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# THE IMPLICATIONS RELATED TO THE MAILLARD REACTION IN THE PRODUCTION OF MILK AND DAIRY PRODUCTS: A REVIEW

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**Abstract:** This manuscript presents a comprehensive review of the implications of the Maillard reaction in the production of dairy products, addressing its nutritional, sensory, and technological effects. The Maillard reaction occurs between reducing sugars and amino compounds and is intensified by heat treatments such as pasteurization, sterilization, and ultra-high temperature (UHT). While it is responsible for desirable aromas and colors in products such as dulce de leche and ghee, it also causes the reduction of essential amino acids, such as lysine, and the formation of potentially toxic compounds, such as 5-hydroxymethylfurfural and advanced glycation end-products (AGEs). The study describes the three phases of the reaction (initial, intermediate, and final), highlighting the formation of melanoidins and intermediate compounds such as furosine and carboxymethyllysine. Several factors affect the reaction, including pH, water activity, sugar type, and temperature. In products such as milk, powdered milk, condensed milk, and cheese whey, increased temperature and prolonged storage have been shown to intensify the reaction. Mitigation strategies include using tea polyphenols as inhibitors and controlling processing conditions. Conversely, in products where browning and aroma are desirable, such as dulce de leche and ghee, the Maillard reaction is considered beneficial and essential for the characteristic sensory profile.

**Keywords**: Milk products. Non-enzymatic browning. Heat treatment. Advanced glycation end-products. Nutritional quality. Sensory properties.

## Introduction

The Maillard reaction is one of the most significant chemical processes that occur during the heat treatment of foods, playing a crucial role in the formation of compounds responsible for sensory changes, including color, aroma, and flavor. In the case of milk, especially when subjected to conventional heat treatments such as pasteurization, sterilization, and UHT (ultra-high-temperature) treatment, this reaction can be intensified, resulting in significant changes to the product's physicochemical composition (Zhang et al., 2020).

While the Maillard reaction is desirable in certain contexts, as it positively contributes to sensory attributes, its effects on milk are ambivalent. In addition to affecting organoleptic characteristics, it can compromise nutritional value, particularly by reducing the availability of essential amino acids, such as lysine. Furthermore, the formation of Maillard Reaction end products (advanced glycation end products – AGEs) raises concerns regarding the safety and nutritional quality of processed milk, with potential implications for consumer health. From a technological perspective, this reaction also influences the functional properties of milk, affecting its stability, protein solubility, and behavior in subsequent manufacturing processes, such as cheese and yogurt production (Kathuria et al., 2023). The Maillard reaction can be divided into three phases. The first step, involves the condensation of the carbonyl group of an amino acid with a reducing sugar, culminating in the formation of the first stable Maillard compound, the Amadori product. With continued heating, the second phase occurs, characterized by chemical reactions from the Amadori compounds, generating the formation of dicarbonyl compounds, reductones, furfural derivatives, such as 5-hydroxymethylfurfural, and Strecker degradation products. These products correspond to chemical compounds with a wide range of molar masses and occur in foods subjected to any heat treatment, in which case they are referred to as glycation reactions. The third and final phase of the Maillard reaction involves the reaction of intermediate compounds with lysine or arginine residues in proteins, resulting in the formation of stable compounds. This process is accompanied by fragmentation and polymerization reactions, resulting in the generation of melanoidins and fluorescent structures (Wang et al., 2024). In this context, understanding the consequences of the Maillard reaction in the production of conventional dairy products is essential for optimizing industrial processes, balancing sensory quality, nutritional safety, and technological feasibility. This fact is due to the growing consumer demand for high-quality products, which also highlights the need for new processing/preservation technologies that ensure microbiological safety in production, increase shelf life, minimize biochemical changes, and promote the maintenance of milk's nutritional and sensory quality (Hamid et al., 2023).

This manuscript presents a literature review on the impacts of the Maillard reaction on the production of milk and dairy products, such as milk powder and dairy compounds; cheese whey, considered a by-product or secondary product; condensed milk; dehydrated yogurt and cheese; and dulce de leche and ghee butter, highkiting the nutritional, sensory, and technological implications in light of recent scientific evidence. It is worth noting that the choice of these products was due to their susceptibility to the Maillard reaction during industrial processing.

## Maillard reaction

Browning in food can occur enzymatically or non-enzymatically. In food, non-enzymatic browning can occur due to caramelization, the Maillard reaction, and the oxidation of vitamin C. In milk and dairy products, the Maillard reaction can be considered a problem; however, its occurrence is desirable in dairy products such as dulce de leche and ghee, in order to guarantee the sensory characteristics of these products. The Maillard reaction occurs between a reducing sugar and a primary amine when the food is subjected to higher temperatures. As a result of these various chemical reactions, aromas, flavors, and colors can be produced in the food, as well as compounds with antioxidant, antimutagenic, and chemoprotective functions. However, toxic compounds, such as acrolein and heterocyclic amines, can be produced, negatively impacting essential amino acids and reducing the nutritional value of the product (Wang et al., 2024). In milk and dairy products, the initial phase of the Maillard reaction occurs through the interaction of the carbonyl group of lactose and the ε-amino group of the amino acid present in casein or whey proteins. By condensation, these groups form unstable imines, and by heating the raw material, the deprotonated amine group (NHR) is added to the carbonyl group (COH) of lactose (reducing sugar). These unstable compounds are known as Schiff bases or N-glycosylamines. Due to this instability, an isomerization reaction occurs, resulting in the initial products of the Maillard reaction (Figure 1), also called Amadori products when the



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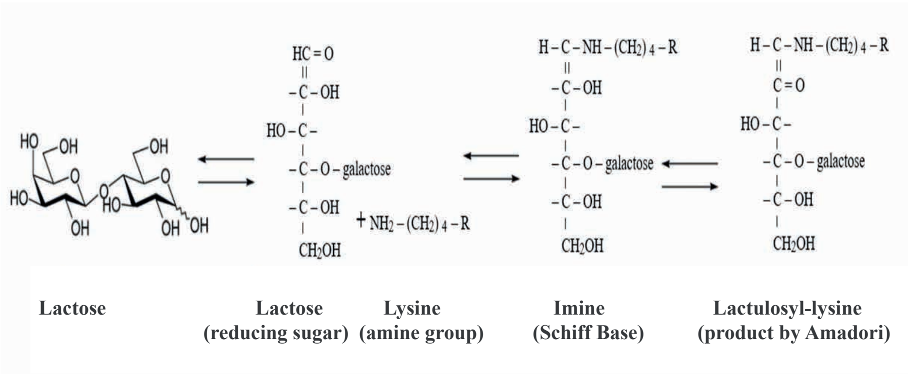
sugar is an aldose (aldosylamines) or Heyns products when it is a ketose (ketosylamines). Thus, these products are glycosylamines that, upon enolization, lose their ring conformation and are colorless and flavorless. Intermediate reactions occur at temperatures above 100°C, resulting in the dehydration and fragmentation of sugars, as well as the degradation of amino acids (Lohinova & Petrusha, 2023).

In reactions with disaccharides, such as lactose, which is found in milk, Amadori products can progress through three reaction pathways, transforming deoxyosones through enolization, cyclization, and dehydration. In the 3-deoxyosone pathway, furfural, hydroxymethylfurfural, and pyrraline are formed through 1,2-enolysis at acidic pH. The 1-deoxyosone pathway operates primarily at neutral or alkaline pH, generating β-pyranone and 3-furanone through a 2,3-enolysis reaction. However, these compounds are unstable, and their fragmentation results in reductones and α-dicarbonyls. The final route of 4-deoxyaminoreductone at slightly alkaline pH forms 4-deoxyaminoreductone and 5,6-dihydro-3-hydroxypyridone, which are degraded upon prolonged heating. This last route occurs when the sugar is a disaccharide, as is the case with lactose in milk. In both routes, the final formation will be melanoidins (Figure 2). These reactions are more complex and can generate a wide variety of byproducts, which are responsible for the development of sensory characteristics. Amadori products are converted into lysine, 30 to 40% to furosine, and between 10 and 20% to pyridoxine, the latter two being amino acids formed by acid hydrolysis (Troise et al., 2016).

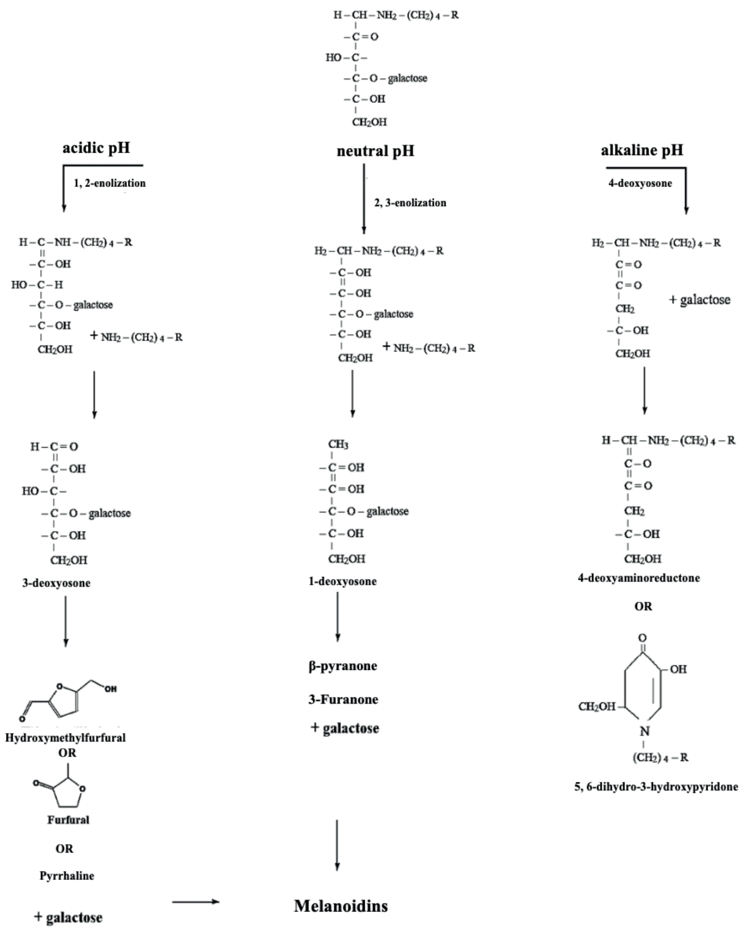
Parallel chemical reactions can form so-called advanced glycation end-products (AGEs) and lipid oxidation end-products (LOE), as shown in Figure 3 (Barbosa et al., 2016). In lactose-free dairy products, due to the enzyme lactase, which produces D-glucose and D-galactose, glycation tends to be more pronounced (Milkovska-Stamenova; Hoffmann, 2016). AGEs are proteins covalently modified by oxidative and non-oxidative processes, between sugars or their degradation products. At the same time, ALEs are products of the reaction between different types of reactive carbonyls and amino acid residues, which are produced from lipid peroxidation and lipid metabolism (Barbosa et al., 2016). AGEs and ALEs are formed in foods and biological systems. They can act on the biological structures of organisms, modifying their properties by generating free radicals, forming cross-links with proteins, altering their functions, and binding to receptors such as RAGE (Receptor for Advanced Glycation End-products), which releases AGE-R1, a receptor for AGEs. These compounds can be formed through other pathways parallel to the Maillard reaction, such as hydrolysis of the Schiff base formed from the initial glycation reaction in the Namiki pathway, and by Wolf oxidation, a metal-catalyzed oxidation reaction (Figure 4). In the Maillard reaction itself, Amadori products can generate α-dicarbonyl compounds considered the main precursors of AGEs and ALEs, as they favor the formation of cross-links between the lysine and arginine residues of proteins (Torres et al., 2018). Some examples of AGEs are CML, Nε-carboxyethyllysine, pyrraline, pentosidine, glucosepane, and imidazole compounds such as GOLD (lysine-glyoxal dimer) and DODIC (condensation product of lysine, arginine, and 3-deoxyglucosone). The carbonyl products generated in the Maillard reaction can undergo condensation with amino acid




R = protein chain

Figure 1: Description of the initial step of the Maillard reaction between lactose and lysine.

Source: Adapted from Newton et al. (2012).




R = protein chain

Figure 2: Description of the intermediate enolization reaction of the Amadori product.

Source: Adapted from Newton et al. (2012).

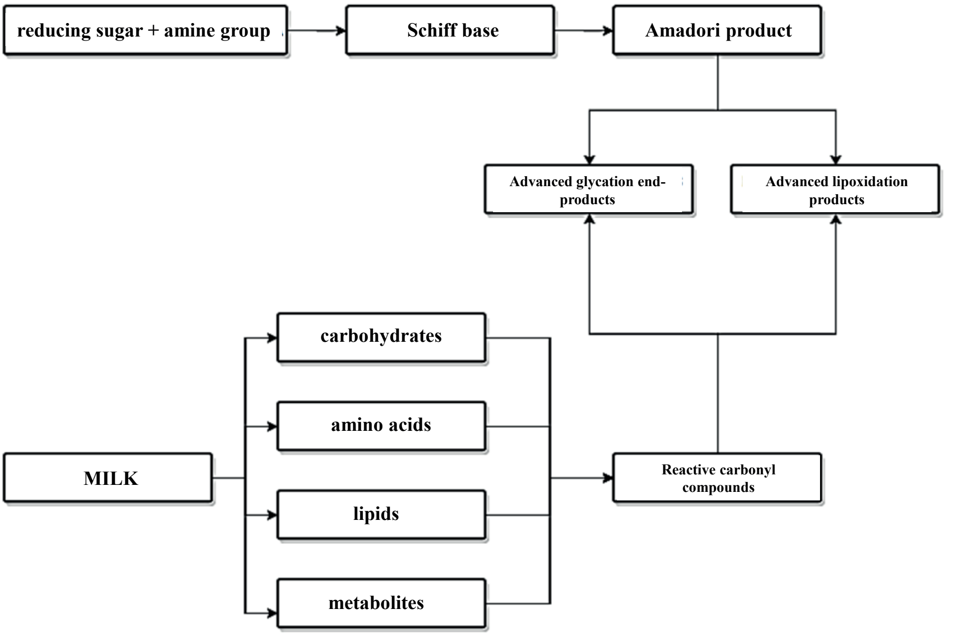



Figure 3: Maillard reaction and the formation of advanced glycation and lipoxidation products.

Source: Adapted from Barbosa et al. (2016).

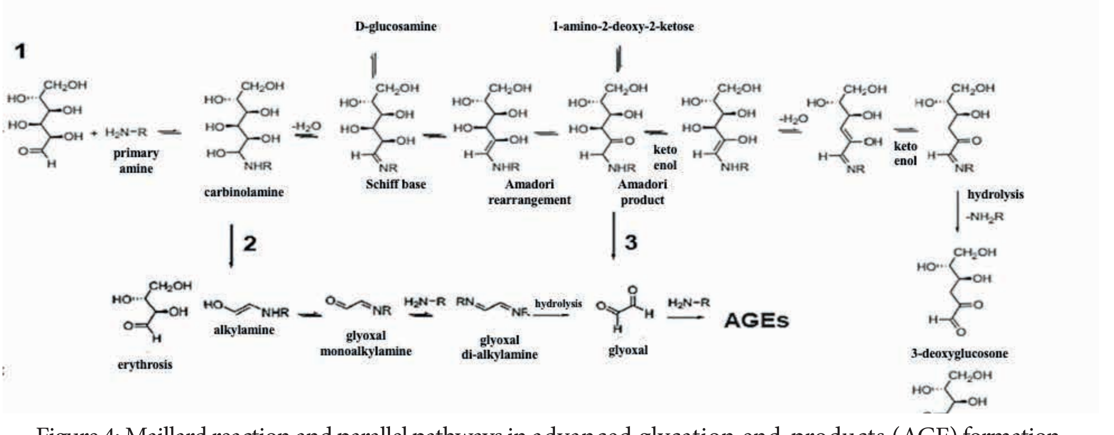



Figure 4: Maillard reaction and parallel pathways in advanced glycation end-products (AGE) formation.

residues, producing high-molecular-weight compounds that are brown in color and difficult to chemically characterize, known as melanoidins (Barbosa et al., 2016).

Factors that affect the Maillard reaction include pH, chemical composition related to the amino acid and sugars present, water activity, time, and, most importantly, the applied temperature. The kinetics of the Maillard reaction are influenced by the external characteristics to which the food is exposed, such as pH, water activity, and time. The compounds formed are related to the type of sugar and amino acid in the food. The pH influences the protonation of the amino group, being important at the beginning of the reaction. It is also important after the formation of the Amadori compound, as it determines the predominant pathway of the reaction and the products it produces. The type of sugar and the nature of its degradation products influence the reaction, producing Amadori intermediates, while ketoses produce the Heyns compound (Newton et al., 2012; Barbosa et al., 2016).

Furthermore, each sugar has a different reaction rate, with monosaccharides reacting faster than disaccharides, as the open structure of the sugar molecule allows for a faster reaction rate compared to cyclic compounds. However, the addition of other sugars can alter the flavor profile. Primary amines are more reactive than secondary amines, while tertiary amines are inactive. Temperature is the primary factor responsible for the Maillard reaction, making the overall reaction rate and relative rates of the reaction pathways dependent on it. Increasing the temperature and using high temperatures cause these reactions to occur at a higher rate (Newton et al., 2012; Barbosa et al., 2016).

Dairy products with a high fat content are exposed to lipid degradation and oxidation. Volatile compounds such as methyl ketones, aldehydes, and free fatty acids are formed and released when fats are heated. These compounds can react with amino acids or Maillard reaction products; however, the Maillard reaction can mitigate this rancidity effect by removing rancid compounds through the reaction and through the antioxidant capacity of some products (Newton et al., 2012). Yáñez et al. (2018) studied the antioxidant activity of Maillard reaction products in dairy products such as powdered milk, condensed milk, and dulce de leche, since milk is a raw material that does not contain other substances with high antioxidant activity. In this study, the Maillard reaction was evaluated by verifying the loss of available lysine in dulce de leche. According to the data obtained, the antioxidant capacity of Maillard reaction products appears to be directly related to the third stage, where melanoidins are formed. These brown compounds are formed in the last stage of the Maillard reaction (Yáñez et al., 2018) (Figure 5).

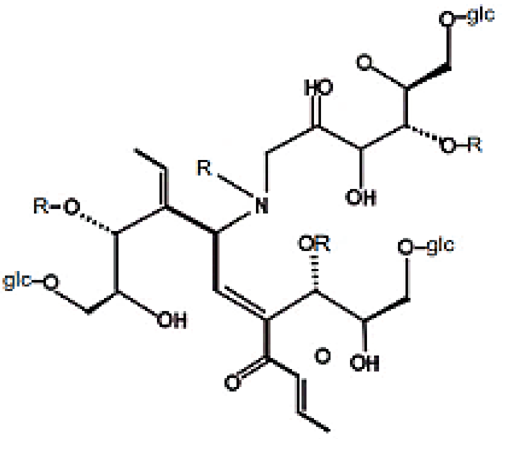



Figure 5: Basic chemical structure of melanoidins..

Source: Nogueira (2019).



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Table 1 presents the main characteristics of the Maillard reaction stages. In milk and dairy products, controlling the production of Maillard reaction compounds remains a significant area of study, as their thermal processing and development can have a positive or negative impact on sensory characteristics, including flavor and aroma. Among the dairy products that are negatively subject to the Maillard reaction due to their processing, fluid milk, condensed milk, powdered milk, powdered dairy compounds, powdered whey, and powdered yogurt stand out. Dulce de leche and ghee have a technologically positive influence.

| Stage | Reaction | Formed products | Characteristics | Activity |
|---|---|---|---|---|
| Initial | Condensation and dehydration | Schiff base, glycosylamine, Amadori product (aldose), or Heyns product (ketose) | No staining, fluorescence, or absorption in the ultraviolet region | - |
| Intermediary | Dehydration, enolization, and retroaldolization | Furosine, hydroxymethylfurfural, carboxymethyllysine, and fluorescent compounds | Fluorescent and absorb ultraviolet radiation.<br>Color and flavor | Carcinogenic<br>Mutagenic |
| Final | Dehydration, cyclization, and polymerization | Melanoidins | Brown to black color<br>Flavor | Antioxidant |

Table 1: Characteristics of the Maillard Reaction stages.

Source: Adapted from Monaro (2012) and Newton et al. (2012)

# The Maillard reaction in milk and dairy products

## Milk

Baptista and Carvalho (2004) evaluated the content of furosine. They blocked lysine (Amadori compounds) and found 9.7 ± 0.2mg/100g of protein and 3% of blocked lysine in raw milk, 89.2 ± 3.1mg/100g of protein and 29% of blocked lysine in pasteurized milk, 42.1 ± 1.1mg/100g of protein and 13% of blocked lysine in lactose-free UHT milk, and UHT milks with samples ranging from 53.2 ± 1.4mg/100g of protein, 78.3 ± 2.7mg/100g of protein and 138 ± 6.2mg/100g of protein with 17%, 25% and 44% of blocked lysine. As heat treatment intensified, these authors observed an increase in the blocked lysine content, as well as an increase in furosine content when compared to raw milk.

Neves and Oliveira (2020) determined the whey protein and hydroxymethylfurfural contents by spectrophotometry in 18 brands of commercial UHT milk with or without lactose. It is worth noting that when the whey protein nitrogen value is above 6 mg/mL, the product is classified as supplied below heating. In contrast, contents between 1.51 and 5.99 mg/mL are classified as medium heating, and below 1.50 mg/mL are classified as high heating. Thus, the results obtained by Neves and Oliveira (2020) indicated that 75% of the UHT milk samples evaluated were classified as medium heating products and 24% as high heating products. In this study, the milk samples with lactose presented free hydroxymethylfurfural levels between 2.30 and 3.27 µmol/L and lactose-free milk samples of 6.08 and 6.89 µmol/L, while the total hydroxymethylfurfural levels were between 11.67 and 12.39 μmol/L for the milk with lactose and 132.28 and 143.22 μmol/L for the lactose-free milk. Therefore, it was shown that the lactose-free milk samples presented the highest values for the hydroxymethylfurfural compound, which would be explained by the high reactivity of glucose in the formation of this compound. In a study by Milkovska-Stamenova and Hoffmann (2016), samples of pasteurized milk and UHT milk, both lactose-free, showed higher glycation levels compared to milks containing lactose. These authors attributed this to greater glucose reactivity, in agreement with the results found by Neves and Oliveira (2020).

In the study by Li et al. (2023), tea polyphenols were used as potential inhibitors of Maillard formation in heat-treated milk. In this study, the results showed that the flavor profile of milk did not change after the addition of 0.08% (w/w) polyphenols. Their inhibition rates on 5-hydroxymethyl-2-furaldehyde (5-HMF), glyoxal (GO), methylglyoxal (MGO), Nε-carboxymethyl lysine (CML), and Nε-carboxyethyl lysine (CEL) were 60.8%, 27.12%, 23.44%, 57.7%, and 31.28%, respectively. After 21 days of storage, the levels of 5-HMF, GO, MGO, CML, and CEL in the polyphenol-fermented whole milk were 46.3%, 9.7%, 20.6%, 5.2%, and 24.7% lower than those in the control group, respectively. Furthermore, the carryover is lower than that in the control group. The importance of this study lies in its inclusion of polyphenols as additives to inhibit Maillard products in fermented whole yogurt, without altering color or flavor, thereby making dairy products safer for consumers.

According to Singh et al. (2021), the main Maillard products formed in lactose-free dairy products are hydroxymethylfurfural, lactulosyl lysine, and advanced glycation end products, such as carboxymethyl lysine and carboxyethyl lysine. These Maillard products are responsible for decreasing the sensory and nutritional quality of dairy products (Singh et al., 2021). Meanwhile, Singh et al. (2021) noted that some strategies to mitigate the Maillard effect in lactose-free products have already been employed, such as the addition of various additives such as green tea or fruit polyphenols; the replacement of sugar with galactose; changing process parameters, such as inlet and outlet temperatures used in the spray dryer equipment; and adding enzymes that react directly or indirectly with the reagents and substances transmitted by the Maillard occurrence.

## Milk powder and dairy compounds

Milk powder is a dairy product obtained through the dehydration process of cow's milk, and can be whole, skim, or partially skimmed. To obtain it, the milk undergoes technologically appropriate processes, but with the application of high temperatures. Milk powder compounds are products obtained from a mixture of milk and other dairy-based products or food substances, or those not obtained through technologically appropriate processes. Dairy compounds can be produced exclusively with dairy ingredients or with the addition of non-dairy ingredients. However, when non-dairy ingredients are used, 51% of their composition must be dairy ingredients (Cunha et al., 2022).

For dairy compounds, replacing milk powder with whey results in a greater formation of Maillard products (Bolchini et al., 2025). Regarding powdered milk, Baptista and Carvalho (2004) evaluated the furosine content during its storage. In fresh powdered milk, this content was 51.5 ± 1.8 mg of furosine per 100 g of protein, with 16% blocked lysine. After one year of storage at 4°C, the furosine value was 56.3 ± 1.9 mg per 100 g of protein and 18% blocked lysine. At room temperature, after one and two years of storage, the furosine value was 275.1 ± 12.4 and 448.3 ± 23.2 mg per 100 g of protein, respectively. The results obtained by Baptista and Carvalho (2004) indicated that, using powdered milk storage at room temperature, 88% and 143% of the lysine was blocked. Furosine is the main indicator investigated because it is related to the unavailability of the essential amino acid lysine. Its formation occurs early in the process when lysine interacts with a reducing sugar, resulting in the loss of its amino group. This process may indicate the intensity of the treatment applied to the dairy product (Monaro, 2012).

Bastos et al. (2011) evaluated the levels of hydroxymethylfurfural, furfurine, and carboxymethyllysine in powdered whole milk. These authors evaluated these compounds because they are produced at different stages of the Maillard process, thus allowing them to determine whether the heat treatment applied was responsible for nutrient losses. Based on the data obtained, the milk had a carboxymethyllysine content of 21 ng/mg of protein, a value considered low, but for furosine, they obtained 58.87 mg/100 g of protein. The low values found can be explained by the compromised thermal processing strategies, under conditions that reduce the occurrence of Maillard to reduce losses in nutritional value (Bastos et al., 2011).

Phosanam et al. (2020) evaluated the effect of storage conditions: 25°C and 11% relative humidity; 35°C and 44% relative humidity; and 45°C and 85% relative humidity; on the color of skim and whole milk powder. As a result of this study, it was observed that during storage for 21 days at 45°C and 85% humidity, there was greater brown coloration, which the authors linked to the occurrence of Maillard, due to the association of lysine with reducing sugars, such as lactose. It was also found that milk samples stored at 85% humidity contained a greater amount of crystallized lactose, resulting in greater darkening, also induced by the occurrence of Maillard. Thus, Phosanam et al. (2020) concluded that the higher storage temperatures and higher moisture content evaluated in their study favored the occurrence of Maillard. These authors also concluded that moisture content was responsible for the final stage of Maillard occurrence. At the same time, increased lactose crystallization increased the darkening rate due to the release of water during the crystallization process, freeing the milk proteins and lactose. The temperature conditions of 25°C and 11% relative humidity achieved the lowest darkening, followed by 35°C and 44% relative humidity (Phosanam et al., 2020).

Li et al. (2021) evaluated the chemical changes in different types of whole milk powder previously treated with different thermal processes. One sample of still-fluid milk underwent a slow pasteurization process (LTLT), while others were subjected to rapid pasteurization (HTST), ultra-high temperature (UHT), and bottle sterilization. All samples were dehydrated in a spray dryer and stored in sealed polyethylene packaging for 18 months at a constant temperature of 25°C. The levels of total furfurals, such as 5-hydroxymethyl-2-furaldehyde, 2-furaldehyde, 5-methyl-2-furfural, and 2-furyl methyl ketone, were evaluated. Lysine residues, initial products of the Maillard reaction with furosine, and advanced glycation end products (AGEs) such as Nε-(-carboxymethyl)lysine, Nε-(carboxyethyl) lysine, and pyrraline were also evaluated. This study found that lysine content decreased with storage in all heat-treated and dehydrated milk samples. Furosine content increased in all types of milk powder during storage. At the beginning of storage, furosine levels in milk powder obtained from milk pasteurized by the LTLT and HTST processes were 1.8- and 3.3-fold lower, respectively, than those observed with the other processes. After 18 months of storage, milk powder previously subjected to LTLT pasteurization had the lowest furosine content, while that sterilized in bottles had the highest content. Also, during storage, the values for Nε-(carboxymethyl)lysine increased the most in milk powders previously sterilized in bottles, followed by milk powders previously subjected to UHT, LTLT, and HTST heat treatments. The Nε-(carboxyethyl)lysine content increased 68% and 90% for milk powders from UHT milk and milk sterilized in bottles, respectively. In the milk powder samples evaluated, the pyrraline content was lower, while the 5-hydroxymethyl-2-furaldehyde content was higher. The 2-furaldehyde content increased 3.6-fold in milk powder obtained from milk pasteurized by the LTLT process, 2.8-fold in milk powder obtained from milk pasteurized by the HTST process, 3.2-fold in milk powder from UHT milk, and 3.1-fold in milk powder from milk sterilized in bottles. The 5-methyl-2-furfural content increased in milk powder produced from UHT milk and sterilized in bottles. The 2-furylmethyl ketone content decreased with storage time and heat treatment intensity (LI et al., 2021).

To better monitor and reduce the generation of Maillard reaction products during heat treatment and storage of milk powder products, Li et al. (2023) developed a reaction kinetic model. This kinetic model aimed to combine the inhibitory effects of tea polyphenols on Maillard reaction products in a milk simulation system. The inhibition of Maillard reaction products by tea polyphenols followed first-order kinetics, while the inhibition of 5-hydroxymethyl-2-furfural was most pronounced at 95 °C. The Arrhenius model showed that the conversion rate of 5-hydroxymethyl-2-furfural was higher than that of Nε-carboxyethyllysine and Nε-carboxymethyllysine after the addition of tea polyphenols, which indicated that 5-hydroxymethyl-2-furfural was the main intermediate product of the Maillard reaction. Again, the shelf life of the two-stage sterile sample containing tea polyphenols was 141 days, 2.1 times longer than that of the control sample (67 days) (Li et al., 2023).

## Cheese whey

Cheese whey is considered a byproduct of the dairy industry. It is defined as the product resulting from the milk coagulation process, used in the production of cheese, edible casein, and similar products. Whey can be reused in the production of dairy products, either in liquid form or dehydrated using appropriate technologies, such as removing part of the water through a concentration process, followed by dehydration. During the process of obtaining



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whey powder, concerns have been raised about the emergence of Maillard reaction compounds (Bolchini et al., 2025).

Gómez-Narváez et al. (2019) analyzed the Maillard reaction in whey through the reduction in the levels of lysine, furosine, hydroxymethylfurfural, and furfural, and the appearance of brown coloration during heating treatments. Thus, this study analyzed five samples with different moisture contents and temperatures ranging from 60 to 90°C. The maximum loss of lysine, furosine, and hydroxymethylfurfural was observed when samples with lower moisture contents were used, after 40 minutes of treatment at a temperature of 90°C. Furfural was not detected and, according to these authors, was likely due to lactose degradation as a result of the Maillard reaction, favoring the formation of hydroxymethylfurfural. Thus, they also concluded that low moisture content causes lactose to remain in an amorphous state for longer, resulting in a longer crystallization delay, favoring the Maillard reaction. These authors also evaluated the browning index of whey powder by increasing the concentration of melanoidins, which are brown pigments formed in the final stages of the Maillard reaction. This effect was more pronounced when a temperature of 90°C was applied for 40 minutes. Another study in whey was carried out by Ferreira et al. (2019), who evaluated ohmic heating in whey-based beverages and concluded that when higher values were used for voltage (~80 V) and frequency (60 Hz), the emergence of secondary compounds from the Maillard reaction was greater. Like these studies, which involve increasing the temperature in whey and the emergence of Maillard reaction compounds, others have been carried out. Akhtar and Dickinson (2007) investigated the antioxidant action and physical properties in a system with whey proteins through the Maillard reaction. Chawla et al. (2009) and Rao et al. (2011) evaluated the antioxidant properties of the Maillard reaction products of whey subjected to gamma irradiation. Spotti et al. (2013), Doost et al. (2019), Wang et al. (2020) and Zhang et al. (2020), obtained good results regarding the functional properties and antioxidant activities of conjugates from the Maillard reaction of whey protein and dextran, only whey proteins, isolated whey proteins and galactose, and isolated whey protein and inulin, respectively.

## Condensed milk

Condensed milk is defined as the product obtained by partially removing water from milk. It can be concentrated or reconstituted with added sugar. This product is obtained in the dairy industry using a multiple-effect evaporator (Sampaio et al., 2024).

Patel et al. (1996) analyzed the hydroxymethylfurfural content in condensed milk at different temperatures (7, 15, 30, 45, and 55°C) during storage for 180 days. At the end of this study, they observed an increase in the hydroxymethylfurfural content in condensed milk, which was greatest when stored at 55°C for 10 days. However, when condensed milk was stored at 7, 15, and 35°C, an increase was observed only after day 30. The greatest increase was observed at 55°C, that is, at the highest temperature evaluated (Patel et al., 1996). Leonhardt (2015) analyzed the color of seven condensed milk samples before and after storage to evaluate the effectiveness of Maillard reaction inhibitors. In this study, the sample produced without the use of Maillard reaction inhibitors showed increased darkening. To minimize the occurrence of the Maillard reaction, sodium metabisulfite (0.01 and 0.05%) and ascorbic acid (0.01, 0.05, and 0.10%) were added to other samples, respectively. Lightening was observed in the samples added with sodium metabisulfite, while the samples with ascorbic acid showed darkening during storage. This study, conducted by Leonhardt (2015), concluded that ascorbic acid did not reduce the effects of the Maillard reaction and is not considered an inhibitor of this reaction in condensed milk. In a study carried out by Milkovska-Stamenova and Hoffmann (2016) was observed differences in color between products with and without lactose (Figure 6), attributing the darker color of condensed milk to its higher glycation rate due to the higher content of D-glucose and D-galactose. On the other hand, Lohinova and Petrusha (2023) reported that the formation of certain reaction products depends on the stage of sucrose addition in condensed milk. If sucrose is added before high-temperature processing, an increase in Maillard reaction in condensed milk is observed.

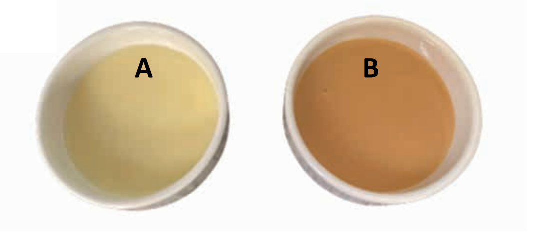


Figure 6: Representation of the color difference of condensed milk (A) with lactose and (B) without lactose.

## Dehydrated yogurt and cheese

Dehydrated yogurt and cheese are considered innovative products designed to extend the shelf life of dairy products and facilitate their use in food preparation. These products can be obtained through spray drying or freeze-drying. Yogurt products, such as yogurt foams dehydrated in a spray dryer or freeze dryer, were evaluated physicochemically and sensorially by Carvalho et al. (2017). These authors observed that freeze-drying, because it does not use high temperatures, was able to maintain the flavor and original color of the dehydrated yogurt foam. In the foam dehydrated in a spray dryer, darkening was selected, which is attributed to the occurrence of Maillard. Thus, in this study, the presence of lactose and yogurt proteins, together with the decrease in water activity during hydration, potentiated the occurrence of Maillard.

Erbay et al. (2015) and Koca et al. (2015) evaluated the optimization of the spray-drying process for cheese dehydration. In these studies, it was found that the outlet temperature (>85°C) of the spray dryer had the greatest influence on the browning of the powdered cheese. In both studies, non--enzymatic browning, resulting from the Maillard process, was attributed to the color change of the cheeses.

In the study by Bolchini et al. (2025), the antioxidant potential of products resulting from the Maillard process of different types of whey was evaluated, such as those resulting from the production of cow's milk and goat's milk cheese. This study highlighted the applicability of the whey dehydration process for cheese preservation. Thus, whey samples were subjected to a temperature of 140°C for 90 min, revealing significant consumption of amino acids and



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sugars, particularly arginine, histidine, and lactose. Subsequently, key compounds such as 2-pyrrolecarboxaldehyde and the maltol isomer were identified, primarily in bovine cheese whey. Additionally, additional antioxidant substances were identified, with distinct production patterns specific to the whey type. Multivariate analyses confirmed that the whey type strongly influences the Maillard occurrence product profiles. The results obtained in this study highlight the potential of Maillard evidence for transforming whey byproducts into valuable sources of natural antioxidants. The approach taken by Bolchini et al. (2025) offers sustainable strategies to improve food preservation, reduce food waste, and support the targeted use of Maillard occurrence products in the food industry.

## Dulce de leche and ghee butter

In some dairy products, such as dulce de leche and ghee, the early stages of the Maillard reaction are desirable, aiming to produce compounds responsible for the product's aroma and flavor. However, prolonged heating can result in the formation of compounds such as 5-hydroxymethylfurfural, classified in the literature as toxic and capable of causing harm to the consumer's health (Francisquini et al., 2017).

Dulce de leche is the product obtained by concentrating fluid milk or reconstituted milk under normal or reduced pressure, with or without the addition of milk solids and/or cream with added sucrose, monosaccharides, and/or other disaccharides, with or without the addition of other food substances, such as sodium bicarbonate, to neutralize acidity and prevent protein coagulation. The mandatory ingredients are milk and sucrose, with the sucrose ratio varying depending on whether the dulce de leche is creamy or bar-like (Stephani et al., 2019). Some compounds formed during the Maillard reaction are important for enhancing the sensory characteristics of dulce de leche, such as furans, lactones, 2-methylfuran, 2-furan-methanol, furfural, and butyrolactone (Vargas et al., 2021).

Pavlovic et al. (1994) conducted an experiment analyzing dulce de leche, proteins, amino acids, hydroxymethylfurfural, and the formation of dark pigments during processing between 0 and 150 minutes. At the end of this study, a reduction in amino acids was observed, with a notable decrease in lysine content, followed by arginine and histidine. In this study, the formation of a darker color in dulce de leche was associated with longer processing time and the loss of lysine, arginine, and histidine. Silva et al. (2020) used pulsed electric fields to treat milk for the production of dulce de leche. They found that increasing the intensity improved the sensory properties of the dulce de leche. Francisquini et al. (2018) investigated whether differences in the dulce de leche formulation could influence the formation of hydroxymethylfurfural. These authors found that the use of glucose and sodium bicarbonate contributed to the intensification of the Maillard reaction (Francisquini et al., 2018).

According to Bottiroli et al. (2023), lactose-free dairy products, such as dulce de leche, can undergo chemical and sensory changes due to the high reactivity of glucose and galactose formed during lactose hydrolysis. In this study, the impact of lactose hydrolysis on the quality of dulce de leche was investigated. A full factorial design was used to study the effect of lactose hydrolysis, sodium bicarbonate ($NaHCO_3$), and sucrose addition on the physicochemical composition, 5-hydroxymethylfurfural formation, color changes, texture, and volatile organic compound profile of dulce de leche. Finally, this study observed that lactose-free dulce de leche was also harder, stickier, and richer in volatile products of the Maillard reaction. The results obtained in this study corroborate those obtained by Mercan and Yüksel (2023), who prepared dulce de leche with two different sucrose concentrations (16% and 20%), with and without lactose. From this study, it was found that lactose hydrolysis caused significant changes in the color parameters and sensory profile of the samples.

Like dulce de leche, ghee is a dairy product in which the Maillard reaction is desirable to some extent. Ghee is composed of at least 95% lipids. However, its manufacturing methods vary depending on the raw material, the intermediate treatment applied, and the post-process handling (Figure 7). The flavor of ghee is attributed to the Maillard reaction compounds, free fatty acids, lipid oxidation, and fermentation (Newton et al., 2012).

Because butter is subjected to heat, the heating process affects its oxidation, flavor, nutritional value, and biological activity (Yokogawa et al., 2023). Therefore, the study by Yokogawa et al. (2023) focused on the progression of the Maillard reaction and free radical scavenging activity with temperature and time during the preparation of ghee. However, ghee was first prepared at low to high temperatures, and its quality (milk fat content, retinol, α-tocopherol, peroxide value, Maillard reaction progress, and free radical scavenging activity) was evaluated. This study showed that the progression of the Maillard reaction was enhanced at medium and high temperatures (120–160°C), and the free radical scavenging activity of ghee corresponded to the progression of the Maillard reaction. However, because ghee is frequently reheated during use, Yokogawa et al. (2023) evaluated the effect of the reheating process. This study concluded that the reheating process did not alter the progress of the Maillard reaction or its free radical scavenging activity. Feng et al. (2022) reported that the Maillard reaction products in ghee are essential for its unique and desirable flavors and aromas, distinguishing it from other dairy products. These authors also highlighted that these compounds increase the antioxidant capacity of ghee, helping to scavenge free radicals and potentially improving shelf life. However, excessive Maillard reaction or prolonged storage can lead to the degradation of some flavor compounds and the formation of potentially harmful byproducts (Feng et al., 2022).

## Conclusions

At the end of this review manuscript, it was concluded that the Maillard reaction represents a central chemical phenomenon in thermal processes in the dairy industry, with ambiguous effects on product quality. While it positively contributes to the sensory properties of some dairy products, it can compromise nutritional value and generate potentially harmful compounds in others. The reaction is more prevalent in lactose-free milks due to the greater reactivity of glucose and galactose formed during lactose hydrolysis. Strict control of processing and storage parameters, combined with the use of inhibitors, emerges as an effective strategy to minimize its undesirable effects. Therefore, a thorough understanding of the Maillard reaction is essential to optimize dairy production, balancing food safety, technological stability, and sensory quality.

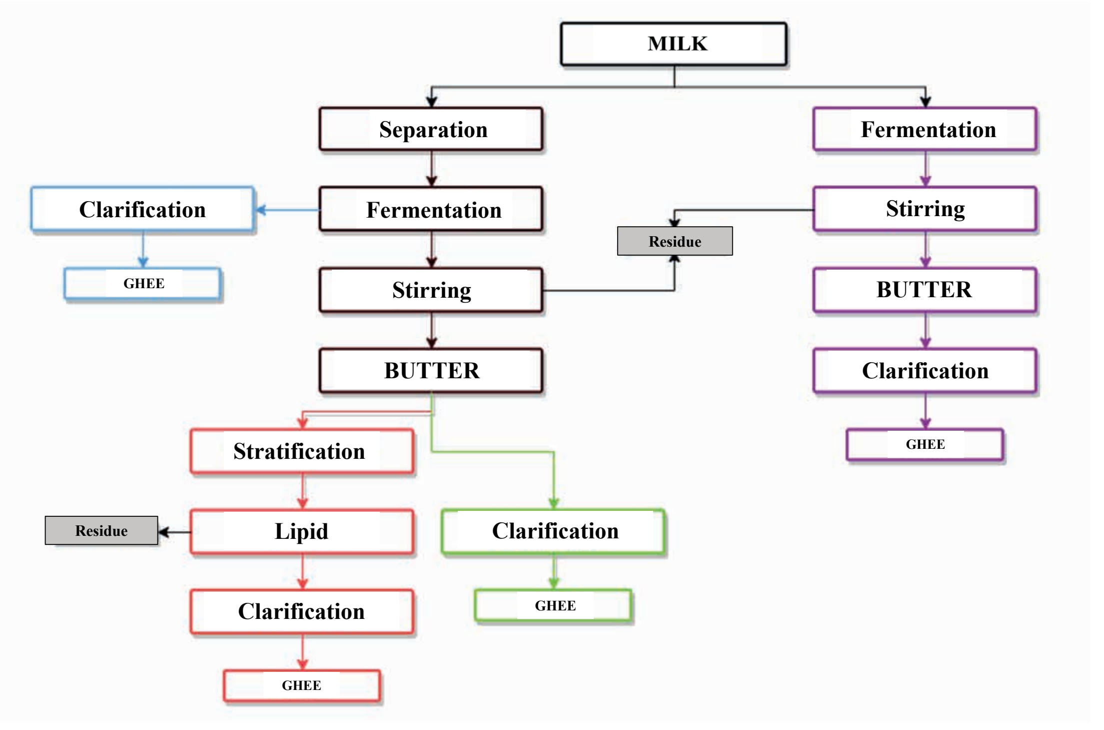


Figure 7: Steps in the methods for obtaining Ghee butter.

Blue = direct cream method, Red = stratification method, Green = cream butter method, Purple = milk butter method, Black = steps common to the different methods of obtaining ghee.

Source: Adapted from Sserunjogia et al. (1998).

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