DKG). DKG can subsequently be decarboxylated to form xylosone, which is later converted to reductones and furan compounds (Corzo-Martínez et al., 2012; Yuan & Chen, 1998). Among these, 2-furoic acid, 3-hydroxy-2-pyrone (3OH2P), and furfural have been identified as the main products from the aerobic degradation of AA. The anaerobic pathway (Figure 2) begins with DKG formation through the keto-tautomer of AA without the formation of DHAA. DKG is subsequently degraded to 3-deoxypentosone, which is converted to furfural in different steps (Kurata & Sakurai, 1967). Alternatively, Yuan and Chen (1998) proposed the cleavage of the lactone ring of AA as a first step, followed by a hydration, decarboxylation, intermolecular rearrangement, and dehydrations to form furfural (Yuan & Chen, 1998). Several authors (Kaanane et al., 1988; Robertson & Samaniego, 1986; Shinoda et al., 2004) reported furfural as a main anaerobic degradation product of AA. Next to this, furfural seems to be formed during the storage of fruit juices at high temperatures as was reported by different authors. Wibowo et al. (2015c) found that furfural was not present in pasteurized (92°C for 30 s) orange juice before storage (i.e., immediately after the pasteurization process) and that furfural was only formed in the orange juice stored at elevated temperature conditions (28 to 42°C, i.e., above room temperature [20°C]). A similar observation was reported by Lee and Nagy (1988) in grapefruit juice. In addition, they concluded that furfural is linked to browning of fruit juices; however, its role in the browning formation is not clear.

As discussed, AA can be degraded via an aerobic and anaerobic pathway. At high oxygen concentrations, the aerobic pathway will dominate and operate at a higher rate than the anaerobic pathway (Berk, 2016; Kennedy et al., 1992; Lee & Nagy, 1996; Rojas & Gerschenson, 2001). Therefore, during storage, the aerobic pathway dominates first when the oxygen is still present at a high concentration, whereas the anaerobic reaction is assumed to dominate in a later phase (Corzo-Martínez et al., 2012). Several authors linked the degradation of AA in different fruit juices (strawberry and orange juice) mainly to the aerobic degradation pathway (Buvé, Kebede, et al., 2018; Polydera et al., 2003; Wibowo et al., 2015c; Zerdin et al., 2003). In contrast, Robertson and Samaniego (1986) reported that the rate of AA degradation in citrus juice was not depending on the initial oxygen level and suggested that the anaerobic AA degradation is predominant and is considered as the most important pathway leading to browning of citrus juices during storage (36°C). Although the rate of aerobic AA degradation has been reported to be 10 times or up to a thousand times the rate of anaerobic degradation pathway (Lee & Nagy, 1996), the contribution of the anaerobic pathway leading to browning of fruit juices should not be underestimated.

The relation of the AA degradation with browning of orange juice was already proposed in the 1930s (Joslyn & Marsh, 1935). Reactive carbonyl compounds such as 3OH2P, furfural, and reductones formed from AA degradation can polymerize with each other to generate brown compounds (Bharate & Bharate, 2014; Paravisini & Peterson, 2016). In the presence of amino acids, these

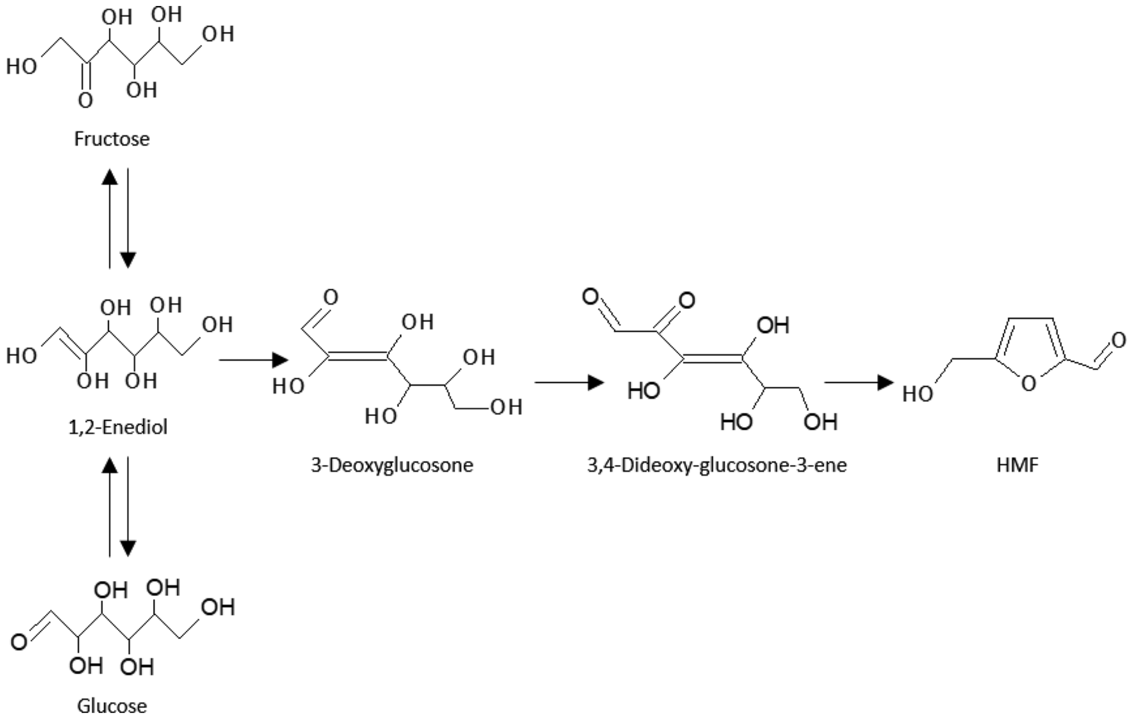

FIGURE 3 Degradation of reducing sugars to HMF under acidic conditions (based on Arena et al., 2001; Belitz et al., 2009)

reactive carbonyl compounds can contribute to browning by reacting with amino acids in Maillard-associated reactions (Corzo-Martínez et al., 2012; Kacem et al., 1987). It was reported that AA degradation was essential for NEB in the early stage of storage and that the presence of amino acids and/or sugars promoted this initial browning (Pham et al., 2021; Shinoda et al., 2005).

2.2 | Acid-catalyzed sugar degradation

The decomposition of sugars under acidic conditions to form reactive intermediates has been proposed to be another mechanism of NEB in fruit juices (Bharate & Bharate, 2014; Paravisini & Peterson, 2019). In acidic matrices like orange juice, the degradation of reducing sugars (e.g., glucose and fructose) (Figure 3) begins with an enolization to form an 1,2-enediol intermediate. This enediol is dehydrated in several steps to form 5-hydroxymethylfurfural (HMF) that is considered as one of the NEB intermediates. Linked to the formation of HMF, Pham et al. (2019) and Wibowo et al. (2015c) reported an increase in the concentration of HMF during storage of orange juice at room (20°C) and elevated storage temperatures (28 to 42°C).

Fructose has been stated to be more reactive than glucose in the formation of HMF because the 1,2-enediol intermediate is formed easier. This is related to the more favorable position of the carbonyl group of fructose compared to glucose (Arena et al., 2001; Shaw et al., 1967). Moreover, Paravisini and Peterson (2019) reported that fructose was the main precursor of other reactive carbonyl compounds such as glyoxal, methylglyoxal, and 3-deoxyglucosone in stored orange juice. They also concluded that the contribution of glucose to the formation of these compounds was lower. Paravisini and Peterson (2019) also stated, for the first time, that acetol and 3-deoxyglucosone were direct key contributors to brown color formation in orange juice during storage. In contrast to fructose and glucose, sucrose does not enter the browning reactions until it is hydrolyzed to the reducing sugars. This hydrolysis is favored by acidic conditions and enhanced at high (storage) temperatures (e.g., 35°C) (Arena et al., 2001; Kennedy et al., 1990; Wibowo et al., 2015c).

There is still debate in the literature about the importance of sugar degradation to the browning of fruit juices. On the one hand, Lee and Nagy (1988) observed a decrease in glucose and fructose content during storage (10 to 50°C) of grapefruit juice thereby suggesting the contribution of reducing sugars to browning of grapefruit juice. Furthermore, they reported that fructose was more reactive than glucose as more fructose was lost at higher storage temperatures (Lee & Nagy, 1988). Recent studies by Paravisini and Peterson (2018, 2019) described the importance of reactive carbonyl compounds (e.g., glyoxal, 3-deoxyglucosone), originating from sugar degradation, to NEB of apple juice and orange juice during storage. Shinoda et al. (2004) observed that an orange juice-based model system containing sugars and amino acids only turned brown after storing for 30 days at 50°C. Hence, they concluded that sugar degradation might be of importance in the later stage of the browning process. The role of sugar degradation in the later browning phase was emphasized again in a recent study by Pham et al. (2021), who observed that the model system containing only sugars (glucose, fructose, and sucrose) turned brown during extended storage (36 weeks at 42°C). Nevertheless, browning of fruit juices due to sugar degradation may occur without transforming large amounts of reducing sugars (Kaanane et al., 1988; Pham et al., 2020a, 2020b; Roig et al., 1999). On the other hand, other authors stated that the contribution of sugar degradation to browning of citrus juices was negligible because an insignificant change in the total sugar content was observed during storage (Kaanane et al., 1988; Kennedy et al., 1990; Robertson & Samaniego, 1986; Roig et al., 1999). Besides, Wibowo et al. (2015c) reported an increase in glucose and fructose content during storage of orange juice at room temperature (20°C) as well as elevated temperatures (28, 35, and 42°C) due to the hydrolysis of sucrose. Kennedy et al. (1990) did not observe any change in individual reducing sugar content during storage of orange juice serum (pH 3.1) at 5°C for 22 days and concluded that there was no hydrolysis of sucrose in these samples. However, when the samples were stored at 38 or 50°C, 70% and 100% of sucrose, respectively, was hydrolyzed, leading to a great increase in reducing sugar content (Kennedy et al., 1990). The hydrolysis of sucrose during storage could also lead to a slight increase in the total reducing sugar content. These increases depend on product-related factors such as the sucrose content and pH, and storage time and temperature. Therefore, the contradictory observations about the changes in sugar content discussed above could be attributed to the differences in the investigated matrices and in the storage conditions. Therefore, any conclusion on the contribution of sugar degradation to NEB through evaluating the change in the reducing sugar content or the total sugar content during storage should be formulated carefully. To better view the sugar-degradation-induced NEB, experiments can be carried out in a model system containing only glucose and/or fructose and measurement of the changes of several attributes such as sugar content, HMF content, and browning index (BI) during storage can be performed.

2.3 | Maillard-associated reactions

The Maillard reactions have been reported as the primary cause of NEB during storage of fruit juices containing high amounts of sugars and low amounts of AA, such as apple juice (Paravisini & Peterson, 2018). The Maillard reactions are initiated by the condensation of a carbonyl group of reducing sugars and the free amino group of amino acids, peptides, or proteins to form an addition product. The formed product is unstable and can enter a series of chain reactions (Berk, 2016; Corzo-Martínez et al., 2012; Nursten, 2005; Rufián-Henares et al., 2009). Different possible pathways of the Maillard reactions have been documented in the literature (Corzo-Martínez et al., 2012; Martins et al., 2008; Nursten, 2005; Rufián-Henares et al., 2009) with nitrogen-containing polymers, the melanoidins, as the final brown compounds from these reactions. Low to medium water activities and neutral to alkaline pH favor these reactions (Martins & Van Boekel, 2005; Rufián-Henares et al., 2009). Ashoor and Zent (1984) showed that below pH 6, the browning in model systems due to reducing sugars and amino acids was not significant. Therefore, this type of Maillard reactions is unlikely to be important in the browning of citrus juices during storage due to low pH values (2.0 to 4.0) and high water activities of the products (Berk, 2016; Clegg, 1964; Kaanane et al., 1988; Stadtman, 1948). However, reactive carbonyl compounds such as AA itself or its degradation products are capable of combining with amino groups and entering the Maillard browning chain (Berk, 2016; Clegg, 1964; Corzo-Martínez et al., 2012; Smuda & Glomb, 2013; Tatum et al., 1969). This pathway is known as Maillard-associated reactions or Maillard-type reactions (Corzo-Martínez et al., 2012). A detailed explanation of the Maillard degradation of AA can be found in the work of Smuda and Glomb (2013). Furthermore, as discussed in the previous section, the acid-catalyzed degradation of sugars also leads to the formation of reactive carbonyl compounds (e.g., HMF, glyoxal, etc.) that can participate in the Maillard-associated reactions (Paravisini & Peterson, 2019).

Besides the effect on the color of fruit juices during storage, the Maillard-associated reactions can contribute to aroma changes that are not the focus point of this review paper. For a comprehensive discussion on aroma changes of orange juice during processing and storage, the readers are referred to the work of Perez-Cacho and Rouseff (2008).

3 | FACTORS AFFECTING NONENZYMATIC BROWNING IN FRUIT JUICES DURING STORAGE

NEB reactions can be affected by many factors related to the inherent properties of juice products and the packaging material and storage conditions. The main juice constituents that result in the browning development are AA, sugars, and amino acids. The contribution of these precursors to NEB is highly dependent on their concentration and the presence of other compounds such as citric acid, metal ions (e.g., copper and iron), oxidants, and reductants in addition to the pH of the product (Sections 3.1 and 3.2). Furthermore, storage conditions including storage temperature and time, packaging material, and oxygen availability can influence the browning reactions (Sections 3.3 and 3.4).

3.1 | Effect of juice constituents

AA, sugars, and amino acids are considered as the main precursors of NEB. It has been reported that NEB in citrus juices occurred faster in concentrated juices compared to single-strength juices (Kanner & Fishbein, 1982; Lee & Chen, 1998). This difference has been attributed to a higher concentration of NEB precursors (e.g., AA) and other compounds (e.g., citric acid) together with a lower pH (see Section 3.2) in the concentrates than in the juice. Table 1 summarizes studies investigating the effect of food-related factors and storage conditions on NEB during storage of fruit juices and model systems.

3.1.1 | Ascorbic acid

Literature data show that browning of citrus juices and model juice systems during storage was found to be proportional to the concentration of AA (Clegg, 1964; Kacem et al., 1987; Roig et al., 1999; Shinoda et al., 2004). This can be explained by a higher formation of reactive degradation products when the concentration of AA is increased (Roig et al., 1999; Shinoda et al., 2005). Pham et al. (2021) and Shinoda et al. (2005) found that AA is essential to induce browning in an orange juice model system. In addition, they also reported that higher concentrations of furfural, 3OH2P, and 2-furoic acid were formed in orange juice model systems when the concentration of AA was higher. It was also observed by Pham et al. (2020b) that supplementation of an orange juice-based model system with AA resulted in a higher formation of furfural and a higher browning intensity of the sample after 4 weeks of storage at 42°C. Similarly, Wibowo et al. (2015b) reported a faster formation of furfural during storage of mango juice when a higher AA concentration was added to the juice. Additionally, the formation of furfural was strongly accelerated by the presence of citric acid, sugars (e.g., glucose), or the decomposition products from sugars, but not by the presence of (extra) amino acids (Shinoda et al., 2005; Wibowo et al., 2015b). In this context, Roig et al. (1996) have stated that care should be taken when AA is added to food products to increase the nutritional value or act as an antioxidant because the addition of AA also increases the degree of browning.

3.1.2 | Sugars

According to Shinoda et al. (2004, 2005), sugars contribute to the browning of orange juice model systems in a later phase of storage (i.e., after 30 days at 50°C). However, it is generally reported that the total sugar loss during storage of juices is relatively small or even negligible (Kaanane et al., 1988; Roig et al., 1999; Wibowo et al., 2015c). Therefore, it can be hypothesized that in citrus juices, only a small fraction of the sugars participate in the browning reactions (Kaanane et al., 1988; Pham et al., 2020a, 2020b; Roig et al., 1999). Nonetheless, Kennedy et al. (1990) showed that the browning intensity of orange juice serum (i.e., the aqueous phase containing soluble compounds such as sugars, vitamin C, and organic acids) stored at 50°C for 5 days increased when adding 15.2 or 30.5 g/L of glucose. As mentioned earlier (Section 2.2), under acidic conditions, fructose is more reactive than glucose in most fruit juices in the formation of intermediates such as HMF (Arena et al., 2001; Shinoda et al., 2005), glyoxal, methylglyoxal, and 3-deoxyglucosone (Paravisini & Peterson, 2018) that are acting as reactive carbonyl compounds in the Maillard-associated browning reactions. Shinoda et al. (2005) reported that HMF was not formed when sugars were not present in an orange juice model system and that sugars stimulate browning development. Moreover, adding more fructose (i.e., increase the initial concentration of fructose 10 times) to an orange-juice-based model system caused an increase in the formation of HMF during storage and resulted in a higher browning intensity of the sample after 6 weeks of storage at 42°C (Pham et al., 2020b).

3.1.3 | Amino acids

Amino acids can accelerate the degradation of AA and sugars to produce brown color during storage of fruit juices (Bharate & Bharate, 2014; Clegg, 1964; Handwerk & Coleman, 1988; Roig et al., 1999). In contrast to AA and sugars, amino acids themselves are no precursors of NEB reaction intermediates (e.g., HMF, furfural, 3OH2P, 2-furoic acid) (Shinoda et al., 2005). Based on this, it can be hypothesized that amino acids on their own are not a source of brown colored compounds. According to Clegg (1964), removal of amino nitrogen by cation exchange delayed the browning of lemon juice. The browning of orange juice semiconcentrates was reduced about three times when the samples were treated with cation exchange (removal

TABLE 1 Examples of studies investigating the effect of food-related factors and storage conditions on NEB during storage of fruit juices and model systems

Matrix	Storage conditions	Investigated factor(s) and effect on browning	Reference
Citrus juice concentrates (orange, lemon, grapefruit, and tangerine)	28, 37, and 45°C, 8 weeks, glass jars	*Storage temperature*: acceleration at higher storage temperatures (37 and 45°C)	Koca et al., 2003
Grapefruit juice	10 to 55°C, 18 weeks, tin-plated cans and glass bottle	*Storage temperature*: Nonbrowning at 10 and 20°C, acceleration at higher storage temperatures (30 to 55°C) *Packaging materials*: Faster and more intensive browning in botted juices and in canned juice	Nagy et al., 1990
Grape juice concentrate	55, 65, and 75°C, 10 days, glass tubes	*Storage temperature*: the rate constant of brown pigment formation increased when increasing the storage temperature	Bozkurt et al., 1999
Lemon juice and lemon juice model systems	37°C, 21 days, glass jars	*Ascorbic acid*: stimulation *Amino acids*: stimulation *pH (2.5 to 7.0)*: maximum browning at pH 4.5 *Citric acid*: stimulation	Clegg, 1964 Clegg, 1966
Lemon juice	37°C, 6 weeks, glass jars	*Initial dissolved oxygen concentration (0.41, 1.44, and 3.74 mg/L)*: no effect on browning intensity	Robertson & Samaniego, 1986
Orange juice serum	5°C, 35 days;38°C, 19 days;50°C, 18 days;glass vials	*Ascorbic acid*: essential *Lysine*: stimulation (when stored at 50 °C) *Glucose*: stimulation (when stored at 50°C) *Sorbitol*: no effect *pH (1.15, 1.95, 4.15, 7.00)*: higher browning at pH 1.15, 4.15, and 7.00 *Storage temperature*: no browning at 5°C, acceleration at higher storage temperatures (38 and 50°C)	Kennedy et al., 1990
Orange juice-based model system	42°C, 8 weeks, glass jars	*Ascorbic acid*: stimulation *Fructose*: stimulation *Arginine*: no effect *pH (1.5, 2.5, 3.8, 4.5)*: higher browning intensity in the later phase of storage at pH 1.5 and 2.5	Pham et al., 2020b
Orange juice model systems	50°C, 2 months, glass vials	*Ascorbic acid*: essential *Amino acids*: stimulation *Sugars*: limited stimulation *Citric acid*: stimulation*No headspace*: stimulation	Shinoda et al., 2004, 2005
Orange juice	20°C, 1 month, glass jars	*pH (3.2 to 7)*: browning increased when increasing the pH from 3.2 to 6	Berlinet et al., 2006
Orange juice	22°C, 22 weeks, glass vials	*Initial dissolved oxygen concentration (0.6 to 10.1 ppm)*: linear relationship	Trammell et al., 1986
Orange juice	20 to 42°C,8 to 32 weeks, PET bottle	*Storage temperature*: a faster decrease on the lightness at higher storage temperatures	Wibowo et al., 2015d
Peach juice	4, 25, and 37°C, 40 days, PET bottle	*Storage temperature*: browning degree increased faster at higher storage temperatures	Lyu et al., 2018

(Continues)

TABLE 1 (Continued)

Matrix	Storage conditions	Investigated factor(s) and effect on browning	Reference
Peach juice concentrate	3 to 37°C, up to 118 days, 12 to 89 Brix	*Storage temperature*: Higher browning rate at higher storage temperature *Soluble solid concentration (Brix)*: Browning rate increased with increasing total soluble solids in the range of 12 to 81 (°Brix), further increase in total soluble solids 89 (°Brix) led to a decrease in browning	Buedo et al., 2000

of approximately 98% of the amino acids with minimum losses in other juice constituents) (Sharma et al., 2014). In addition, the effect of amino acids on browning was found to be linear with concentration and was more pronounced at a higher concentration of AA (Kacem et al., 1987). The latter observation suggests that amino acids promote NEB reactions, as was also reported by Shinoda et al. (2005) and Pham et al. (2021) for orange juice model systems. Among different major amino acids in orange juice (e.g., serine, asparagine, alanine, arginine, proline, glutamic acid), arginine and proline were found to be the most effective ones on the browning of an orange juice model system (Shinoda et al., 2004). In the context of browning, these authors suggested that the Maillard-associated reactions between AA degradation products and amino acids play an important role. However, it is worth noting that browning of orange juice and other fruit products can occur without transforming large amounts of amino acids (Stadtman, 1948). As observed by Pham et al. (2020b), adding more arginine to an orange juice-based model system did not show any significant change in browning compared to the sample without addition. These authors hypothesized that the naturally present amino acids in the juice-based model system were sufficient for the NEB reactions to take place.

3.1.4 | Organic acids

Citric acid has been reported to promote the degradation of AA and corresponding browning (Clegg, 1966). Removal of citric acid from a model orange juice system decreased its browning by about half (Shinoda et al., 2005). In addition, the authors also reported that the presence of citric acid in an orange juice model system (with AA, sugars, and amino acids at pH 3.0) promoted the formation of HMF, but repressed the formation of 3OH2P. From this observation, it was concluded that citric acid repressed the aerobic degradation of AA and accelerated the anaerobic degradation (see Section 2.1). In addition, the presence of large amounts of organic acids (e.g., citric acid) favors the degradation of reducing sugars by promoting the enolization of the sugars (Lee & Nagy, 1990). These authors reported that the formation of HMF from fructose was five times faster in the presence of citric acid. Despite the reported observations, the exact role of citric acid in brown compound formation is not yet fully elucidated (Adams & Brown, 2007). Shinoda et al. (2004) reported a stimulation effect of citric acid on browning, whereas others have suggested that citric acid does not act as a catalyst or as a source of carbonyl compounds (Berk, 2016; Clegg, 1966).

3.1.5 | Metal ions, oxidants, and reductants

Besides the aforementioned constituents, browning of fruit juices can also be affected by other compounds such as metal ions, oxidants, and reductants. The role of these compounds in the degradation of AA, one of the main precursors of brown compounds, has been reported extensively in literature (Serpen & Gökmen, 2007; Shinoda et al., 2004). Shinoda et al. (2004) added Fe^{2+} or Cu^{2+} ions to an orange juice model system. The presence of these metal ions promoted browning in the first phase of storage compared to a control sample without metal ions. According to Serpen and Gökmen (2007), the presence of an oxidizing (Fe^{3+} ions) or reducing (cysteine) agent seems to have a significant effect on the rate of oxidation/reduction in the degradation pathway of AA. The presence of metal ions seems to accelerate browning linked to the Maillard reactions. However, the extent to which these reactions are affected depends on the type of ion, the amino acid involved, and heating time (Kwak & Lim, 2004; Ramonaityte et al., 2009).

3.1.6 | Insoluble fruit juice fractions

Although fruit juices are heterogeneous multiphase systems consisting of a serum, cloud, and pulp fraction (Ringblom, 2004; Ting & Rouseff, 1986), the contribution of the different fractions toward NEB has only recently being investigated (Pham et al., 2019, 2020a). The serum is a clear aqueous phase containing soluble compounds such as sugars, organic acids (e.g., AA and citric acid), and amino acids, whereas the cloud and pulp are an insoluble phase that is made up of mainly insoluble compounds such as proteins and polysaccharides (Brat et al., 2003; Ting & Rouseff, 1986).

In relation to the importance of the different fractions to NEB of orange juices during storage, a recent publication by Pham et al. (2019) showed that the brown-colored compounds formed during accelerated storage (42°C) of orange juice were present in the serum, cloud, and pulp. However, when these fractions were stored separately, only the orange juice serum turned brown, whereas the orange juice cloud and pulp did not (Pham et al., 2020a). Therefore, they concluded that the soluble compounds in orange juice serum play an important role in browning and that the brown compounds present in the cloud (after storage of the whole juice) were associated with proteins, arabinogalactan proteins, and/or protein–pectin complexes (Pham et al., 2019). Further studies focusing on the importance of the different fractions in NEB are highly recommended.

3.2 | Effect of pH

The effect of pH on the degradation of NEB precursors (e.g., AA and sugars) and the formation of NEB intermediates (e.g., furfural and HMF) in fruit juices and model systems has been investigated by several researchers (Berlinet et al., 2006; Clegg, 1964; Kennedy et al., 1990; Pham et al., 2020b; Shallenberger & Mattick, 1983; Yuan & Chen, 1998). Kennedy et al. (1990) observed a low AA retention in orange juice serum during storage at 5, 38, and 50°C when the pH of the juice (3.1) was adjusted to a more acidic pH (1.15 or 1.95) or a less acidic pH (4.15 or 7.0). When investigating the effect of pH values (1.5, 2.5, 3.8, and 4.5) on AA degradation in an orange juice-based model system during storage at 42°C, Pham et al. (2020b) reported the highest degradation rate constant at pH 4.5 followed by the one at pH 1.5. At pH values above the first pK_a of AA (pK_a = 4.1 to 4.2), this compound is mainly present in the monoionic form that is inherently unstable (Herbig & Renard, 2017; Lee et al., 1977; Tikekar et al., 2011). This could explain the low retention of AA at pH values close to its first pK_a. No clear explanation was found in the literature for the instability of AA at a very low pH value such as pH 1.15. The pH of the sample will influence the stability of AA and the type of AA degradation products (Yuan & Chen, 1998). The same authors stated that low pH conditions favored the formation of furfural, 2-furoic acid, and 3OH2P, whereas the formation of furfural was found to dominate at extremely low pH (i.e., pH 1). At pH 10, no 2-furoic acid was detected and only small amounts of furfural and 3OH2P were formed (Yuan & Chen, 1998). However, such a high pH value (pH 10) is not within the typical pH range of fruit juices.

Regarding the effect of pH on the changes of sugars in orange-juice-based model systems during storage, a faster hydrolysis of sucrose to glucose and fructose was reported when the pH of the sample was lowered from 3.10 to 1.15 or 1.95 (Kennedy et al., 1990) or from 3.8 to 2.5 (Pham et al., 2020b). This is not surprising as sugars are prone to an acid-catalyzed degradation (Section 2.2). Shallenberger and Mattick (1983) investigated the stability of glucose and fructose in model systems under acid pH (pH value from 1 to 6) and showed that glucose and fructose became less stable below pH 2 and pH 4, respectively. Furthermore, acidic conditions favored the formation of HMF. Compared to pH 4 to 6, the rate of HMF formation from fructose was reported to be double at pH 3, 10 times as fast at pH 2 and 40 times as fast at pH 1 (Shallenberger & Mattick, 1983).

The effect of pH/acidity on browning of fruit juices has been investigated by several research groups, yet the obtained results are not fully consistent (Joslyn & Marsh, 1935; Kennedy et al., 1990; Pham et al., 2020b; Rassis & Saguy, 1995; Roig et al., 1999). Overall, most authors observed a faster browning when the pH is lowered. For instance, Joslyn and Marsh (1935) stated that lowering the pH of fruit juices increased the juice darkening during storage. Furthermore, Berk (2016) reported that lemon juice is more prone to browning than grapefruit juice and orange juice and this difference was attributed to, together with other factors, the lower pH of lemon juice (a typical pH range of 2.2 to 2.5) compared to grapefruit juice (pH 3.0 to 3.5) and orange juice (pH 3.1 to 3.8) (Berk, 2016). This is in accordance with the results from Rassis and Saguy (1995) and Roig et al. (1999) who showed a faster browning in grapefruit juice than in orange juice and also attributed this to the lower pH of the former one. Nonetheless, other factors such as a higher initial AA concentration and citric acid concentration in the investigated grapefruit juice compared to orange juice could contribute to the difference in browning formation during storage (Rassis & Saguy, 1995; Roig et al., 1999). A study of Clegg (1964) on the effect of pH (2.5 to 7.0) on the browning of lemon juice and model systems after 5 and 21 days of storage at 37°C also confirmed that the degree of browning was influenced by the pH value of the product. Although browning occurred at the natural pH of the lemon juice (pH 2.5), a maximum browning was obtained at pH 4.5 (Clegg, 1964). While it was reported that adjusting the pH of the orange juice model system from 3.10 to pH 1.15, 4.15, or 7.00 but not 1.95 lead to a faster onset of browning formation at elevated storage temperatures (38 and 50°C) (Kennedy et al., 1990). A higher browning intensity of the orange-juice-based model system was also observed after 4 and 6 weeks of storage at 42°C when lowering the pH of the sample from 3.8 to 1.5 and 2.5, respectively (Pham et al., 2020b). The effect of pH on NEB of fruit juices should thus be carefully considered taking into account the investigated matrices and storage conditions.

3.3 | Effect of oxygen availability

In packed fruit juices, oxygen can be present as dissolved oxygen that is incorporated in the juices during processing and packing and as gaseous oxygen in the headspace of the package (Bacigalupi et al., 2013; Kacem et al., 1987). Depending on the characteristics of the packaging material, oxygen can diffuse from the surrounding environment into the juices during storage (Bacigalupi et al., 2013; Zerdin et al., 2003).

Oxygen can indirectly affect the NEB reactions in fruit juices through the oxidation of AA to DHAA (Section 2.1), which is further degraded to form reactive carbonyl compounds and eventually can lead to the formation of brown pigments (García-Torres et al., 2009). Despite this mechanistic information, different conclusions about the effect of oxygen on AA degradation and NEB have been formulated in literature. It was reported by Solomon et al. (1995) that the rate of AA oxidation was significantly correlated with the level of dissolved oxygen. Likewise, the results from a study by Trammell et al. (1986) on orange juice showed a linear relationship between the initial dissolved oxygen concentration (0.6 to 10.1 mg/l) and AA loss and browning during 22 days of storage at 22°C. The effect of higher AA concentrations on NEB was enhanced when more oxygen was available (Kacem et al., 1987). In contrast, Robertson and Samaniego (1986) observed that there was no effect of different initial dissolved oxygen concentrations (0.41, 1.44, and 3.74 mg/L) on the rate constant of AA degradation, furfural formation, and browning development in lemon juice stored at 36°C for 6 weeks. However, the lag period before browning became visual was prolonged for the samples with lower initial dissolved oxygen concentrations. These authors also concluded that anaerobic degradation was the major pathway of AA breakdown at the investigated storage conditions and that the degradation of other compounds (e.g., sugars), besides AA, might contribute to the formation of brown polymers (Robertson & Samaniego, 1986).

The effect of different packaging materials in relation to oxygen availability on the degradation of AA and browning of fruit juices during storage was intensively investigated in the literature (Berlinet et al., 2006; Buvé, Kebede, et al., 2018; Kacem et al., 1987; Nagy et al., 1990; Zerdin et al., 2003). Packages with low oxygen permeability greatly reduced AA degradation and browning formation during storage of pasteurized orange juice (Berlinet et al., 2006), orange drinks (Kacem et al., 1987), single strength grapefruit juice (Nagy et al., 1990), and pasteurized strawberry juice (Buvé, Kebede, et al., 2018). Berlinet et al. (2006) stated that glass packaging materials provided better preservation of AA, whereas in plastic packaging materials (e.g., PET), the losses of AA were correlated with their oxygen permeability. A long-term storage study (1 year at 25°C) carried out on Not-From-Concentrate orange juice packed in an oxygen scavenging film and in an oxygen barrier film showed a slower browning process and AA loss for the juice in the first package compared to the latter one. This was attributed to the quick removal of the dissolved oxygen in the juice by the oxygen scavenger, thereby becoming less available for oxidation of AA (Zerdin et al., 2003). In addition to the use of oxygen scavengers, there are other possible ways of oxygen removal such as deaeration, vacuum packaging (García-Torres et al., 2009), or the juice can be processed under low oxygen conditions in, for example, a spiral-filter press (Buvé, Kebede, et al., 2018). However, it was also stated that although low levels of dissolved oxygen could decrease the rate of oxidation of AA, the shelf-life of orange juice may not be significantly extended due to the anaerobic AA degradation occurring in the absence of oxygen (Kennedy et al., 1992). The reader is referred to the review of García-Torres et al. (2009) for more details on the impact of dissolved oxygen on the quality of fruit juices.

3.4 | Effect of storage conditions

Storage temperature, storage time, and light (in relation to packaging material) are the main storage-related factors that may affect NEB of fruit juices. Storage temperature is considered as the most important factor influencing browning in fruit juices (Berk, 2016; Kennedy et al., 1990; López-Gómez et al., 2010; Stadtman, 1948). Several authors showed that browning is strongly accelerated at higher storage temperatures and longer storage times, and hence, is the major shelf-life determining factor of fruit juices during prolonged storage under nonrefrigerated conditions (Berk, 2016; Buvé, Kebede, et al., 2018; Lee & Nagy, 1988; Wibowo et al., 2015c; Zerdin et al., 2003).

To give the reader an idea about the impact of storage on the stability of vitamin C and sugars in fruit juice/concentrate, the results of different studies are summarized in Tables 2 and 3, respectively. In these tables, the matrix, the storage conditions, the change in concentration of compound, and the availability of kinetic parameters are listed. The availability of kinetic parameters is very useful to quantitatively describe the change in concentration of vitamin C and sugars and to make predictions. Tables 2

TABLE 2 Degradation of ascorbic acid (AA) as affected by the type of fruit juice/concentrate and storage conditions

Matrix	Storage conditions	Initial AA concentration	Loss of AA	Kinetic parameters[a] (units: k [weeks^{-1}]; E_a [kJ/mol]	Reference
Grapefruit concentrate (59 °Brix, pH = 2.56)	28°C, dark, 8 weeks, glass jars37°C, dark, 8 weeks, glass jars45°C, dark, 8 weeks, glass jars	206 mg/100 g	30% 73% 85%	$k = 0.0470 \pm 0.0067$ $k = 0.1626 \pm 0.0197$ $k = 0.2420 \pm 0.0184$ $E_a = 76.86 \pm 4.519$	Burdurlu et al., 2006
Lemon concentrate (44.5 °Brix, pH = 1.82)	28°C, dark, 8 weeks, glass jars37°C, dark, 8 weeks, glass jars45°C, dark, 8 weeks, glass jars	225 mg/100 g	45% 76% 80%	$k = 0.0670 \pm 0.0059$ $k = 0.1830 \pm 0.0041$ $k = 0.2070 \pm 0.0330$ $E_a = 53.43 \pm 4.058$	Burdurlu et al., 2006
Mango juice (pH = 4.02, Brix not reported)	42°C, dark, 8 weeks, PET bottle	13 mg/l	35%	$k = 0.04 \pm 0.02$	Wibowo et al., 2015b
Orange concentrate (61 °Brix, pH = 3.23)	28°C, dark, 8 weeks, glass jars37°C, dark, 8 weeks, glass jars45°C, dark, 8 weeks, glass jars	233 mg/100 g	16% 78% 83%	$k = 0.0276 \pm 0.0108$ $k = 0.1850 \pm 0.0133$ $k = 0.2550 \pm 0.0287$ $E_a = 105.27 \pm 17.95$	Burdurlu et al., 2006
Orange juice (11.01 °Brix, pH = 3.72)	20°C, dark, 8 weeks, PET bottle42°C, dark, 8 weeks, PET bottle	433 mg/L	32% 74%	$k = 0.060 \pm 0.002$ $E_a = 44.59 \pm 2.06$	Wibowo et al., 2015c
Orange juice (pH and brix not reported)	15°C, 30 days, polypropylene bottle30°C, 30 days, polypropylene bottle	~55 mg/100 mL	36% 12%	$k = 0.2401 \pm 0.0066$ $k = 0.5005 \pm 0.0468$	Polydera et al., 2005
Strawberry juice (7.50 °Brix, pH = 3.58)	20°C, dark, 8 weeks, PET bottle42°C, dark, 8 weeks, PET bottle20°C, dark, 8 weeks, multilayer PET bottle	438 μg/g juice	21% 44% 11%	$k_{20\,^{\circ}C} = = 0.019 \pm 0.003$; $E_a = 41.1 \pm 8.7$ - (can be calculated using $k_{20^{\circ}\mathrm{C}}$ and E_a value) $k_{20\,^{\circ}C} = 0.007 \pm 0.002$; $E_a = 69.6 \pm 10.3$	Buvé, Van Bedts, et al., 2018
Tangerine concentrate (59.5 °Brix, pH = 3.23)	28°C, dark, 8 weeks, glass jars37°C, dark, 8 weeks, glass jars45°C, dark, 8 weeks, glass jars	98 mg/100 g	34% 76% 85%	$k = 0.0460 \pm 0.0033$ $k = 0.1670 \pm 0.0108$ $k = 0.2480 \pm 0.0297$ $E_a = 79.24 \pm 3.096$	Burdurlu et al., 2006

The initial AA concentration and percentage of loss are presented. If available, the kinetic parameters (reaction rate constant k and/or activation energy E_a) to describe the change in AA are also included (- not available). If reported in the original reference, the pH and Brix of the sample were included in the table.

[a] Obtained using a first-order kinetic model $C = C_0 \exp(-kt)$ in combination with the Arrhenius equation $k = k_{T_{ref}} \exp[\frac{E_a}{R}(\frac{1}{T_{ref}} - \frac{1}{T})]$.

TABLE 3 Change in sugar content as affected by the type of fruit juice/concentrate and storage conditions

Matrix	Storage conditions	Initial sugar concentration	Change in sugars	Kinetic parameters	Reference
Grapefruit juice (10.2 °Brix, pH 3.34)	10°C, 15 weeks, can	fructose 2.44 g/100 mL glucose 2.32 g/100 mL	+0.41%+0.43%	–	(Lee & Nagy, 1988)
	20°C, 15 weeks, can	fructose 2.44 g/100 mL glucose 2.32 g/100 mL	+7.9%+8.3%	–	
	30°C, 15 weeks, can	fructose 2.44 g/100 mL glucose 2.32 g/100 mL	+27.6%+31.0	–	
	40°C, 15 weeks, can	fructose 2.44 g/100 mL glucose 2.32 g/100 mL	+31.0%+34.6%	–	
	50°C, 15 weeks, can	fructose 2.44 g/100 mL glucose 2.32 g/100 mL	+30.7%+34.1%	–	
Mango juice (pH = 4.02, Brix not reported)	42°C, dark, 8 weeks, PET bottle	sucrose 31.2 g/L fructose 19.4 g/L glucose 9.43 g/L	−52.3%+38.5% +8.8%	$k = 0.0044 \pm 0.0007$ [b] $k = 0.20 \pm 0.17$ [c] $k = 0.14 \pm 0.08$ [c]	(Wibowo et al., 2015b)
Orange juice model system	5°C, 22 days, glass vial	sucrose 40.3 g/L fructose 25.5 g/L glucose 24.6 g/L	−3.7%+0.7% +5.0%	–	(Kennedy et al., 1990)
	38°C, 22 days, glass vial	sucrose 40.3 g/L fructose 25.5 g/L glucose 24.6 g/L	−72.0%+39.6% +40.9%	–	
	50°C, 22 days, glass vial	sucrose 40.3 g/L fructose 25.5 g/L glucose 24.6 g/L	−100%+47.3% +49.5%	–	
Orange juice (11.01 °Brix, pH = 3.72)	20°C, dark, 8 weeks, PET bottle	sucrose 31.4 g/L fructose 20.8 g/L glucose 15.9 g/L	−16.8%+11.2% +41.3%	$k = 0.0008 \pm 3.1 \times 10^{-5}$ [b]; $E_a = 108.23 \pm 2.33$ kJ/mol $k = 0.29 \pm 0.01$ [a]; $E_a = 88.02 \pm 1.79$ kJ/mol $k = 0.21 \pm 0.01$ [a]; $E_a = 96.27 \pm 3.34$ kJ/mol	(Wibowo et al., 2015c)
	42°C, dark, 8 weeks, PET bottle	sucrose 31.4 g/L fructose 20.8 g/L glucose 15.9 g/L	−98.2%+139.1 +166.9%	- (can be calculated using $k_{20\,°C}$ and E_a value; see row above)	

Formation of a sugar is represented by a positive percentage, whereas degradation is represented by a negative percentage. The initial sugar concentrations and percentage of change are presented. If available, the kinetic parameters (reaction rate constant k and/or activation energy E_a) to describe the change in AA are also included (- not available). If reported in the original reference, the pH and Brix of the sample were included in the table.

[a] Modeled with a zero-order model $C = C_0 - kt$; unit of k [g/L].

[b] Modeled with a second-order model $C = \frac{C_0}{1+C_0 kt}$; unit of k [L/g weeks] in combination with the Arrhenius equation $k = k_{T_{ref}} \exp[\frac{E_a}{R}(\frac{1}{T_{ref}} - \frac{1}{T})]$.

[c] Modeled with a first-order fractional conversion model $C = C_\infty + (C_0 - C_\infty)\exp(-kt)$; unit of k [weeks^{-1}].

and 3 show that the rate of AA and sugar degradation (i.e., *k* value) depends on the storage conditions (time, temperature, and packaging) as well as the characteristics of the matrix. Comparing the data of different publications gives a good idea about the behavior of a food constituent, but it should be done with caution as experimental conditions are mostly different. Kinetic parameters describing changes in sugar content (Table 3) are less abundant in the literature compared to those describing changes in AA (Table 2). The nature of the sugar determines its stability during storage, with sucrose being more stable compared to glucose and fructose. As both AA and sugars are linked to NEB, the rate of degradation of these precursors will determine, together with other parameters, how the color of the fruit juice will change.

Storage temperature directly affects the degradation rate of AA and sugars and enhances the effect of other factors such as oxygen and pH (Buvé, Kebede, et al., 2018; Kaanane et al., 1988; Roig et al., 1996, 1999; Wibowo et al., 2015c; Zerdin et al., 2003). It is generally reported that AA degradation in fruit juices or concentrates increases as the storage temperature increases (Table 2, represented by the activation energy E_a value) (Burdurlu et al., 2006; Buvé, Kebede, et al., 2018; Kaanane et al., 1988; Lee & Chen, 1998; Polydera et al., 2003, 2005; Roig et al., 1999; Wibowo et al., 2015c). A higher E_a value indicates that the reaction rate constant is more temperature-sensitive. For instance, more than 75% of AA of pasteurized shelf-stable orange juice decreased after storing for 32 weeks at 20°C, which was comparable to the amount that decreased after 8 weeks at 42°C (Wibowo et al., 2015c). A 44% reduction in AA content of pasteurized strawberry juice during 8 weeks of storage at 42°C in standard PET bottles was observed by Buvé, Kebede, et al. (2018). The same work reported that storage at 20°C for 8 weeks resulted in a loss in AA concentration of 21%. The accelerating effect of storage temperature on sugar and AA degradation during storage of orange juice can also be seen in Figures 4(a)–(c) and (e). The effects of oxygen and pH on AA degradation in orange juice have been reported to be more pronounced at higher storage temperatures (Kennedy et al., 1990; Nagy et al., 1990; Zerdin et al., 2003). Like AA, the change in sugar concentration of fruit juices increased with increasing storage temperature (Table 3) (Kaanane et al., 1988; Kennedy et al., 1990; Lee & Nagy, 1988; Wibowo et al., 2015c). Kaanane et al. (1988) observed that sucrose hydrolysis did not occur when the orange juice was stored at 4°C, whereas a complete hydrolysis of sucrose was reached after 30 days at 45°C. Likewise, Wibowo et al. (2015c) reported a higher hydrolysis of sucrose for an orange juice stored at elevated temperatures (28, 35, and 42°C) compared to the juice stored at room temperature (20°C) (Figure 4**c**). As a result, more reducing sugars were formed when the juice was stored at higher temperatures (Kaanane et al., 1988; Lee & Nagy, 1988; Wibowo et al., 2015c). Also, Lee and Nagy (1988) reported that 5% and 9% of the sugars in grapefruit juice were lost after 15 weeks of storage at 30 and 50°C, respectively, thereby showing that the total sugar loss was also influenced by storage temperature.

As the degradation of NEB precursors such as AA and sugars in fruit juices is affected by storage temperature and time, these factors will also influence the formation of their degradation products (e.g., furfural and HMF) and thus the browning of the juice (Figure 4c, f). Furfural is the main degradation product of AA through the anaerobic pathway, whereas HMF is mainly formed from sugar degradation (Shinoda et al., 2004). Both of them were absent in pasteurized nonstored citrus juices and concentrates (Burdurlu et al., 2006; Lee & Nagy, 1988; Wibowo et al., 2015c). It was reported by Marcotte et al. (1998) that furfural and HMF can only be detected in heat-treated products after more severe thermal treatments than what is usually applied for industrial pasteurization of high acid products such as fruit juices. In case of fruit juices and concentrates, many studies reported that furfural and HMF were not formed in the pasteurized products prior to the storage (Burdurlu et al., 2006; Pham et al., 2019, 2020a; Wibowo et al., 2015c). However, their concentration increased with storage time and their formation was accelerated by higher storage temperatures (Figure 4d, f) (Burdurlu et al., 2006; Lee & Nagy, 1988; Wibowo et al., 2015c). Lee and Nagy (1988) reported that when the storage temperature was increased from 10 to 50°C, the amount of furfural accumulated in the grapefruit juice after 15 weeks of storage and increased approximately 390 times. Similarly, HMF was not formed during 15 weeks storage at 10°C, whereas the amount of HMF formed after 15 weeks at 30°C was 2.9 μg/mL that increased to over 303.5 μg/L for the same storage period at 50°C. 3OH2P is another degradation product of AA and is also considered as one of the NEB intermediates (Shinoda et al., 2004, 2005). Shinoda et al. (2004) observed that the concentration of 3OH2P was zero in a nonstored model orange juice system and increased in the first 3 days of storage at 50°C, and then decreased to almost zero after 60 days of storage. The disappearance of 3OH2P suggested that it might be used for browning reactions (Shinoda et al., 2004). The rate of browning of citrus juices and concentrates and other fruit juices is also temperature-dependent, whereas the browning intensity (as can be indicated by several parameters as discussed in Section 4) increases with storage time (Buvé, Kebede, et al., 2018; Kennedy et al., 1990; Koca et al., 2003; Wibowo et al., 2015c; Zerdin et al., 2003).

Light is another storage factor that may affect color changes and related reactions in fruit juices during storage. However, only a limited number of studies were carried

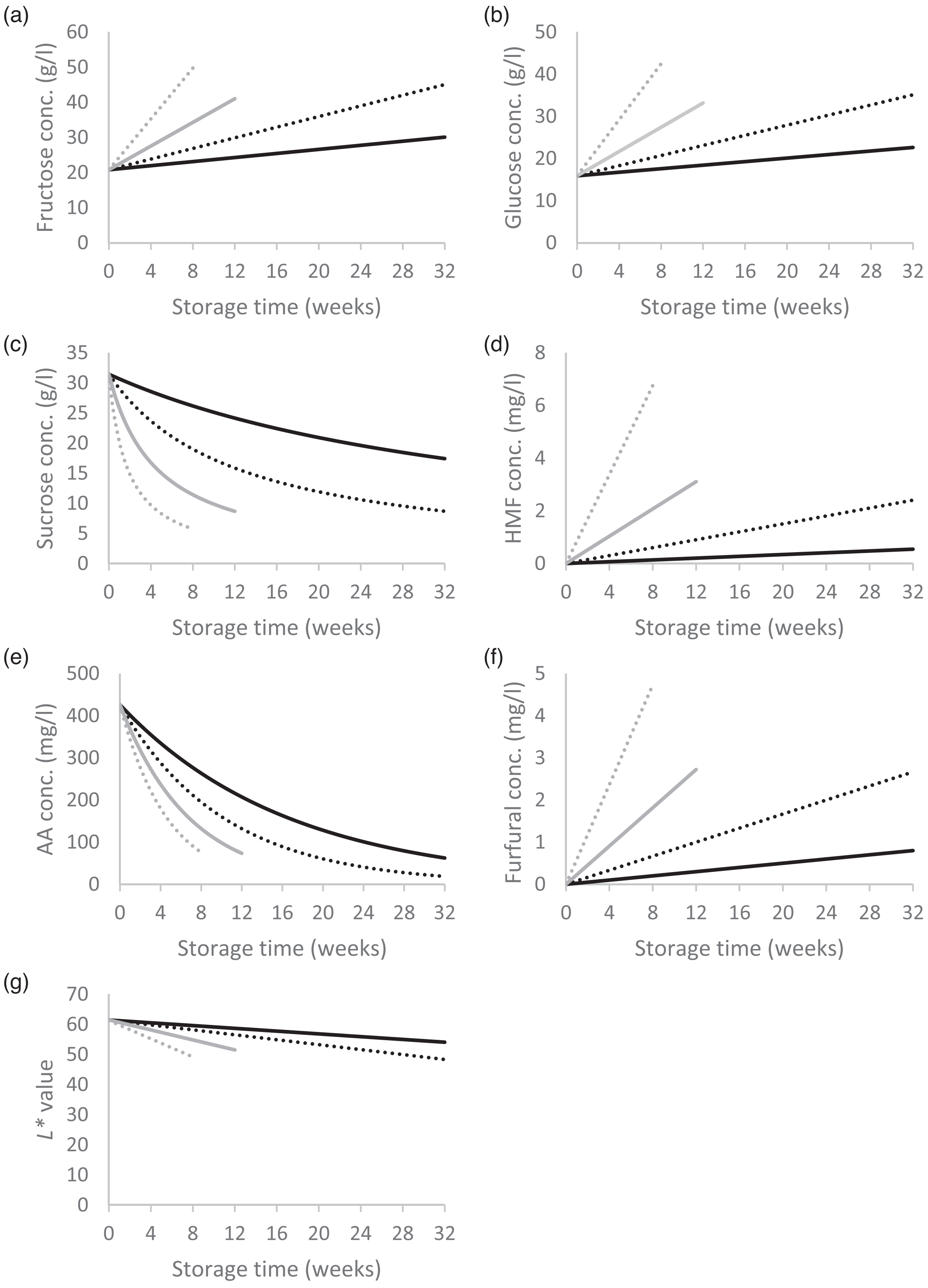

FIGURE 4 Visualization of the change of some important NEB precursors (fructose, glucose, sucrose, and AA) and reaction products (HMF and furfural) (a–f) and change in L^* value (g) during storage of pasteurized orange juice at 20°C ▬▬ (full black line), 28°C ⋯⋯ (black dotted line), 35°C ▬▬ (full gray line), and 42°C ⋯⋯ (gray dotted line). The plots are based on the kinetic parameters reported by Wibowo et al., 2015c, 2015d). Fructose, glucose, HMF, furfural, and L^* were plotted using a zero-order kinetic model, AA with a first-order kinetic model, and sucrose with a second-order kinetic model

out on fruit juices (Ahmed et al., 1976; Sattar et al., 1989; Solomon et al., 1995). Sattar et al. (1989) reported a higher loss of AA (60.6%) for a pasteurized orange drink packed in clear glass and exposed to cool-white fluorescent light for 32 days at room temperature compared to the unexposed control juice (42.4% loss of AA). However, a study on orange juice stored in glass containers with airtight lids at 8°C for 52 days showed no significant difference in AA degradation between the samples that were exposed and not exposed to light. Moreover, no browning due to the light exposure was observed in the juice under the investigated conditions (Solomon et al., 1995). The stability of natural pigments, such as carotenoids and anthocyanins, to light can also result in color changes (Boon et al., 2010; Mercadante & Bobbio, 2008). This effect will not be discussed in this review paper.

4 | EVALUATION OF COLOR CHANGES AND BROWNING

Different techniques have been used in the literature to directly or indirectly assess browning and color changes in fruit juices. It has been described in previous sections that NEB involves multiple chemical reactions resulting in a brown color formation in food products. Consequently, researchers have used different approaches (from model systems to real systems) in trying to characterize color changes and browning (Section 4.1). The occurrence of NEB can be evaluated directly through the measurement of the color changes and the development of brown color (Section 4.2) or indirectly by quantifying/analyzing the changes in different compounds that are proposed to be NEB precursors (e.g., AA) or intermediates (e.g., furfural) (Section 4.3). Table 4 summarizes the studies measuring different NEB-related attributes during storage of fruit juices and juice model systems.

4.1 | Strategies to study color changes and nonenzymatic browning

Several approaches and techniques have been applied by food scientists when trying to characterize NEB during storage. Many researchers investigated browning of real fruit juices (e.g., Buvé, Kebede, et al., 2018; Pham et al., 2019; Wibowo et al., 2015c). As highlighted before, browning of fruit juices is a complex problem due to the high number of compounds and reactions that could be involved. To reduce the complexity and obtain fundamental insights, scientists can opt to use fruit juice model systems instead of real systems. Several papers studying browning of fruit juices using model systems have already been published (e.g., Kennedy et al., 1990; Pham et al., 2020b; Pham et al., 2021; Shinoda et al., 2005; Shinoda et al., 2004). Upon formulation of the model system, food scientists should carefully evaluate which compounds to be added and the concentrations. In relation to the formulation of fruit juice model systems, labeled compounds (e.g., ^{13}C or ^{15}N browning precursors such as AA, sugars, or amino acids) can be added to obtain further mechanistic insights into NEB. Adding labeled compounds and identification (and quantification) of formed reaction products will allow to determine how a labeled compound is degraded (i.e., which atoms in the precursor are reactive) and how it is further reacting to eventually result in brown-colored compounds. In this context, the use of advanced analytical equipment (e.g., NMR, LC-TOF-MS, and GC-MS) is required to unravel the reaction pathways and to identify reaction products. The results of both approaches (i.e., model and real systems) are valuable and complementary and researchers must carefully consider the advantages and disadvantages of both.

When studying browning of shelf-stable fruit juices, it can take some time before the color starts to darken. To speed up color changes, an accelerated shelf-life test (ASLT) can be performed during which the samples are stored at abuse storage conditions (e.g., higher temperatures) (Buvé, Kebede, et al., 2018; Pham et al., 2019; Pham et al., 2020a, 2020b; Wibowo et al., 2015a to 2015d). When performing an ASLT, one should carefully select the storage conditions to ensure that reactions are only accelerated and that no new reactions are being initiated.

4.2 | Measurement of color changes and brown color formation

The overall color changes and brown color formation in fruit juices during storage can be evaluated directly through visual assessments and instrumental analyses (Buvé, Kebede, et al., 2018; Buvé, Van Bedts, et al., 2018; Meléndez-Martínez et al., 2005; Wibowo et al., 2015c, 2015d). A visual assessment is a fast method that can describe the color of a product, the color changes, and the formation of browning. Nonetheless, as this method is subjective and can be biased (Meléndez-Martínez et al., 2005), it is important to measure the color changes and brown color formation more objectively.

4.2.1 | CIE color space

Color measurements, using CIE color spaces (e.g., CIE XYZ, CIELAB, and CIELCh), are widely used for the color characterization of food samples. The CIELAB color space

TABLE 4 Studies evaluating different nonenzymatic browning-related attributes during storage of fruit juices and juice model systems

Measurement of nonenzymatic browning	Fruit juices or model systems		References
Color changes and/or browning index	Fruit juices	Apple juice, grapefruit juice, grape juice, lemon juice, mango juice, orange juice, strawberry juice	Berlinet et al. (2006); Buvé, Van Bedts et al. (2018); Bozkurt et al. (1999); Clegg (1964); Lee and Nagy (1988); Nagy et al. (1990); Paravisini et al. (2018); Paravisini et al. (2019); Pham et al. (2019); Pham et al. (2020a); Polydera et al. (2005); Rassis and Saguy (1995); Robertson and Samaniego (1986); Roig et al. (1996); Roig et al. (1999); Solomon et al. (1995); Trammell et al. (1986); Wibowo et al. (2015d); Zerdin et al. (2003)
	Fruit juice concentrates	Citrus juice (orange, lemon, grapefruit, and tangerine) concentrates, peach juice concentrate	Buedo et al. (2000); Kanner and Fishbein (1982); Koca et al. (2003); Lee and Chen (1998); Rassis and Saguy (1995)
	Model juice systems	Lemon juice models, grape juice models, orange drinks containing 10% (v/v) orange juice, orange juice models, orange juice serum	Bozkurt et al. (1999); Clegg (1964); Kacem et al. (1987); Kennedey et al. (1990); Pham et al. (2020b); Shinoda et al. (2004, 2005)
Precursor compounds (e.g., ascorbic acid, sugars, and/or amino acids)	Fruit juices	Apple juice, grapefruit juice, mango juice, orange juice, strawberry juice	Berlinet et al. (2006); Buvé, Van Bedts et al. (2018); Lee and Nagy (1988); Paravisini et al. (2018, 2019); Polydera et al. (2005); Pham et al. (2019); Pham et al. (2020a); Rassis and Saguy (1995); Robertson and Samaniego (1986); Roig et al. (1996); Roig et al. (1999); Solomon et al. (1995); Trammell et al. (1986); Wibowo et al. (2015b, 2015c)); Zerdin et al. (2003)
	Fruit juice concentrates	Citrus juice (orange, lemon, grapefruit, and tangerine) concentrates	Burdurlu et al. (2006); Kanner and Fishbein (1982); Lee and Chen (1998); Rassis and Saguy (1995)
	Model juice systems	Orange juice models, orange juice serum	Kennedey et al. (1990); Pham et al. (2020b); Shinoda et al. (2004, 2005)
Intermediate compounds (e.g., Furfural, HMF, and/or other carbonyl compounds)	Fruit juices	Apple juice, grapefruit juice, grape juice, mango juice, orange juice	Bozkurt et al. (1999); Lee and Nagy (1988); Paravisini et al. (2018, 2019); Pham et al. (2019); Pham et al. (2020a); Robertson and Samaniego (1986); Roig et al. (1996); Roig et al. (1999); Solomon et al. (1995); Wibowo et al. (2015b, 2015d))
	Fruit juice concentrates	Citrus juice (orange, lemon, grapefruit, and tangerine) concentrates	Burdurlu et al. (2006); Kanner and Fishbein (1982)
	Model juice systems	Grape juice models, orange juice models, orange juice serum	Bozkurt et al. (1999); Kennedey et al. (1990); Pham et al. (2020b); Shinoda et al. (2004, 2005)

is extensively applied for the measurement of the overall color changes during processing and storage of fruit juices (Aguiló-Aguayo et al., 2009; Buvé, Kebede, et al., 2018; Meléndez-Martínez et al., 2005; Pathare et al., 2013; Wibowo et al., 2015d). This color space consists of three coordinates: L^*, a^*, and b^*, which are measured by a colorimeter. The L^* value is a measure of lightness, ranging from black (0) to white (100). The a^* and b^* values indicate color direction green ($-a^*$)/ red ($+a^*$) and blue ($-b^*$)/ yellow ($+b^*$), respectively. These values can be used to calculate the total color difference (ΔE^*) (Equation 1) that is a measure of the difference in color between two samples (a sample of interest and a reference sample indicated with subscript 0 in Equation 1) (Buvé, Kebede, et al., 2018; Pathare et al., 2013; Pham et al., 2019; Wibowo et al., 2015d). In addition, the hue angle (h_{ab}; nature of the color) and chroma (C^*_{ab}; saturation of the color) can be calculated from the a^* and b^* values (Equations 2 and 3).

$$\Delta E^* = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2}, \qquad (1)$$

$$h_{ab} = \tan^{-1}\left(b^*/a^*\right), \qquad (2)$$

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}}. \qquad (3)$$

Most studies on color changes of orange juice and citrus juice concentrates during storage showed a decrease in L^* and b^* values and an increase in a^* and ΔE^* values (Koca et al., 2003; Wibowo et al., 2015d). The authors attributed the decrease in L^* values to the darkening of the juices and concentrates due to NEB occurring upon storage at room temperature (20 °C) and elevated temperatures (28 to 45 °C) (Figure 4g). The decrease in b^*, C^*_{ab}, and h_{ab} values and the increase in a^* values signified a reduction of yellowish tone and an increase of reddish tone (Wibowo et al., 2015d). Buvé, Kebede, et al. (2018) reported a decrease in a^* value (redness) and an increase in ΔE^* value during storage of pasteurized strawberry juice at 20 to 42 °C. At all temperatures, the L^* and b^* values were rather stable. Teribia et al. (2021) observed a decrease in the a^* and C^*_{ab} values during storage of pasteurized strawberry puree at 35 °C for 42 days in glass jars in the dark. At the same time, the h_{ab} increased. The change in these parameters indicated a loss in red color and the appearance of an orange/dark color. During storage of pasteurized mango juice at 42 °C, the L^*, b^*, C^*_{ab}, and h_{ab} decreased and the a^* and ΔE^* values increased, indicating a loss of the yellow and bright color (Wibowo et al., 2015d). The observed color changes of orange, strawberry, and mango juice/puree during storage are most probably due to a combination of the degradation of the naturally occurring pigments (i.e., carotenoids or anthocyanins) and the formation of brown colored compounds. It should also be noted that depending on the matrix, a different trend for the CIEL$^*a^*b^*$ values and derived parameters (C^*_{ab} and h_{ab}) was observed. The rise in ΔE^* values should solely be used as an indicator for the increase in the color difference between nonstored and stored samples (Buvé, Kebede, et al., 2018; Pham et al., 2019; Wibowo et al., 2015d). Consequently, ΔE^* values may not be used as a good NEB indicator, as ΔE^* is a measure of color changes in general.

4.2.2 | Browning index

The BI is specifically used for the determination of browning development during storage. It is the optical density of the sample at a certain wavelength (e.g., 420 nm), which is measured by a spectrophotometer. The procedure for BI measurement usually involves several preparation steps such as extraction and clarification that can be varied depending on the characteristics of the samples. Most of the studies concerning NEB in citrus juices determine the BI following the procedure proposed by Meydav et al. (1977). However, Klim and Nagy (1988) found this procedure to be imprecise and sensitive to variation due to the sample preparation, temperature, and filtration. The wavelength of 420 nm has generally been used to measure the BI in different fruit juices and concentrates (Aguiló-Aguayo, et al., 2009; Cao et al., 2012; Fustier et al., 2011; Koca et al., 2003; Manso et al., 2001; Paravisini & Peterson, 2016; Pham et al., 2019). It was reported that the BI of orange juice and concentrate and strawberry juice increased with storage time, indicating an increase in the browning intensity (Cao et al., 2012; Kennedy et al., 1990; Koca et al., 2003; Paravisini & Peterson, 2016; Pham et al., 2019; Solomon et al., 1995). The increase in BI was attributed to the accumulation of brown compounds resulting from NEB reactions during storage. In addition, higher BI values were observed for juices that were stored at higher temperatures (Kennedy et al., 1990; Koca et al., 2003).

The CIELAB color parameters (e.g., L^* values) have been related to the BI in NEB studies on citrus juices and concentrates (Koca et al., 2003; Lee & Nagy, 1988). For instance, Koca et al. (2003) found a high correlation between the change in BI (absorbance at 420 nm) of citrus juice concentrates and the changes in both L^* and b^* values during 8 weeks storage at 28, 37, and 45 °C. Therefore, they suggested that, together with the BI, the L^* and b^* values could be used as NEB indicators. Pathare et al. (2013) also suggested an equation to calculate the BI based on the L^*, a^*, and b^* values. A high correlation between the ΔE^* and the BI of orange juice during storage at an elevated temperature of 42 °C was also reported (Pham et al., 2019). These authors hypothesized that the formation of brown-colored compounds had an important contribution to the overall color change of the juice during storage.

The measurements of color and BI have widely been applied in NEB studies and give valuable information on color changes and brown color formation. Nonetheless, the results of these measurements do not give any insight into the chemistry of the NEB reactions. Hence, it is necessary to assess NEB measuring the changes in different compounds related to the browning reactions.

4.3 | Measurement of compounds linked to the nonenzymatic browning reactions

4.3.1 | Precursors, intermediates, and degradation products

It has been mentioned in Section 2 that AA, reducing sugars, and amino acids are proposed in the literature to be precursors of the NEB reactions in fruit juices. Reactive carbonyl compounds such as furfural, 3OH2P, 3-deoxyglucosone, acetol, and HMF resulting from AA and/or sugar degradation are considered as NEB reaction intermediates or markers of browning in fruit juices (Arena et al., 2001; Bharate & Bharate, 2014; Burdurlu et al., 2006; Kanner & Fishbein, 1982; Kanner et al., 1981; Paravisini & Peterson, 2019). Therefore, the changes in these precursors and intermediates during the storage of fruit juices are often investigated in studies on NEB as also presented in Tables 2 and 3. Authors often reported AA degradation as a major pathway of NEB in orange juice, whereas sugar degradation seems to be less important (Lee & Nagy, 1988; Manso et al., 2001; Paravisini & Peterson, 2019; Polydera et al., 2005; Roig et al., 1999; Solomon et al., 1995; Zerdin et al., 2003). The role of amino acids in NEB of fruit juices was previously discussed (Section 3). Paravisini and Peterson (2019) analyzed the amino acid composition of the orange juice before and after 8 weeks storage at 35 °C and observed the largest losses of tryptophan and glutamine due to storage compared to other amino acids. Furthermore, these two amino acids were reported to significantly impact the composition of the reactive carbonyl compounds and brown color formation (Paravisini & Peterson, 2019).

The formation of reactive carbonyl compounds (e.g., 3-deoxyglucosone and glyoxal, etc.) was found to have a high correlation with the browning development during storage of pasteurized orange juice and apple juice at 35 °C (Paravisini & Peterson, 2018, 2019). In addition, 3-deoxyglucosone and acetol were reported as key browning intermediates in orange juice, whereas in apple juice, glyoxal and methylglyoxal were important intermediates. Applying isotopic enrichment techniques in an NEB study on orange juice, Paravisini and Peterson (2019) could identify AA as the main precursor of acetol and fructose as the main precursor of 3-deoxyglucosone. Another study showed that a furfural solution with added amino acids showed similar browning behavior as an orange juice model system (Shinoda et al., 2005). A high correlation between browning development in citrus juices and the formation of furfural and/or HMF was also reported by other research groups (Lee & Nagy, 1988; Robertson & Samaniego, 1986).

4.3.2 | Melanoidins

In contrast to the amount of the literature on NEB precursors and intermediates in fruit juices, less attention was given to the determination of the final brown compounds (Nagy, Lee, Rouseff, & Fisher, 1992; Rouseff et al., 1989). Up to date, the chemical structures of the brown compounds and the chemical pathways to brown compound formation in fruit juices have not been completely elucidated. Melanoidins, the final brown products resulting from the Maillard reactions between sugars and amino groups, have been reported to have a complex structure. Many research efforts have been done to determine the structure of melanoidins in model systems using advanced analytical techniques such as nuclear magnetic resonance spectroscopy, mass spectrometry, and application of ^{13}C-labeling experiments (Frank et al., 2001; Hofmann, 1997, 1998a, 1998b). Based on the results from simple model systems of sugars and amino acids, different suggestions on the melanoidin structure have been made. Nonetheless, real food systems are much more complex and the reaction conditions are highly variable. Therefore, the Maillard reactions and the resulting melanoidins are much more complex in food products than in model systems (Cämmerer et al., 2002; Gniechwitz et al., 2008). Considering NEB in fruit juices, the reaction pathways to brown compound formation may involve, but are not limited to, the Maillard reactions (see Section 2). Hence, the chemical structure and composition of the brown compounds resulting from NEB reactions in fruit juices may be very complicated. Nevertheless, knowledge that has been obtained from research on melanoidins in model and food systems can be used as a basis for research on the brown compounds resulting from NEB in fruit juices.

Most melanoidins in food systems were reported to have high molecular weight, whereas low molecular weight melanoidins were found only to a smaller extent

(Echavarría et al., 2012; Gniechwitz et al., 2008; Rogacheva et al., 1999; Wang et al., 2011). Based on this characteristic of melanoidins, most of the procedures for isolation of these compounds involve one or more of the following techniques: dialysis in a cellulose dialysis tubing, filtration, and ultrafiltration (Bekedam et al., 2006, 2008; Cämmerer et al., 2002; Daglia et al., 2008). Other techniques such as ethanol precipitation, gel filtration, anion exchange chromatography, copper-chelating chromatography, and so forth, were employed for further isolation and purification of melanoidins (Bekedam et al., 2006, 2008; Daglia et al., 2008; Echavarría et al., 2012; Lopes et al., 2016; Nunes & Coimbra, 2007). The melanoidin-rich fractions were commonly characterized in terms of physical and chemical properties including molecular weight, absorbance at a certain wavelength (e.g., 405 and/or 420 nm), and composition (e.g., neutral sugar composition and protein content, etc.) (Adams et al., 2005; Bekedam et al., 2006, 2007, 2008; Lopes et al., 2016; Nunes & Coimbra, 2007). More detailed information about isolation and characterization of melanoidins formed by Maillard reactions in food and model systems can be found in the work of Wang et al. (2011) and Echavarría et al. (2012).

5 | STRATEGIES TO PREVENT NONENZYMATIC BROWNING

Different approaches have been investigated to reduce NEB in fruit juices during storage. These can be related to the modification of the juice composition and/or the control of process/storage factors.

As to juice composition, it has been discussed in Section 3 that amino acids accelerate the browning process in fruit juices. It has been shown that the removal of amino acids by ion-exchange can reduce or delay the browning of the products (Bharate & Bharate, 2014; Clegg, 1964; Sharma et al., 2014). For instance, Sharma et al. (2014) reported that around 98% of amino acids in orange juice semiconcentrate could be removed by ion exchange leading to the reduction of juice browning by a factor of three. Therefore, the authors stated that ion-exchange treatment could be a potential method to control the browning process in fruit juice. On the other hand, the addition of some compounds such as AA derivatives (e.g., erythorbic acid, 2- and 3-phosphate derivatives of AA) and SH-containing compounds (e.g., L-cysteine, N-acetyl-L-cysteine) has been shown to inhibit browning in fruit juices (Bharate & Bharate, 2014; Montgomery, 1983; Naim et al., 2002). AA and its derivatives are antioxidants that can be used to prevent browning and other oxidative reactions (Gabriel et al., 2015; Gómez Ruiz et al., 2018). However, AA is unstable and can be degraded to form reactive carbonyl compounds, which accelerate NEB. Addition of AA as such should thus be done with some caution. AA derivatives can overcome the problem related to AA because they are more stable than AA (Bharate & Bharate, 2014). The NEB inhibiting effect of L-cysteine or N-acetyl-L-cysteine could be due to the reduction of AA degradation in fruit juices upon addition of these compounds (Naim et al., 2002). Although removing amino acids or adding AA derivatives and SH-containing compounds can inhibit or reduce the browning process in fruit juices, these treatments should be carried out with caution as consumers prefer original and natural products.

NEB is affected by the storage temperature and oxygen availability (Berlinet et al., 2006; Kennedy et al., 1990; Koca et al., 2003; Lyu et al., 2018; Trammell et al., 1986; Zerdin et al., 2003). Therefore, fruit juice manufacturers can consider different methods to control these factors to reduce the browning process during storage. Although one of the advantages of shelf-stable products is that they can be stored at room temperature, reducing the storage temperature to refrigerated conditions would lead to a significant reduction in the rate of the browning process (Buedo et al., 2000; Kennedy et al., 1990; Koca et al., 2003; Lyu et al., 2018). In addition, attention should be given to the transportation conditions to avoid drastic fluctuations in temperature. Oxygen availability in fruit juices prior to and during storage can be minimized by selecting proper processing techniques and packaging material. The initial oxygen concentration can be reduced by deaeration, vacuum packaging, or by processing the juice under low oxygen conditions in, for example, a spiral-filter press. Using proper packaging material with low oxygen permeability (Berlinet et al., 2006; Kacem et al., 1987; Nagy et al., 1990) or with oxygen scavengers (Zerdin et al., 2003) can minimize the oxygen available during storage, and thus, slow down the browning process.

6 | CONCLUSION AND FUTURE PERSPECTIVES

Browning of shelf-stable fruit juices during storage is a major problem in the food industry. Despite the fact that browning of fruit juices is a well-known problem and that it has been the topic of many studies, it has not been fully understood yet. An extensive literature review showed that NEB involves three main reactions: AA degradation, acid-catalyzed sugar degradation, and Maillard-associated reactions. It seems that the degradation of AA is the most important reaction pathway leading to browning of fruit juices during storage. Next to the three reactions involved, it has been clearly demonstrated that NEB reactions are affected by many different factors, such as the juice constituents (e.g., concentration and presence of AA, sugars, amino acids, metal ions), the pH of the system, the oxygen availability (linked to the packaging material), and the storage conditions. Due to its complexity, controlling of NEB is not evident. Nevertheless, fruit juice industries can slow down the process of browning by reducing the storage temperature and by selecting proper processing techniques as well as packaging materials to minimize the oxygen availability prior to and during storage.

Different approaches can be applied to evaluate color changes and browning. Food scientists can work with fruit juice model systems or they can study real fruit juices. In future studies, the addition of labelled NEB precursors (such as ^{13}C and ^{15}N) to a model or real system combined with the use of advanced analytical techniques like LC-TOF-MS, GC-MS, and (two-dimensional) NMR can result in more mechanistic insight into NEB. In addition, speeding up the NEB reactions by ASLT can also be useful. Measurement techniques to characterize color changes and brown color formation can include the use of the CIE color space or the BI. Analyzing the concentrations of precursors and reaction products can allow to obtain mechanistic insight. Lastly, one can try to characterize melanoidins. Although it will not be evident, future work should try to obtain in-depth mechanistic insight into the NEB problem using advanced analytical techniques in combination with model systems and/or the addition of labeled compounds. Once the mechanistic insight into NEB is obtained, practical solutions to mitigate/eliminate NEB can be formulated and applied in fruit juice industry.

CONFLICT OF INTEREST

The authors declare that no companies, authorities, or individual persons directly benefit from the results of this work neither personally or financially.

AUTHOR CONTRIBUTIONS

Carolien Buvé: Conceptualization; visualization; writing-original draft. Huong Tran Thuy Pham: Conceptualization; visualization; writing-original draft. Marc Hendrickx: Conceptualization; writing-review & editing. Ann Van Loey: Conceptualization; resources; supervision; writing-review & editing. Tara Grauwet: Conceptualization; writing-review & editing. Ann Van Loey: Conceptualization; resources; supervision; writing-review & editing.

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