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MINI REVIEW

Browning and pigmentation in food through the Maillard reaction

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Abstract

The Maillard reaction was discovered in 1912 by Louis C. Maillard when he observed the browning phenomena with aroma formation in a heated solution containing a sugar and an amino acid. The Maillard reaction starts from the reactions between carbonyl groups of various sugars and amino groups of amino acids/ proteins, following the formation of intermediate compounds or poly-carbonyl compounds, which further react with each other and amino acids/proteins. Through various chemical reactions such as condensation, polymerization, degradation, cyclization etc., color and aroma are formed. The imparting of brown color is mainly attributed to melanoidins. However, the chemical structure of melanoidins remains unclear because melanoidins are complex and heterogeneous polymers. On the other hand, various kinds of low-molecular-weight pigments formed through the Maillard reaction have been isolated and their structures have been identified. Even though the contribution of each pigment is small, the recognition of color is cumulative. In some case, these pigments form brown polymers or significantly contribute to the total color of a model solution. These chemically clear information gives us a novel aspect for an overview of browning or pigmentation through the Maillard reaction.

Keywords Maillard reaction · Melanoidin · Browning · Color · Pigment

Brief history of the Maillard reaction and food

The Maillard reaction is one of the most important chemical reaction which occurs during food processing and storage, and significantly affects the quality of food. The name of this reaction is derived from a French chemist, Louis Camille Maillard (1878–1936). In 1912 he discovered by chance that a solution containing amino acids and sugars turned intensively brown during heating. At that time, he investigated the formation of peptide from amino acids in glycerol. Then he used glucose as a polyol compound instead of glycerol. Although the expected peptides were not formed, he observed that the reaction solution turned brown with the formation of aroma and carbon dioxide [1]. This reaction occurs ubiquitously because starting materials such as sugars and amino acids exist everywhere, meaning that Maillard reaction occurs in food as well as in body and soil.

This article belongs to the Topical Collection: Advances in Glycation: from food to human health and disease

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The significance of this reaction in food was first recognized by a researcher of brewing. Lintner described that malt aroma is formed by the reaction from leucine [1]. The importance of Maillard's discovery had been gradually recognized by other researchers and this browning phenomenon or the reaction between amino acids and sugars became to be called as the Maillard reaction till 1950's. Hodge summarized the outline of complicated pathway of the Maillard reaction [2]. Briefly, this reaction is divided into three stages, the early, intermediate, and late stages. In the early stage, a carbonyl group of glucose or reduced sugars react with an amino group of an amino acid to form a Schiff base, the double bond of which migrates to form Amadori compound, a stable intermediate compound. In the intermediate phase, from Amadori compound, various kinds of carbonyl compounds, especially dicarbonyl compounds such as 1-deoxyglucosone, 3-deoxyglucosone, and methylglyoxal are formed. These dicarbonyl compounds are more reactive than a starting material or a reducing sugar. Reactive dicarbonyls react with each other and amino groups of amino acids and proteins to form color or aroma.

Table 1 is the summary of the effects of the Maillard reaction on the quality and safety of food. The Maillard reaction has a close relationship with food preference or palatability as well as food safety. The Maillard reaction products usually stimulate appetite, while a small quantity of genotoxic

Table 1 Effect of the Maillard reaction on food quality and safety

Food quality and safety	Example or explanation
Browning or pigmentation	Color of beer, soy sauce, bread crust, and roasted coffee
Formation of aroma	Toasted bread, grilled meat, and roasted coffee
Formation of taste enhancer	Boiling of beef broth and ripening of soy sauce.
Dietary fiber-like property	Melanoidins are indigestible high-molecular-weight substances
Antioxidant and antimutagenic activity	Partial structures of endiol and enaminol in melanoidins and various compounds formed through the Maillard reaction
Loss of lysine	Long-storage of milk powder
Formation of mutagens	Acrylamide and heterocyclic aromatic amine

compounds such as acrylamide and heterocyclic aromatic amines are produced [3, 4].

Table 2 shows the relationship between the Maillard reaction and the color, aroma, and taste. We must take food as nutrients or essential components for life. We must know that this is food or edible. The Maillard reaction products are mainly derived from sugars and amino acids/proteins and are formed by heating. Therefore, the brown color and aroma formed through the Maillard reaction tell us that this food contains sugar and amino acids or proteins and are heated, which is essential information for human beings to eat. In addition to the browning and aroma, recent research has shown that various Maillard reaction products function as taste enhancers or modifiers [5–8].

Melanoidins

Brown pigment formed by the Maillard reaction is called melanoidins. In the late stage of the Maillard reaction, various chemical reactions such as condensation, polymerization, degradation, cyclization etc. happen to form melanoidins, which are heterogeneous polymers. The unit structure is unspecified, although several theories for the chemical structure of melanoidins are postulated [9]. One is that melanoidin skeleton is formed from sugar degradation products branched with amino compounds (Fig.1A and B). Considering the CP-MAS and NMR data of model melanoidins [10], Hayase proposed a polymer as shown in Fig. 1A [11]. In a model Maillard reaction system containing only a monosaccharide and an amino acid, the major skeleton forming high-molecular-weight melanoidins is considered to be polymers of sugar degradation products, because dicarbonyl compounds such as 1-deoxyglucosone, 3-deoxyglucosone, and methylglyoxal could be condensed by Aldol reaction (Fig. 1B) [12]. However, these backbone structures itself do not show color. So, melanoidins should have partial structures of various chromophores. Second theory is that melanoidins are polymers of low-molecular-weight pigments formed from sugars and amino acids (Fig. 1C). As described later, Hayase showed that a blue pigment formed from xylose and glycine turned brown by polymerization [13]. Recently, Kanzler and Haase proposed that melanoidins were formed by heterocyclic Maillard reaction intermediates via aldol reaction and Michael addition [14]. Hoffman proposed that melanoidins in food were derived from cross-linking products of proteins and that colored Maillard reaction products formed cross-linkage (Fig. 1D) [15]. As shown in Fig. 1E, melanoidins do not show a specific absorption maximum in the visible light region (380–780 nm), which strongly suggest that melanoidins have mixed or various chromophores.

Low-molecular-weight pigment formed by the Maillard reaction

Although the browning or pigmentation through the Maillard reaction is attributed to melanoidins, the structure is

Table 2 Relationship between the Maillard reaction and the color, aroma and taste as food information

Flow of information from food to human	Color → (appearance) →	Aroma →	Taste → Intake
Maillard reaction	Browning	Heated or process aroma	Taste enhancer
Sugars and amino acids	No	No	Sweetness and umami
Nutritious or physiological significance	No	No	Essential or direct
Amount of intake	No	Little	Fairly
Risk	No	Little	Fairly
Sensory system	Visual	Olfactory	Gustatory

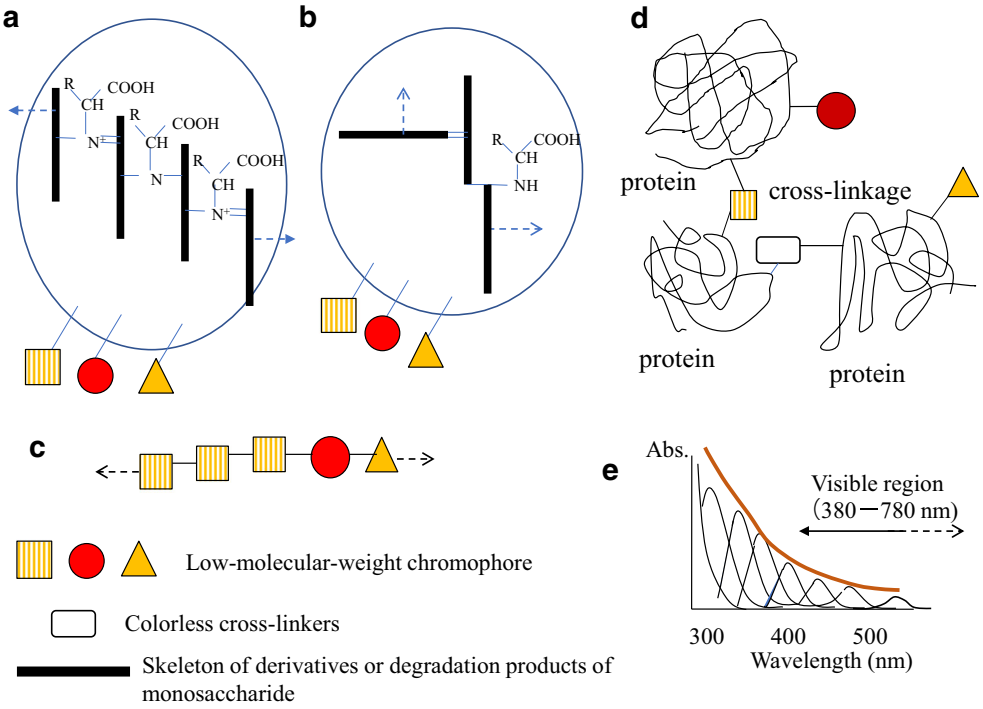

Fig. 1 Images (A-D) and a UV-vis (E) spectrum of melanoidins. In A and B, derivatives or degradation products of monosaccharide are assumed to be a skeleton of melanoidins. (**a**), conjugation of Amadori-like compound; (**b**), condensation of dicarbonyl compounds by the aldol reaction; (**c**), polymerization of various low-molecular-weight chromophores. (**d**), polymerization of through low-molecular-weight cross-linker or chromophores

unspecified. On the other hand, various low-molecular-weight pigments formed by the Maillard reaction have been reported. Considering that color recognition is cumulative and that low-molecular-weight pigments could be precursors of melanoidins, the investigation of low-molecular-weight pigments is significant to understand the browning or pigmentation by the Maillard reaction. Table 3 shows the comparison of melanoidins and low-molecular-weight pigments. Low-molecular-weight pigments having less than 1000–2000 of molecular could be chemically identified, while melanoidins are hardly identified because of their heterogeneity and difficulties of identification of unit structure [16]. Although Hoffman proposed that melanoidins derived from amino acids and not from proteins are also low-molecular-weight compounds [15], in general melanoidins are considered to be high-molecular-weight pigments or having molecular weights above 1000–2000.

Impressive research on low-molecular-weight Maillard pigments was done by a group of Hayase [13, 17–19], who identified blue, yellow, and red pigments formed in a solution containing xylose and glycine. (Fig. 2). These pigments contained nitrogen and turned brown during storage at room temperature. These findings suggest that these pigments are precursors of melanoidins [13]. In 1990s, groups of Ames

Table 3 Classification of Maillard pigments based on molecular weight

Maillard pigments	Low-molecular-weight pigments	High-molecular-weight pigments (melanoidins)
Molecular weight	<1000–2000	>1000–2000
Pigment	Single molecule	Mixture (similar substance derivatives)
Color tone	Yellow, orange, red, blue	Brown
Intensity of color	Weak because of small amount of each pigment, but cumulative	Major pigments
Chemical structure	Possible to identify	Difficult to identify
Polymerization and cross-linkage	It plausibly forms melanoidins or high-molecular-weight substances by polymerization or by cross-linkage between proteins	Polymers containing skeletons derived from sugar and amino acids/proteins
Electric charge	Various	Negatively charged (nitrogen-containing acidic substances)

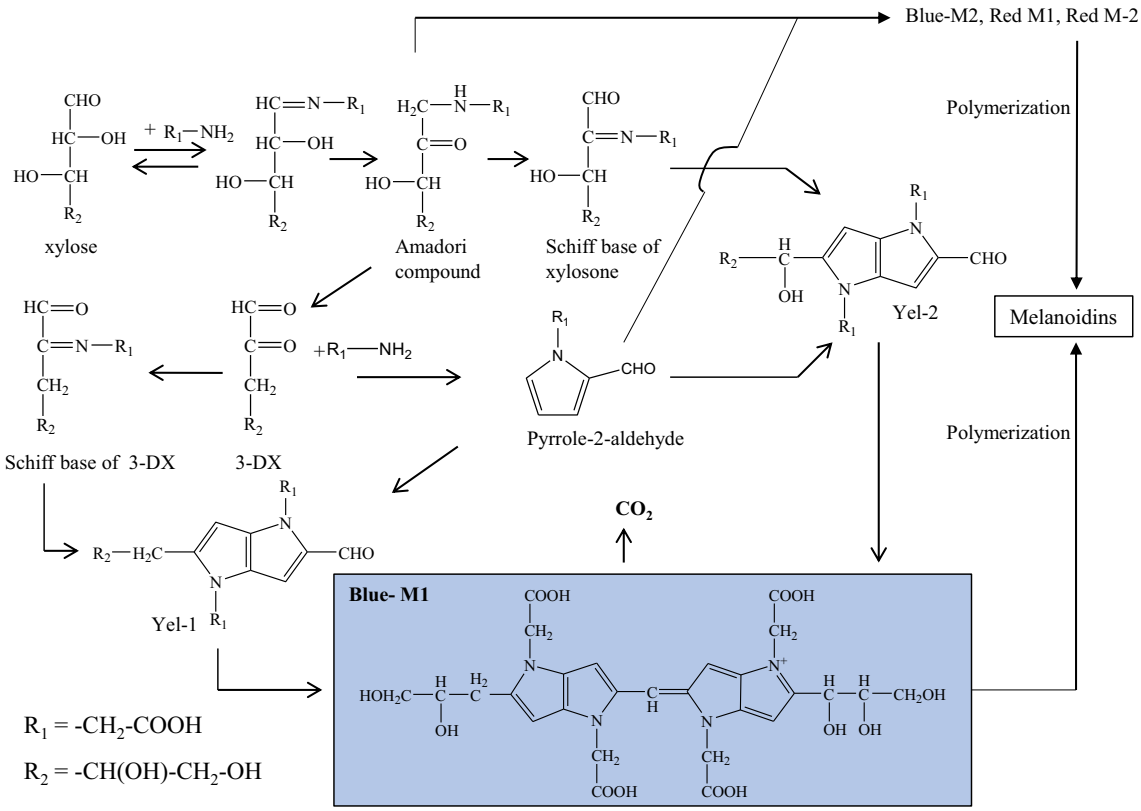

Fig. 2 Formation of blue (Blue-M1 and Blue-M2), red (Red-M1 and Red-M2), and yellow (Yel-1 and Yel-2) pigments and melanoidins in a solution containing xylose and glycine, depicted by reference to [13]. 3-DX, 3-deoxyxyloson

et al. [20–22] and Hoffman et al. [23–29] discovered various Maillard pigments (**1**–**17** in Fig. 3) including furan and pyrrole derivatives.

Through these backgrounds, we have assumed that a wide variety of low-molecular-weight Maillard pigments which are still unidentified exist in model systems and food. Color is recognized cumulatively. When a wide variety of different pigments exist at low concentrations of individual pigments, the sum of absorption in the visible light region become larger and the total color deepens. An HPLC system equipped with a diode-array detector (DAD) is a useful instrument to find pigments. As we recognize light having a wavelength of 380–780 nm as visible light, a compound which shows the absorption maximum at or near wavelength of this region is a pigment. We have examined model systems and food using DAD-HPLC. As a result, several unique Maillard pigments have been identified. Various Maillard pigments we isolated from model systems and food are shown in Fig. 4.

Furfural and 5-hydroxymethylfurfural (HMF) are relatively stable or detectable major aldehydes derived of pentose and hexose, respectively. Food is usually in weakly acidic conditions, although physiological condition or body is at almost neutral pH. A solution containing furfural and lysine was heated at pH 5, before being analyzed with DAD-HPLC. As a result, a major pigment peak (absorption maximum at 370 nm) and a minor one (absorption maximum at 360 nm) were detected. The former was a novel pipecolic acid derivative and named furpipate (**A** in Fig. 4) [30]. The later was a decarboxylated derivative of the former (**B** in Fig. 4) [31]. Form a HMF-lysine system, the corresponding compounds that are 5-hydroxymethylfurpipate (**C** in Fig. 4; absorption maximum at 380 nm) and its decarboxylated derivative (**D** in Fig. 4; absorption maximum at 380 nm) were identified [31]. Later a group of Katts reported the existence of a decarboxylated derivative of 5-hydroxymethylfurpipate (**D** in Fig. 4) in bread crust [32].

Next the contribution of these compounds to the total color of a reaction solution was estimated according to the color dilution method described by Hoffman [24]. The detection thresholds (*X* and *Y*) of furpipate and a reaction solution were visually determined by diluting furpipate and reaction solutions, respectively. The concentration (*Z*) of furpipate in the reaction solution was determined using HPLC. The color contribution rate (%) of furpipate to the reaction solution was estimated from $Z/X/Y \times 100$. Thus, the color contribution of furpipate was estimated 25%. Similarly, the color contribution of decarboxylated furpipate was 3%. These results showed that 28% of the total color intensity was explained by only the two low-molecular-weight pigments. In an HMF-lysine system, the contributions of 5-hydroxymethylfurpipate and its decarboxylated derivative to the total color intensity were 43% and 18%, respectively. These findings surprised us

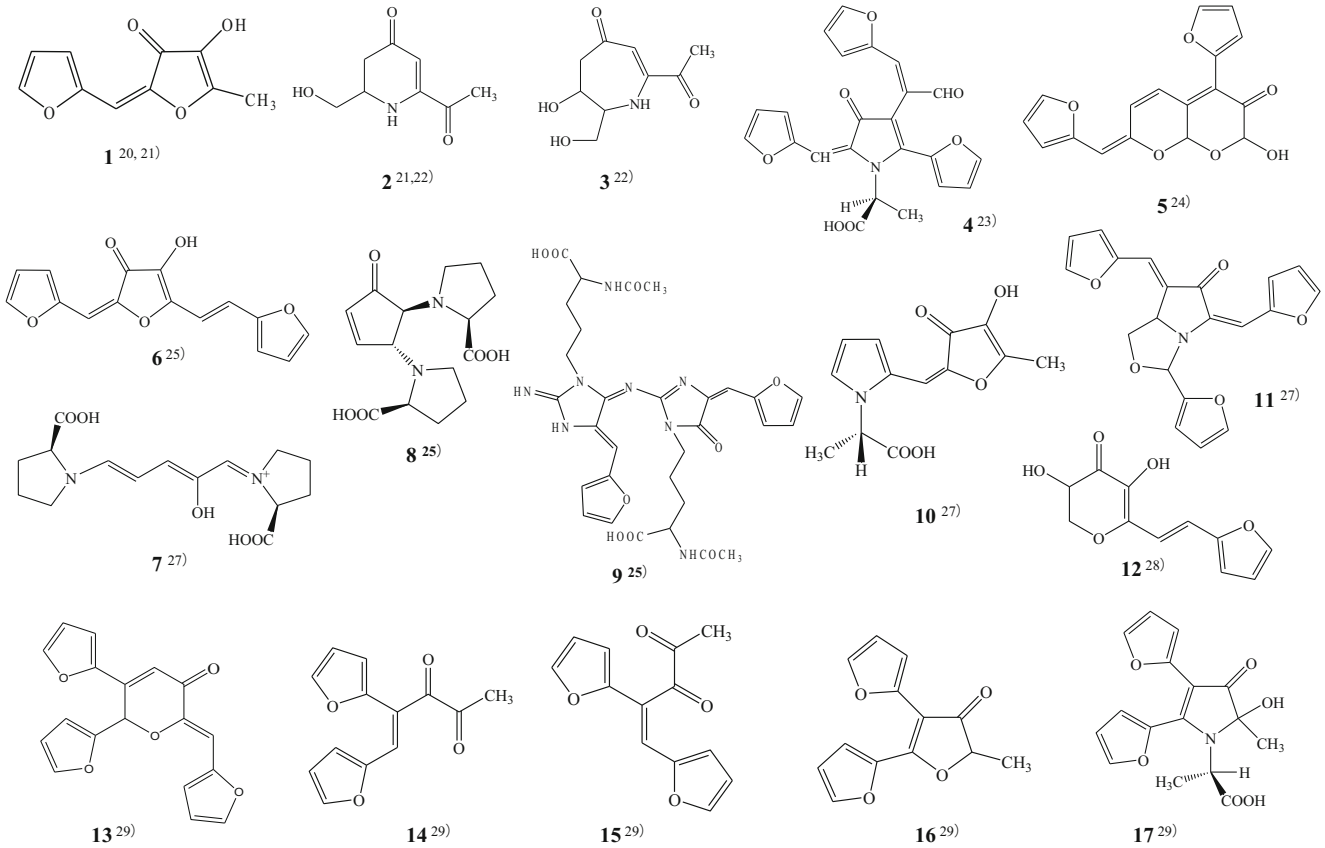

Fig. 3 Low-molecular-weight pigments (compounds **1**–**17**) formed through Maillard reaction

because we had been sure that the major pigment formed through the Maillard reaction was melanoidins and that the contributions of low-molecular-weight pigments to a total color were practically negligible. However, this result suggests that when reaction conditions are controlled to be suitable for the formation of a low-molecular-weight pigment having a specific absorption maximum, its color tone becomes brilliant.

Furfural is formed from pentose such as xylose and ribose. In general, a heated solution of a xylose-lysine system shows several times denser than that of a furfural-lysine system. Therefore, pigments in a solution of a xylose-lysine system were examined using DAD-HPLC. As a result, four peaks showing a specific absorption maximum in the visible light region were detected in addition to a big and broad peak of melanoidins which did not show a specific absorption maximum in the visible light region but detected at 400 nm (Fig. 5). A peak (**1** in Figs. 5) appearing at the latter part of the chromatogram, which was extracted with an organic solvent, was a well-known furanone derivative not containing nitrogen, 4-hydroxy-5-methyl-2-furfurylidene-3(*2H*)-furanone (**1** in Fig. 3) [20, 21]. The other three peaks (**E-G** in Fig. 5) showed an absorption maximum near 440 nm, which were isolated and identified using instrumental analyses. These compounds named dilysyldipyrrolones A, B, and C (**E-G** in Fig. 4) were orange pigments having a pyrrolyl-methylidene-pyrrolone structure as a chromophore and were formed from 2 mol of lysine and 2 mol of xylose [33–35]. The color contributions of dilysyldipyrrolones A and B to a reaction solution were 5% and 10%, respectively. Dilysyldipyrrolone B whose chromophore contains two ε-amino groups of two lysines was the major pigment. Considering its structure, dilysyldipyrrolone B could form a cross-linkage between lysine residues of proteins. On the other hand, the chromophore of dilysyldipyrrolone A contains one ε- and one α-amino groups of two lysines. This suggests that the same chromophore is formed from one ε-amino group of lysine and one α-amino group of another amino acid. In fact, expected derivatives of the pigment (**H** in Fig. 4) were formed by adding other amino acids to a reaction solution containing lysine and xylose.

In the browning of the Maillard reaction, pentoses such as xylose and ribose turn more intensively or rapidly brown that hexoses such as glucose and fructose. The reason is that more open form of sugar exists in pentose than in hexose. Further, the pigmentation itself is promoted in a pentose system compared with a hexose system. Comparing the browning of xylose and glucose systems at the same level of decrease in sugars by heating, the pigmentation was larger in a xylose system than glucose one [36]. 1-Deoxypentosone and 3-deoxypentosone derived from xylose are more reactive than 1-deoxyglucosone and 3-deoxyglucosone. Dilysyldipyrrolone

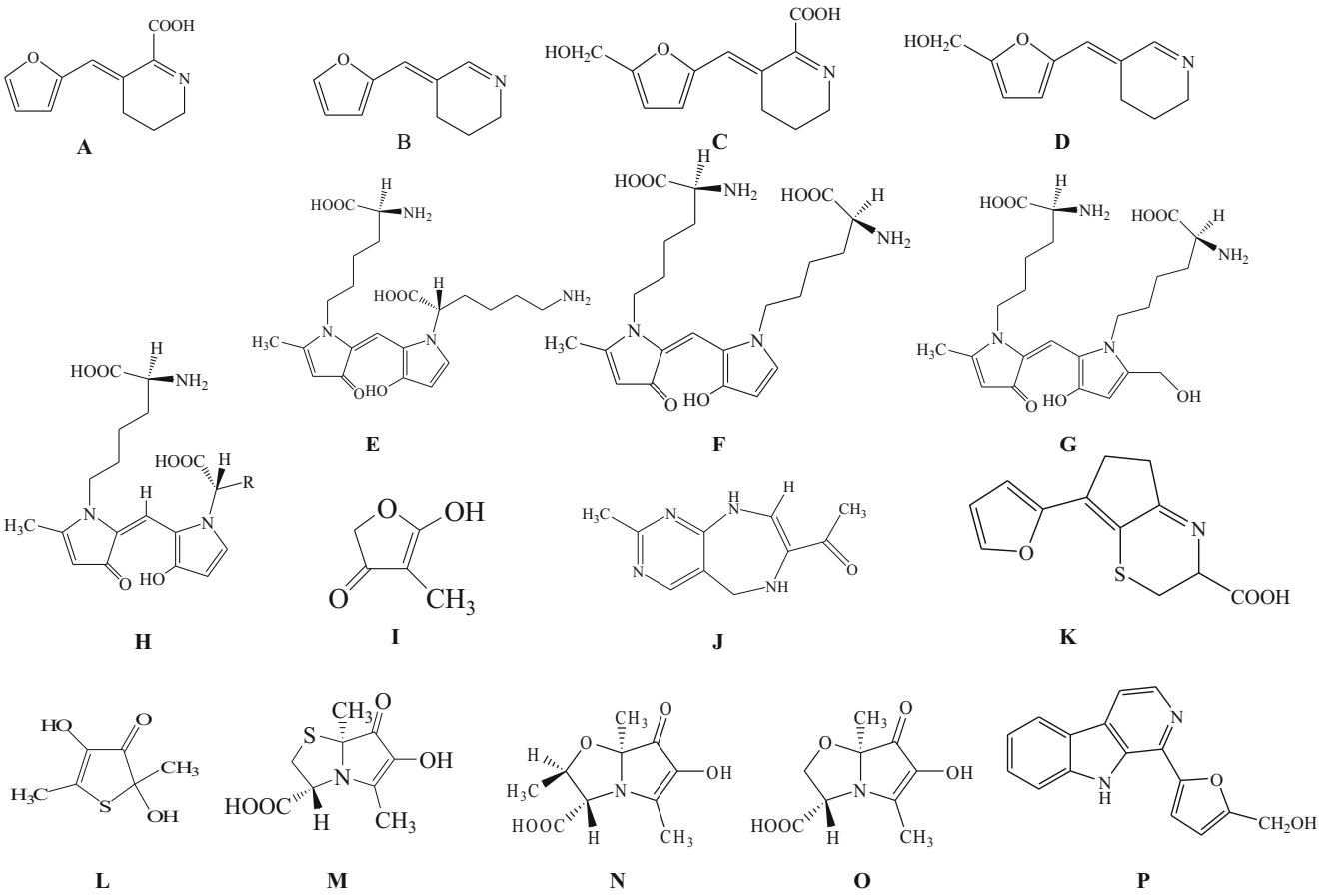

Fig. 4 Low-molecular-weight pigments (compounds **A**-**H** and **J**-**P**) and a related compound (**I**) formed through Maillard reaction

described above is considered to be formed from these deoxypentosone derivatives. We recently showed that 4-hydroxy-5-methyl-3(*2H*)-furanone (**I** in Fig. 4), an intermediate compound formed from deoxypentosone, was an important precursor for the browning of a pentose system [37].

In hexoses, more open form exists in galactose than in glucose, which makes a practical effect on the browning of cheese. Usual cheese contains little galactose. However, some cheese samples contain galactose. Cheese containing more galactose turned more intensively brown during storage [38, 39]. In food containing high concentrations of amino acids or proteins, a sugar concentration is a limiting factor of browning. A concentration of galactose in cheese was dependent on lactic acid bacteria used as a starter culture [40].

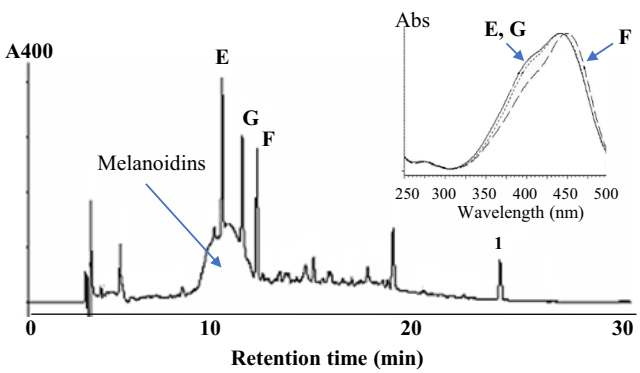

Fig. 5 Typical chromatogram of DAD-HPLC of a heated solution containing xylose and lysine. Compound **1** and compounds **E**-**G** are shown in Figs. 3 and 4, respectively

The major origin of an amino group is amino acids, peptides, and proteins. But some vitamins play a role of a substrate of the Maillard reaction. Thiamine containing nitrogen and sulfur is a well-known precursor for important aroma in meat products [41]. However, there was no information regarding a relationship between thiamine and browning or pigmentation. Recently, a novel pigment, pyrizepine (**J** in Fig. 4), was identified in a model Maillard reaction system containing thiamin and glucose [42]. Pyrizepine has a unique structure of pyrimidodiazepine, a fused ring consisting of pyrimidine and diazepine. This pigment is a zwitter ion in an aqueous solution (Fig. 6A). Pyrizepine is formed by condensation reaction between a 1-deoxytetrosone derivative and 4-amino-5-aminomethyl-2-methylpyrimidine, a degradation product of thiamine.

In food analyses, samples are often acid-hydrolyzed. It is well known that these solutions turn brown during acid hydrolysis. By chance we observed a formation of a yellow pigment during the acid-hydrolysis of soybean protein in the

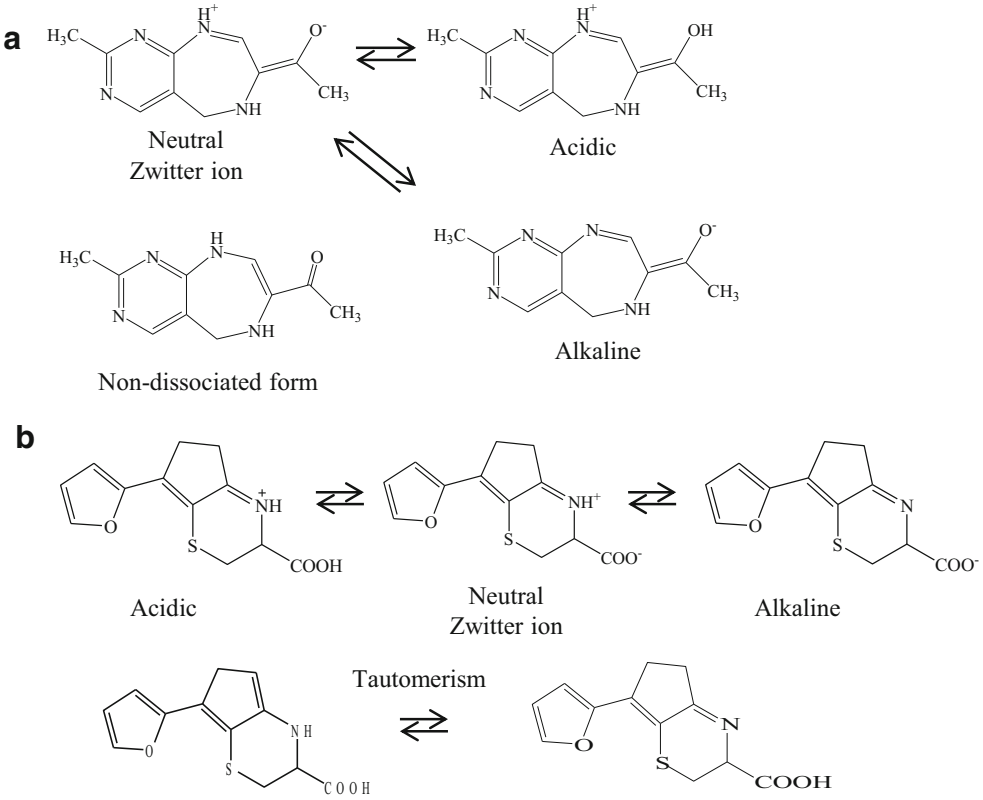

Fig. 6 Dissociated and non-dissociated forms of pyrizepine (**a**) and furpenthiazinate (**b**), and tautomerism of furpenthiazinate (**b**)

presence of xylose. The pigment, named furpenthiazinate (**K** in Fig. 4), has furan and cyclopentathiazine rings [43]. Furpenthiazinate shows tautomerism and is a zwitter ion in an aqueous solution (Fig. 6B). This compound is considered to be formed by the condensation of three compounds of furfural, a C-4 intermediate, and cysteine under strongly acidic conditions.

Low-molecular-weight Maillard pigments in food

As the Maillard pigments in food are thought melanoidins, there is little data on low-molecular-weight Maillard pigments in food. In fact, when beer and soy sauce samples are applied to DAD-HPLC, we cannot detect any clear peaks of pigments. We supposed that a wide variety of Maillard pigments were formed and each concentration was low and that peaks of these pigments were overlapped with those of melanoidins and could not be detected with DAD-HPLC. In general, melanoidins are water soluble polymers. Then samples extracted with an organic solvent were analyzed with DAD-HPLC. A soy sauce sample extracted with ethyl acetate showed a clear peak having an absorption maximum at 365 nm was detected. This yellowish pigment was identified as dihydroxy-2,5-dimethyl-3(*2H*)-thiophenone (**L** in Fig. 4) [44], which is known as an aroma compound of soy sauce. This compound was formed by a reaction between hydrogen sulfide derived from cysteine and carbonyl intermediates derived from glucose and that existed widely in brown food such as soy sauce, miso, and beer [45].

Cysteine having a thiol group easily reacts with carbonyl intermediates and represses the pigmentation or browning of the Maillard reaction. However, the identification of dihydroxy-2,5-dimethyl-3(*2H*)-thiophenone in soy sauce suggests that another pigment containing sulfur derived from cysteine is formed during the Maillard reaction. So, we analyzed a heated solution containing cysteine and glucose. As a result, a small peak having absorption maxima at 300 and 360 nm was detected on DAD-HPLC. This peak was several times increased by adding lysine to the model solution containing cysteine and glucose. This pigment was then isolated and identified as **M** shown in Fig. 4, being a pyrrolothiazole carboxylate derivative and named pyrrolothiazolate [46]. This novel pigment showed ant oxidative activities and existed in soy sauce, miso, and beer [47]. The color contribution of this compound to soy sauce was very small and less than 1%. It seems that these brown foods contain a wide variety of low-molecular-weight pigments in addition to melanoidins and that these pigments partly contribute to the total color of these foods.

Pyrrolothiazole structure of the pigment was considered to be formed by the addition of thiol and amino groups of cysteine to derivatives of 1-deoxyglucosone. If the amino group

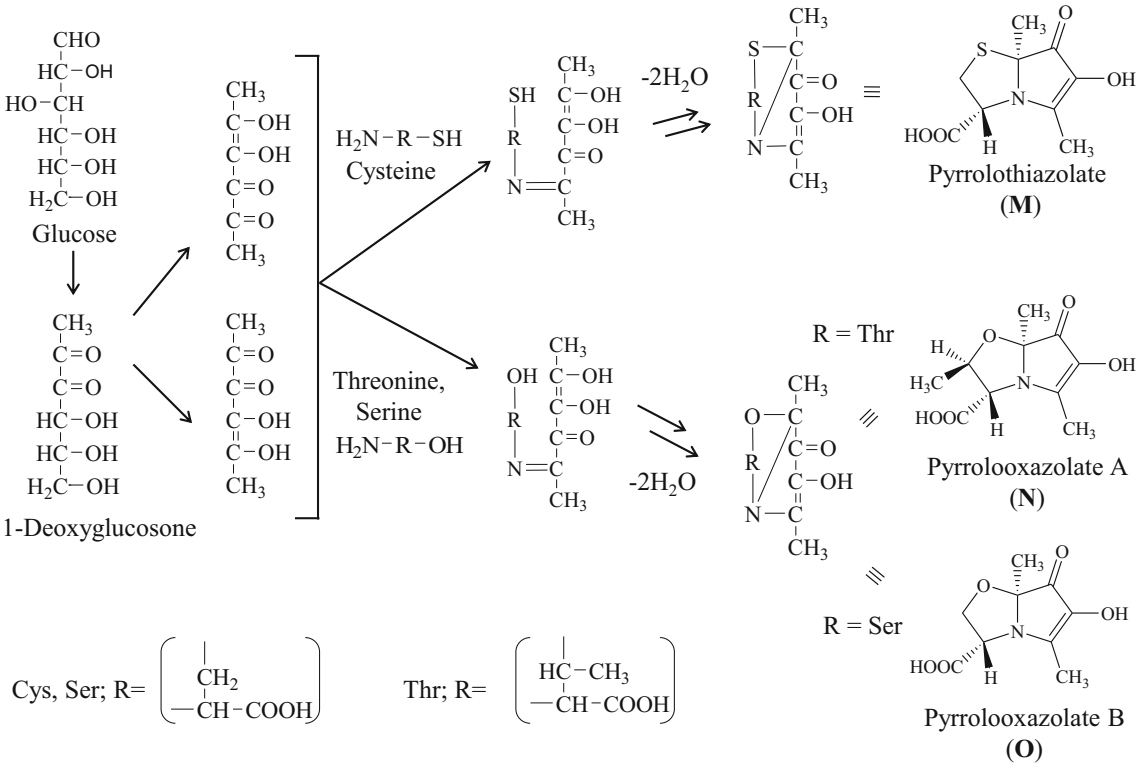

Fig. 7 Formation pathways of pyrrolothiazolate, pyrrolooxazolate (**a**), and pyrrolooxazolate (**b**) from cysteine, threonine, and serine

first reacts with an intermediate compound, a pyrrolooxazole derivative was supposed be formed in a reaction mixture containing threonine or serine having a hydroxy group instead of cysteine having a thiol group (Fig. 7). We prepared model Maillard solutions containing threonine or serine and glucose, then analyzed them with DAD-HPLC. As a result, we detected peaks showing similar UV-Vis spectra to pyrrolothiazolate and having two absorption maxima at 300 and 360 nm. These peaks were isolated and identified as the supposed compounds (pyrrolooxazolates A and B; **N** and **O** in Fig.4) [48]. The existence of these compounds in food has not been examined.

Next, a pigment in beer is described. Some chromatographic characteristics and UV-vis spectra of beer were examined, and the imparting of yellow or brown color of beer is mainly attributed to melanoidins [49]. When we analyzed beer with DAD-HPLC, we observed wide and trapezoidal chromatogram showing no specific absorption maxima at or near visible region and could not detect any clear peaks of pigments, which was like HPLC analysis of soy sauce. The basic substance fraction of beer was then prepared using an organic solvent, before being analyzed. This fraction was separated from a main part of melanoidins. As a result, a unique peak showing absorption maxima at 275, 340, and 405 nm was detected. After isolation, this compound was identified as perlolyrine (**P** in Fig. 4) [50]. Perlolyrine was first isolated from perennial rye grass (*Lolium prenne*) as an alkaloid showing fluorescence [51] and then from soy sauce as a yellow pigment [52], a weakly mutagenic beta-carboline derivative [53] and a taste modifier activating a vanilloid receptor [54]. This compound was also formed through the Maillard reaction between tryptophan and 5-hydtoxymethylfurufural or sugars [55, 56]. Various beers contained this pigment at the level of 3.2–8.0 μg/100 mL (pale beer) and 4.8–14.0 μg/100 mL (dark beer). The color contribution of this compound to the total color of the beer was less than 1% and small [50].

As described above, the browning or pigmentation through the Maillard reaction has been mainly attributed to melanoidins for a long time. However, the chemical structure is hardy specified. On the other hand, with the progress in instrumental analyses, various low-molecular-weight pigments have been recently identified. Our recognition of color is cumulative. Various pigments directly and cumulatively impart the color even though concentrations of individual pigments were low. Reaction conditions affect the formation of these pigments, meaning that the color tone of reaction solution or food products are changeable. Further, some of these pigments are incorporated into melanoidins, are polymerized to form melanoidins, or become cross-linkers between proteins. We hope that these basic findings will lead to more detailed understanding the browning or pigmentation through the Maillard reaction and the quality improvement of food products.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Hellwig, M., Henle, T.: Baking, ageing, diabetes: a short history of the Maillard reaction. Angew. Chem. Int. Ed. **53**, 10316–10329 (2014)
2. Hodge, J.E.: Chemistry of browning reactions in model systems. J. Agric. Food Chem. **1**, 928–943 (1953)
3. Freedman, M.: Chemistry, biochemistry, and safety of acrylamide. A review. J. Agric. Food Chem. **51**, 4504–4526 (2003)
4. Carthewa, P., DiNovib, M., Setzer, R.W.: Application of the margin of exposure (MOE) approach to substances in food that are genotoxic and carcinogenic. Example: CAS No: 105650–23-5 PhIP (2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine). Food Chem. Toxicol. **48**, 598–510 (2010)
5. Shima, K., Yamada, N., Suzuki, E., Harada, T.: Novel brothy taste modifier isolated from beef broth. J. Agric. Food Chem. **46**, 1465–1468 (1998)
6. Ottinger, H., Hofmann, T.: Identification of the taste enhancer alapyridaine in beef broth and evaluation of its sensory impact by taste reconstitution experiments. J. Agric. Food Chem. **51**, 6791–6796 (2003)
7. Festring, D., Hofmann, T.: Discovery of N^2-(1-carboxyethyl)guanosine 5′-monophosphate as an umami-enhancing Maillard-modified nucleotide in yeast extracts. J. Agric. Food Chem. **58**, 10606–10613 (2010)
8. Kaneko, S., Kumazawa, K., Nishimura, O.: Isolation and identification of the umami enhancing compounds in Japanese soy sauce. Biosci. Biotechnol. Biochem. **75**, 1275–1282 (2011)
9. Wang, H.-Y., Qjan, H., Yao, W.-R.: Melanoidins produced by the Maillard reaction: structure and biological activity. Food Chem. **128**, 573–584 (2011)
10. Hayase, F., Kim, S.B., Kato, H.: Analyses of the chemical structures of melanoidins by ^{13}C NMR, ^{13}C and ^{15}N CP-MAS NMR spectrometry. Agric. Biol. Chem. **50**, 1951–1957 (1986)
11. Hayase, F.: Chemistry of melanoidins (in Japanese). Nippon Nōgeikagaku Kaishi. **61**, 970–973 (1987)
12. Cammerer, B., Jalyschko, W., Kroh, L.W.: Intact carbohydrate structures as part of the melanoidin skeleton. J. Agric. Food Chem. **50**, 2083–2087 (2002)
13. Hayase, F., Usui, T., Watanabe, H.: Chemistry and some biological effects of model melanoidins and pigments as Maillard intermediates. Mol. Nutr. Food Res. **50**, 1171–1179 (2006)
14. Kanzler, C., Haase, P.: Melanoidins formed by heterocyclic Maillard reaction intermediates via aldol reaction and Michael addition. J. Agric. Food Chem. **68**, 332–339 (2020)
15. Hofmann, T.: Studies on the relationship between molecular weight and the color potency of fractions obtained by thermal treatment of glucose/amino acid and glucose/protein solutions by using ultracentrifugation and color dilution techniques. J. Agric. Food Chem. **46**, 3891–3895 (1998)
16. Echavarría, A.P., Pagán, J., Ibarz, A.: Melanoidins formed by Maillard reaction in food and their biological activity. Food Eng. Rev. **4**, 203–223 (2012)
17. Hayase, F., Takahashi, Y., Tominaga, S., Miura, M., Gomyo, T., Kato, H.: Identification of blue pigment formed in a D-xylose-glycine reaction system. Biosci. Biotechnol. Biochem. **63**, 1512–1514 (1999)
18. Sasaki, S., Shirahashi, Y., Nishiyama, K., Watanabe, H., Hayase, F.: Identification of a novel blue pigment as a melanoidin intermediate in the D-xylose-glycine reaction system. Biosci. Biotechnol. Biochem. **70**, 2529–2531 (2006)
19. Shirahashi, Y., Watanabe, H., Hayase, F.: Identification of red pigments formed in a D-xylose-glycine reaction system. Biosci. Biotechnol. Biochem. **73**, 2287–2292 (2009)
20. Ames, J., Apriyantono, A., Arnoldi, A.: Low molecular weight coloured compounds formed in xylose-lysine model systems. Food Chem. **46**, 121–127 (1993)
21. Bailey, R.G., Ames, J.M., Mann, J.: Identification of new heterocyclic nitrogen compounds from glucose-lysine and xylose-lysine Maillard model systems J. Agric. Food Chem. **48**, 6240–6246 (2000)
22. Ames, J.M., Bailey, R.G., Mann, J.: Analysis of furanone, pyranone, and new heterocyclic colored compounds from sugar −glycine model Maillard systems. J. Agric. Food Chem. **47**, 438–443 (1999)
23. Hofmann, T.: Determination of the chemical structure of novel colored 1H-pyrrol-3(2H)-one derivatives formed by Maillard-type reactions. Helv. Chim. Acta. **80**, 1843–1856 (1997)
24. Hofmann, T.: Characterization of the most intense coloured compounds from Maillard reactions of pentoses by application of colour dilution analysis. Carbohydr. Res. **313**, 203–212 (1998)
25. Hofmann, T.: Characterization of the chemical structure of novel colored Maillard reaction products from furan-2-carboxaldehyde and amino acids. J. Agric. Food Chem. **46**, 932–940 (1998)
26. Hofmann, T.: A novel colored substructure in melanoidins formed by Maillard reactions of bound arginine with glyoxal and furan-2-carboxaldehyde. J. Agric. Food Chem. **46**, 3896–3901 (1998)
27. Hofmann, T.: Identification of novel colored compounds containing pyrrole and pyrrolinone structures formed by Maillard reactions of pentoses and primary amino acids. J. Agric. Food Chem. **46**, 3902–3911 (1998)
28. Hofmann, T., Heuberger, S.: The contribution of coloured Maillard reaction products to the total colour of browned glucose/l-alanine solutions and studies on their formation. Z. Lebensm. Unters. Forsch. A. **208**, 17–26 (1999)
29. Frank, O., Hofmann, T.: Characterization of key chromophores formed by nonenzymatic browning of hexoses and L-alanine by using the color activity concept. J. Agric. Food Chem. **48**, 6303–6311 (2000)
30. Murata, M., Totsuka, H., Ono, H.: Browning of furfural and amino acids, and a novel yellow compound, furpipate, formed from lysine and furfural. Biosci. Biotechnol. Biochem. **71**, 1717–1723 (2007)
31. Totsuka, H., Tokuzen, K., Ono, H., Murata, M.: A novel yellow compound and furpipate derivatives formed from furfural or 5-hydroxymethylfurfural in the presence of lysine. Food Sci. Technol. Res. **15**, 45–50 (2009)
32. Chen, X.M., Dai, Y., Kitts, D.D.: Detection of Maillard reaction product [5-(5,6-dihydro-4H-pyridin-3-ylidenemethyl)furan-2-yl]methanol (F3-a) in breads and demonstration of bioavailability in Caco-2 intestinal cells. J. Agric. Food Chem. **64**, 9072–9077 (2016)
33. Sakamoto, J., Takenaka, M., Ono, H., Murata, M.: Novel yellow compounds, dilysyldipyrrolones a and B, formed from xylose and lysine by the Maillard reaction. Biosci. Biotechnol. Biochem. **73**, 2065–2069 (2009)
34. Nomi, Y., Sakamoto, J., Takenaka, M., Ono, H., Murata, M.: Conditions for the formation of dilysyl-dipyrrolones a and B, and novel yellow dipyrrolone derivatives formed from xylose and amino acids in the presence of lysine. Biosci. Biotechnol. Biochem. **75**, 221–226 (2011)

35. Nomi, Y., Masuzaki, R., Terasawa, N., Takenaka, M., Ono, H., Otsuka, Y., Murata, M.: Formation mechanism and characterization of dilysyl-dipyrrolones, the Maillard-type yellow pigments. Food Funct. **4**, 1067–1075 (2013)
36. Mikami, Y., Murata, M.: Effects of sugar and buffer types, and pH on formation of Maillard pigments in the lysine model system. Food Sci. Technol. Res. **21**, 813–819 (2015)
37. Mikami, Y., Nakamura, M., Yamada, S., Murata, M.: 4-Hydroxy-5-methyl-3(2H)-furanone (HMFO) contributes to browning in xylose-lysine Maillard reaction system. Food Sci. Technol. Res. **23**, 283–289 (2017)
38. Igoshi, A., Sato, Y., Kameyama, K., Murata, M.: Galactose is the limiting factor for the browning or discoloration of cheese during storage. J. Nutri. Sci. Vitaminol. **63**, 412–418 (2017)
39. Adachi, K., Igoshi, A., Murata, M.: Analyses of factors affecting the browning of model processed cheese during storage. J. Nutri. Sci. Vitaminol. **66**, 365–370 (2020)
40. Arai, A., Igoshi, A., Inoue, A., Noda, K., Tsutsuura, S., Murata, M.: Relationship between lactose utilization of lactic acid bacteria and browning of cheese during storage. Biosci. Biotechnol. Biochem. **84**, 1886–1893 (2020). https://doi.org/10.1080/09168451.2020.1768508
41. Kosowska, M., Majcher, M.A., Fortuna, T.: Volatile compounds in meat and meat products. Food Sci Technol. **37**, 1–7 (2017)
42. Igoshi, A., Noda, K., Murata, M.: A novel thiamine-derived pigment, pyrizepine, formed by the Maillard reaction. Biosci. Biotechnol. Biochem. **82**, 1425–1432 (2018)
43. Noda, K., Masuzaki, R., Terauchi, Y., Yamada, S., Murata, M.: Novel Maillard pigment, furpenthiazinate, having furan and cyclopentathiazine rings formed by acid hydrolysis of protein in the presence of xylose or by reaction between cysteine and furfural under strongly acidic conditions. J. Agric. Food Chem. **66**, 11414–11421 (2018)
44. Satoh, M., Nomi, Y., Yamada, S., Takenaka, M., Ono, H., Murata, M.: Identification of 2,4-dihydroxy-2,5-dimethyl-3(2H)-thiophenone as a low molecular weight yellow pigment in soy sauce. Biosci. Biotechnol. Biochem. **75**, 1240–1244 (2011)
45. Furusawa, R., Goto, C., Satoh, M., Nomi, Y., Murata, M.: Formation and distribution of 2,4-dihydroxy-2,5-dimethyl-3(2H)-thiophenone, a pigment, an aroma, and a biological active compound formed by the Maillard reaction, in foods and beverages. Food Funct. **4**, 1076–1081 (2013)
46. Noda, K., Yamada, S., Murata, M.: Isolation, identification, and formation conditions of a novel Maillard yellowish pigment, pyrrolothiazolate. Biosci. Biotechnol. Biochem. **79**, 1350–1355 (2015)
47. Noda, K., Terasawa, N., Murata, M.: Formation scheme and antioxidant activity of a novel Maillard pigment, pyrrolothiazolate, formed from cysteine and glucose. Food Funct. **7**, 2551–2556 (2016)
48. Noda, K., Murata, M.: Two novel pyrrolooxazole pigments formed by the Maillard reaction between glucose and threonine or serine. Biosci. Biotechnol. Biochem. **81**, 343–349 (2017)
49. Kuntcheva, M.J., Obretenov, T.D.: Isolation and characterization of melanoidins from beer. Z. Lebensm. Unters. Forsch. **202**, 238–243 (1996)
50. Nagai, C., Noda, K., Kirihara, A., Tomita, Y., Murata, M.: A low-molecular weight Maillard pigment from beer was identified as perlolyrine, a Maillard reaction product from tryptophan. Food Sci. Technol. Res. **25**, 81–88 (2019)
51. Jeffreys, J.A.D. The alkaloids of perennial rye-grass (*Lolium perenne* L.). Part IV. Isolation of a new base, perlolyrine; the crystal structure of its hydrobromide dihydrate, and the synthesis of the base. J. Chem. Soc. C. 1091–1103 (1970)
52. Nakatsuka, S., Feng, B., Goto, T., Kihara, K.: Structures of flazin and YS, highly fluorescent compounds isolated from Japanese soy sauce. Tetrahedron Lett. **27**, 3339–3402 (1986)
53. Ohshita, I., Kanamori, H., Mizuta, M., Sakamoto, I.: A mutagenic β-carboline derivative in soy sauce (in Japanese). Food Hyg. Safe. Sci. **32**, 272–277 (1991)
54. Oshida, M., Matsuura, Y., Hotta, S., Watanabe, J., Mogi, Y., Watanabe, T.: Isolation and identification of a humanTRPV1 activating compound from soy sauce. Biosci. Biotechnol. Biochem. **81**, 987–994 (2017)
55. Ohshita, I., Kanamori, H., Mizuta, M., Sakamoto, I.: Formation of β-carboline derivatives during the soy sauce manufacturing process and their changes during storage (in Japanese). J. Jpn. Soc. Nutr. Food Sci. **46**, 179–182 (1993)
56. Lee, S.H., Jeong, S.J., Jang, G.Y., Kim, M.Y., Hwang, I.G., Kim, H.Y., Woo, K.S., Hwang, B.Y., Song, J., Lee, J., Jeong, H.S.: Isolation and identification of an antiproliferative compound from fructose-tryptophan Maillard reaction products. J. Agric. Food Chem. **64**, 3401–3047 (2016)