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Advanced glycation end product in food: Formation, dietary sources, and strategies for health

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Abstract

Advanced glycation end products (AGEs) are compounds formed when sugars react with proteins and fats, especially during cooking and food processing. Once in the body, they interact with receptors like receptor for advanced glycation end-products (RAGE), triggering biological responses linked to chronic diseases. The most common AGEs found in foods is Nε-carboxymethyllysine which is linked to a number of possible negative health outcomes. Growing concerns about their health impact have increased interest in understanding their dietary sources and formation. This review explores how AGEs develop in food and ways to reduce their intake through cooking methods and dietary choices. By making informed food decisions, we can limit AGEs exposure and promote better health.

1. Introduction

Advanced glycation end products are a class of compounds that have attracted growing attention in the field of nutrition and health due to their potential implications for human well-being (Meerwaldt *et al.*,2008). AGEs can originate from external sources or within the body, through diverse processes and from variety of precursors (Chaudhuri *et al.*,2018). Typically, they form through non-enzymatic reactions where carbonyl groups of sugars react with free amine groups of nucleic acids, proteins, or lipids, leading to stable, irreversible products after subsequent rearrangements (Prashad *et al.*,2017). The generation of AGEs in food is a complex procedure encompassing the Maillard reaction, known for its role in the browning and flavor enhancement of numerous cooked food items (Vlassara *et al.*, 2002). Standard cooking techniques like grilling, frying, baking, and roasting can enhance the formation of AGEs in different food preparations (Šebeková and Somoza, 2007).

While AGEs are naturally formed in small quantities as part of normal metabolism, their excessive accumulation has been associated with a wide range of chronic diseases and the ageing process itself. These compounds are known for their ability to provoke inflammation, oxidative stress, and tissue damage, thus contributing to the pathophysiology of conditions such as diabetes, cardiovascular disease, neurodegenerative disorders, and more (Rajendran *et al.*, 2018). Moreover, dietary intake of AGEs, often through the consumption of foods subjected to high-heat cooking methods, can further exacerbate the burden of these compounds in the body (Liguori *et al.*, 2018). More and more research is highlighting the benefits of functional foods and plant-based bioactive compounds in reducing the intake of harmful dietary AGEs. Natural compounds like polyphenols, flavonoids, and other phytochemicals found in fruits, vegetables, herbs, and medicinal plants are known for their powerful antioxidant and anti-glycation effects. These plant-derived compounds not only help slow down AGE formation, but also offer protective health benefits, making them valuable in promoting a healthier diet and reducing the risks associated with excessive consumption (Vignesh *et al.*, 2024; Tadiboyina *et al.*, 2024; Ullagaddi and Murkhandi, 2024).

This review provides an indepth examination of the formation of AGEs in food, their sources in the diet, and strategies for managing AGE intake to mitigate health risks.

2. Exploring AGE consumption patterns and dietary correlations

No regulation address AGEs formation, but provide guidance and regulations related to food safety, which indirectly contribute to reducing AGEs during food preparation by promoting healthier cooking methods and proper food handling. Limited data exists regarding the general population's consumption of AGEs. In a research study conducted with healthy adults in New York, the average daily intake of AGEs was identified as 14,700 kilounits (kU). These factors were significant contributors to the development of conditions like diabetes, cardiovascular diseases, and ageing-related disorders (Uribarri *et al.*, 2010). Male participants consumed an average of 10570.92 ± 794.57 kU of AGEs per day, whereas female participants had an intake of 8534.12 ± 318.97 kU (p<0.05). A notable correlation was noted between participants consumption of red meat, potatoes, almonds,

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and pistachios and their AGE intake ($p<0.05$). However, there was no significant correlation observed between participants intake of milk, yogurt, cheese, dairy products, and their AGE consumption ($p>0.05$) reported by Erim and Garipoðlu (2020). Dietary exposure to AGEs results from the Maillard reaction, where sugars react with proteins or fats during high-heat cooking methods like frying, grilling, and baking. High AGE levels in the diet are associated with increased inflammation and oxidative stress, contributing to negative health outcomes.

3. Mechanism of AGE formation in food

3.1 Maillard reaction

The Maillard reaction is a fundamental chemical process in food science, responsible for the rich flavors, aromas, and browning observed in cooked and processed foods (Liu *et al.*, 2023). This intricate reaction occurs when reducing sugars, such as glucose and fructose, interact with amino acid particularly lysine and arginine as well as proteins and lipids under high-temperature conditions (Ames, 1992). While this process enhances sensory qualities, it also leads to the formation of AGEs, compounds that have raised concerns due to their potential health implications (Goldberg *et al.*, 2004). The production of AGEs is especially pronounced during high-heat cooking methods like grilling, frying, baking, and roasting (Nursten, 2005).

This complex series of reactions occurs over a span of weeks or months, as illustrated in Figure 1. It begins with the formation of unstable Schiff bases, which convert into more stable keto-amines known as Amadori products. These early reactions are reversible and influenced by substrate concentration and reaction time. Schiff bases can undergo oxidation, generating free radicals and reactive carbonyl intermediates (Abdul and Khaleel, 2009). In the propagation phase, Amadori rearrangement leads to oxidation and the formation of carbonyl compounds like methylglyoxal, glyoxal, and 3-deoxyglucosone. These intermediates set the stage for the advanced phase, where dicarbonyl compounds react irreversibly with arginine and lysine residues in proteins, forming AGEs (Thorpe and Baynes, 2003). Key AGEs produced include pyrraline and pentosidine. Since the advanced phase is irreversible, it marks the completion of the Maillard reaction, contributing to the formation of AGEs in food and biological systems.

AGEs include compounds such as methylglyoxal-lysine dimer (MOLD), pentosidine, pyrraline, carboxymethyl-lysine (CML), and carboxyethyl-lysine (CEL), all linked by lysine residues. These compounds serve as biomarkers for AGEs accumulation in disease conditions like diabetes, with CML being the most prevalent AGEs *in vivo* (Khan *et al.*, 2018). AGEs also include glyoxal, methylglyoxal, furan, acrylamide, and bis (lysyl) imidazolium derivatives like glyoxal-derived lysine dimer (GOLD) and deoxyglucosone-derived lysine dimer (DOLD), commonly found in food (Gill *et al.*, 2019).

It is important to understand that the presence of amine and free carbonyl groups, as well as temperature, pH, humidity, and other variables, all have a complex impact on this reaction process. According to Gokhale *et al.* (2009), these variables also affect the final compounds variety of chemical structures and biological effects, as well as their colour, scent, taste, and general palatability.

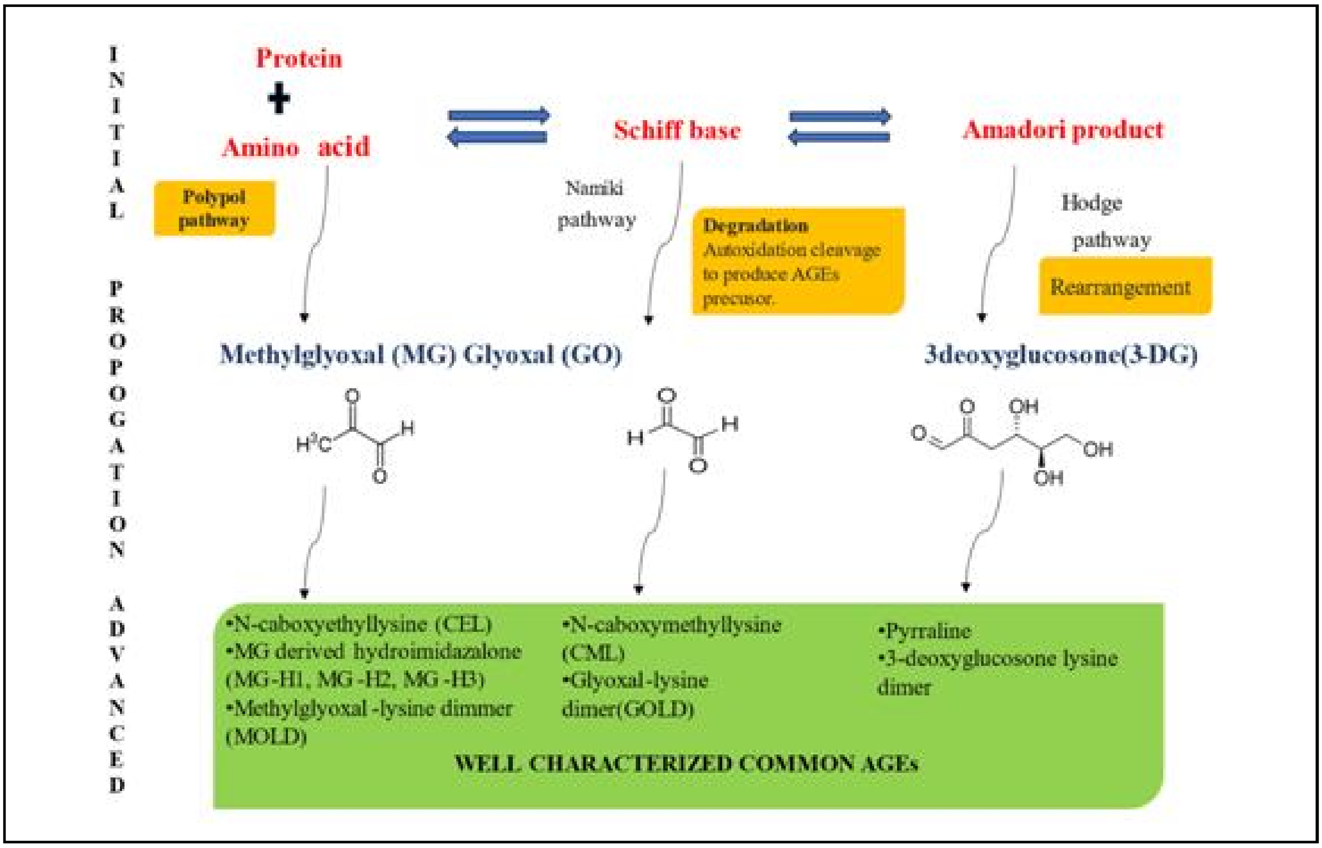

Figure 1: Pathway of the AGEs formation from the Maillard reaction including three phases.

3.2 Lipooxidation

Lipoxidation is primarily driven by lipid autoxidation and the formation of lipid hydroperoxides, which results in the production of highly reactive carbonyl molecules. When these carbonyl compounds start glycation processes in the presence of reducing sugars, early glycation products are created (Vistoli *et al.*, 2013). These intermediates have the ability to undergo further rearrangements and cross-linking to produce stable AGEs, which are known to contribute to a number of chronic illnesses, including as diabetes and cardiovascular conditions. A crucial stage in this process involves the oxidative alteration of proteins by lipid hydroperoxides, which makes proteins more vulnerable to glycation (Chen *et al.*, 2022). Numerous lipid peroxidation products, including RCCs and more stable compounds like ketones and alkanes, are produced when oxidants and oxidative stress promote lipid peroxidation (Figure 2). Glycation and lipoxidation interact in a way that emphasises how important it is to understand these processes in regard to food and human health (Bochkov *et al.*, 2010).

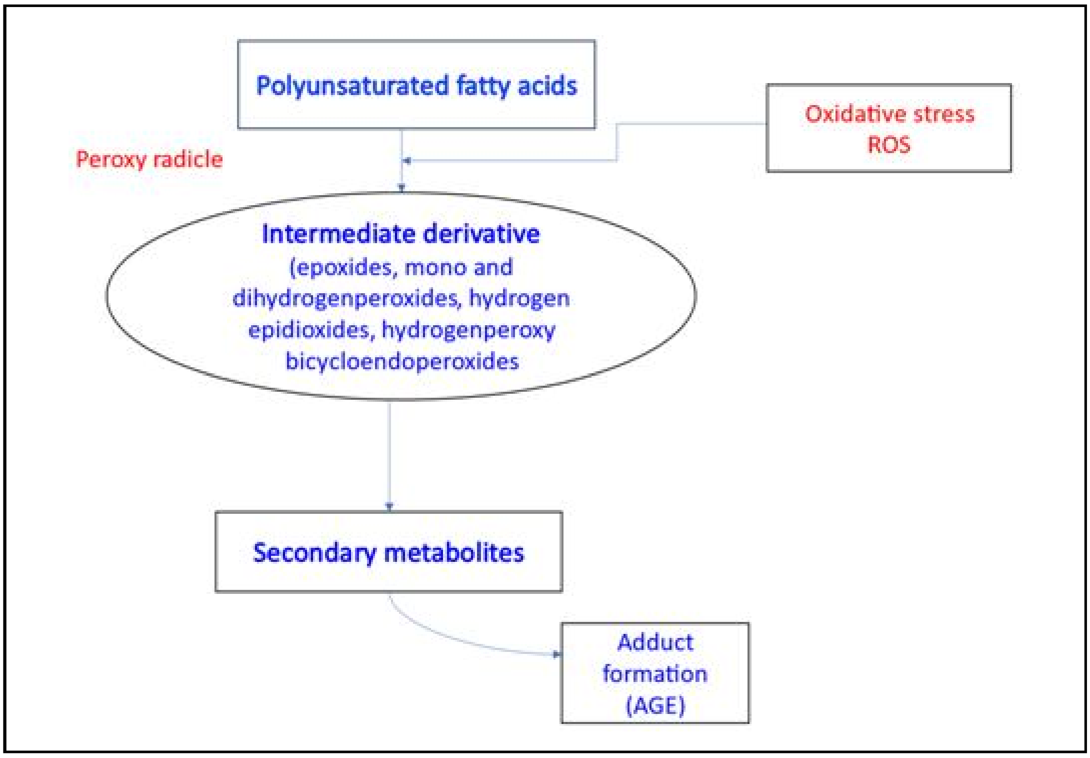

Figure 2: Pathway of the AGEs formation from the polyunsaturated fatty acid (Negre-Salvayre *et al.*, 2008).

3.3 Glycooxidation

This intricate process results in the formation of Schiff bases or Amadori products through the non-enzymatic reaction between reducing sugars and the free amino groups of proteins, lipids, or nucleic acids. These early glycation products eventually experience additional oxidative processes like fragmentation, dehydration, and rearrangements, which result in the creation of extremely reactive and irreversible AGEs (Shamsi *et al.,* 2019). These AGEs can then interact with their receptors, such as the RAGE, triggering proinflammatory pathways and oxidative stress, ultimately contributing to tissue damage and chronic diseases (Vlassara *et al.,* 2002; Singh *et al.,* 2001).

4. Dietary sources of AGE

4.1 Animal-derived foods

Meat and meat products have high AGE levels due to their protein and fat content. Cooking techniques significantly impact AGE formation, with dry-heat methods like roasting, grilling, and frying increasing levels, while boiling and steaming reduce them. Various meats, including beef, chicken, and fish, showed the highest AGE concentrations when cooked with dry heat (Estévez *et al.*, 2017). In contrast, lamb had significantly lower AGE levels. Cooking methods also influence AGE content, as boiling or steaming chicken reduces AGEs by approximately 25% compared to roasting or grilling. Similarly, frying, roasting, and grilling elevate AGE levels compared to moist-heat methods. For instance, grilled chicken contains more AGEs than boiled red meat (Uribarri *et al.*, 2010).

Cheese has the highest amount of AGEs among milk and dairy products (Goldberg *et al.*, 2004). Even though, it is well known that heating causes the development of new AGEs in food, uncooked, animal-based foods like cheese have been shown to have significant levels of AGEs (Table 2). The pasteurisation procedure and the waiting period at room temperature are the causes of AGE formation in dairy products (El-Tayeb *et al.,*2023). AGE content is higher in full-fat or aged cheeses like Parmesan than in low-fat cheeses like cottage cheese and cheddar. Furthermore, foods high in water content, including yoghurt and milk, have a low AGE content (Uribarri *et al.*, 2010).

4.2 Plant-derived foods

Fruits and vegetables are rich sources of vitamins, minerals, fibre, organic acids, and cellulose while being low in calories (Ay, 2020).

They support digestive health and provide essential nutrition. Research indicates that their AGEs content is minimal due to their low protein and fat content and high water content (Nowotny *et al.*, 2018). Additionally, their abundant antioxidants may help reduce AGE levels in meals (Abdel-Daim *et al.*, 2019). While freezing, canning, and juicing do not affect AGE levels, drying increases them, though dried fruits still contain fewer AGEs than animal-based foods (Uribarri *et al.*, 2010).

Grains serve as a vital dietary staple for over 60% of the global population, offering a rich source of proteins, fats, carbohydrates, vitamins, minerals, and dietary fiber (Ay, 2020; Bouchard *et al.,* 2022). Their high nutritional value makes them excellent carriers of bioactive compounds and nutraceuticals. Compared to meat and fat-based foods, grains generally contain lower levels of advanced glycation end products (AGEs), likely due to their high water content, antioxidants, and carbohydrates. Even after cooking, staples like rice and pasta maintain relatively low AGE levels (Van Nguyen, 2006). However, processed grain products such as chips, crackers, and biscuits exhibit elevated AGE concentrations (Table 2), primarily due to the addition of butter, oil, and cheese, which accelerate AGE formation during dry heat processing. While their AGE levels remain lower than those found in meats, excessive consumption of such snacks may still pose health risks (Uribarri *et al.,* 2010).

4.3 Beverages

Sugary drinks, including sodas and sweetened fruit juices, are major dietary sources of AGEs due to their high sugar content, which promotes AGE formation during preparation and storage (Khan *et al.*, 2023). Additionally, certain processing methods, such as coffee bean roasting and caramelization in carbonated drinks, further increase AGE levels. Frequent consumption of these beverages may lead to higher AGE intake (Green *et al.*, 2024).

5. Health implications of AGEs

Non-enzymatic glycation reactions produce AGEs, which can occur exogenously in food during processing or endogenously in the body (Zhang *et al.,* 2020). Ageing and the development of several chronic diseases, including as diabetes, cardiovascular disease, and neurological diseases, are intimately linked to the buildup of AGEs (Nediæ *et al.,* 2013). According to Merhi *et al.* (2019), AGEs cause oxidative stress and chronic inflammation by activating the receptor for AGEs (RAGE), which upsets cellular homeostasis and speeds up pathogenic processes. AGEs cause vascular and neurological damage in diabetics, which is a major factor in the development of problems such neuropathy, nephropathy, and retinopathy (Singh *et al.,* 2001). AGEs also raise the risk of cardiovascular illnesses by promoting an oxidative and pro-inflammatory milieu in blood vessels, which speeds up atherosclerosis (Basta *et al.,* 2004). AGE-RAGE interactions are also linked to chronic inflammation, which is a key cause of ageing and age-related disorders. According to Kikuchi (2003), AGEs cause damage to extracellular matrix proteins like collagen and elastin, which speeds up skin ageing and exacerbates conditions like psoriasis and acne. Dietary AGEs (dAGEs), which are produced by heating processes, pH, and the reactivity of carbonyl and amino groups in food, increase the body's AGE burden and worsen these health risks (Zhang *et al.,* 2020). Dietary changes, limiting exposure to exogenous AGEs, and preventing their synthesis during food processing are methods to lessen the negative health impacts of AGEs (Galiniak and Biesiadecki, 2019).

Table 1: Effect of temperature and time on the formation of AGEs product

Conditions	Temperature (°C)	Time (min)	Food \Substrate	AGE product	Increment (Folds) of AGEs from the raw	References
Frying	160	2	Fillets	CML	9.0	Liu *et al.,* 2023
		5			9.6	
		8			9.7	
Roasting	150	15	Beef	CML	6	Uribarri *et al.,* 2010
Baking	150	14	Butter cookies	CML	5	Hu *et al.,* 2022
Grilling	204	20	Beef	CML	10.6	Chen *et al.,* 2022
		18	Chicken		9.6	
Heating	98	210	Raw milk	3DG	9.5	Yu *et al.,* 2020
				MG	13.23	
				CML	1.8	
Drying	90	60	Black tea	CML	10	Zhang *et al.,* 2020
Heating	95	1	Infant milk formula	CML	-	Prosser *et al.,* 2019
		90			33.33	
Roasting	135	30	Cocoa	MG	1.32	Tas and Gokmen, 2016
		60			1.80	

Table 2: Correlation of AGE content with common food sources

Category	Food items	AGE content (kU/100g)	Risk level	Remarks
Animal-based foods	Grilled/Broiled/Seared meat	5,000 - 9,000	▲ (High)	Dry heat cooking increases AGE content significantly.
	Processed meats (Sausages, Bacon)	7,000 - 9,000	▲ (High)	Preserved meats contain additional AGE precursors.
	Roasted/Baked meat	3,000 - 6,000	▲ (Moderate)	Roasting and baking produce moderate AGEs.
	Hard cheese (Cheddar, Parmesan)	2,000 - 5,000	▲ (Moderate)	Fermentation increases AGE formation.
	Boiled/Steamed meat	1,000 - 2,000	▲ (Low)	Moist heat cooking limits AGE formation.
	Milk and Yogurt	50 - 100	▲ (Low)	Low-temperature processing minimizes AGE content.
Plant-based food	Fried potatoes (Fries, Chips)	1,500 - 2,500	▲ (High)	High-temperature frying increases AGE formation.
	Roasted nuts and Seeds	500 - 1,500	▲ (Moderate)	Dry roasting elevates AGE levels.
	Toasted bread and Baked Goods	500 - 1,200	▲ (Moderate)	Baking and toasting increase AGEs.
	Fresh fruits and Vegetables	<50	▲ (Low)	Natural antioxidants may counteract AGE effects.
	Whole grains (Boiled rice, Oats, Quinoa)	<50 - 100	▲ (Low)	Minimal processing limits AGE formation.
	Legumes (Lentils, Beans)	<100	▲ (Low)	Moist cooking prevents excessive AGE formation.

▲ :High ▲ :Moderate ▲ :Low

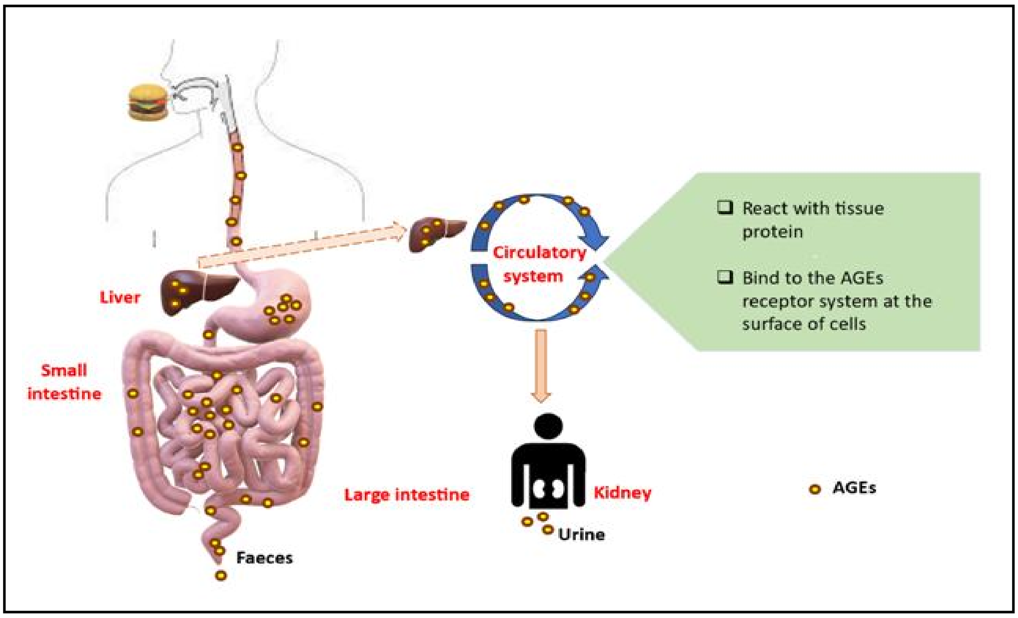

Figure 3: Fate of dietary AGEs after oral intake (Liang *et al.*, 2019).

Table 3: Detection methods used for the determination AGEs product

Method	Specificity	Non-Destructive?	Quantifies specific AGE compounds?	Suitablefor detecting	Advantages	Limitations	References
Fluorescence spectroscopy	Low	Yes	No	AGEs with autofluorescent properties	Rapid, cost-effective, non-invasive	Limited to fluorescent AGEs, lacks specificity	Perrone *et al.*, 2020
High-performance liquid chromatography	High	No	Yes	Almost all AGEs compounds	High precision, widely used	Time-consuming sample preparation	Kalousová *et al.*, 2002
Enzyme-linked immunosorbent assay	High	No	Yes	AGEs requiring specific antibodies	Sensitive and specific	Requires specific antibodies, limited to known AGEs	Corica *et al.*, 2021
Liquid chromatography-mass spectrometry	High	No	Yes	Non-volatile and polar AGEs	Highly sensitive and accurate, detects multiple AGEs	Expensive, complex instrumentation, requires expertise	Putta and Kilari, 2015
Gas chromatography-mass spectrometry	High	No	Yes	Volatile AGEs compounds	Ideal for volatile AGEs, high-resolution analysis	Requires derivatization for non-volatile compounds	Kalousová *et al.*, 2002

6. Fate of dietary AGEs

The manner in which dietary (AGEs) are processed after ingestion is pivotal in determining the relationship between dietary AGEs and their physiological impacts as shown in Figure 3. AGEs have the capability to bind with proteins, inducing alterations in tissue structure and function (Goldin *et al.*, 2006). The buildup of these compounds is linked to a range of age-related ailments and complications related to diabetes. AGEs have the ability to engage with particular receptors, like RAGE. This interaction can trigger various cellular responses, including inflammation (Lee and Park, 2013). The body may attempt to clear AGEs by this receptor-mediated process, but it can also contribute to AGE related pathologies, if the process becomes chronic or dysregulated. Some AGEs can be broken down and cleared from the body by enzymes and other metabolic pathways. For example, the enzyme glyoxalase I is involved in breaking down the AGE methylglyoxal (Rabbani and Thornalley, 2011).

7. Strategies for managing AGE intake

7.1 Dietary modifications

Managing dietary AGEs is crucial for overall well-being and reducing age-related risks. Choosing lean proteins like skinless poultry and fish, along with plant-based options such as tofu and legumes, helps lower AGE intake (Uribarri *et al.*, 2010). Cooking with low-heat methods like steaming and simmering minimizes AGE formation, while marinating foods in acidic solutions further reduces their levels. Antioxidant-rich herbs, whole grains, and olive oil instead of saturated fats also aid in AGE management (Matsuura *et al.*, 2003). Limiting processed and sugary foods, staying hydrated, and consuming green tea can further help. Consulting a dietitian ensures personalized dietary guidance. These adjustments promote long-term health and lower AGE exposure.

7.1.1. Increasing intake of fresh fruits and vegetables

Increasing fresh fruit and vegetable intake helps manage AGEs while promoting overall health. Colorful produce like berries, oranges, and leafy greens are rich in antioxidants that combat AGE formation (Uribarri *et al.*, 2010). Berries, in particular, offer high antioxidant content and can be easily incorporated into meals (Golovinskaia and Wang, 2021). Opting for whole, unprocessed produce over canned or processed options lowers AGE intake and retains more nutrients (Uribarri *et al.*, 2010). Incorporating fruits and vegetables into meals, snacks, and smoothies enhances diet quality, providing essential nutrients and fiber (Uribarri *et al.*, 2010)

7.1.2. Choosing lean protein sources

Selecting lean protein sources is a crucial strategy for managing AGEs while maintaining overall health. Opting for skinless poultry, lean cuts of meat, and fish such as salmon or cod helps reduce fat intake and subsequently lowers AGE formation. Plant-based proteins, including tofu, tempeh, legumes, and edamame, serve as excellent low-AGE alternatives that also provide essential nutrients (Uribarri *et al.*, 2010). Cooking methods play a significant role in AGE management, with techniques like steaming, boiling, poaching, and slow cooking being preferable as they involve lower temperatures and minimize dry heat exposure (Uribarri *et al.*, 2010). Additionally, marinating proteins in acidic solutions, incorporating herbs and spices for flavour enhancement, and carefully managing portion sizes can further aid in controlling AGE consumption (Matsuura *et al.*, 2003; Uribarri *et al.*, 2010). By following these dietary practices, individuals can effectively regulate their AGE intake while supporting overall well-being.

7.1.3. Selecting whole grains

Selecting whole grains is a strategic approach for managing AGE intake while maintaining a nutritious diet. Opting for whole grains such as brown whole wheat, rice, quinoa, oats and barley offers the advantage of lower AGE content and enhanced nutritional value(Verma *et al.*, 2021). Employing cooking methods that involve lower temperatures, such as simmering or steaming, when preparing whole grains can help minimize AGE formation (Uribarri *et al.*, 2010). By incorporating whole grains into meals, starting the day with whole grain breakfast options, and experimenting with a variety of grains, individuals can reduce AGE intake while enjoying diverse and flavorful dietary choices. This approach also promotes better overall health by providing essential nutrients and dietary fiber (Lafiandra *et al.*, 2014).

7.2 Cooking practices

AGEs form abundantly in foods, especially during high-temperature processing. Broiling (225°C) and frying (177°C) generate the highest CML levels, followed by roasting (177°C) and boiling (100°C) (Goldberg *et al.*, 2004). Dry heat processing can increase dAGEs by 10- to 100-fold compared to raw foods (Uribarri *et al.*, 2010).

Table 1 highlights how various cooking techniques like frying, baking, roasting, grilling, drying, and heatingaffect AGE formation in foods like fillets, steak, biscuits, tea, and milk. Frying significantly raises CML in fillets, while baked and grilled meats and cookies contain higher AGEs. Dried black tea exhibits elevated CML, and prolonged heating, particularly in baby formula, drastically increases CML levels. To minimize AGE intake, low-heat methods like steaming, boiling, and simmering are recommended (De Castro *et al.*, 2020). Marinating foods in acidic solutions (Uribarri *et al.*, 2010) and using antioxidant-rich herbs and spices (Matsuura *et al.*, 2003) help counteract AGEs. Avoiding grilling, broiling, and deep frying reduces AGE levels (Goldberg *et al.*, 2004). These strategies can lower AGE consumption and improve overall health (Semba *et al.*, 2010).

Grilling, frying, roasting, and baking all significantly speed up the Maillard reaction, especially when the temperature rises beyond 120°C. These techniques lead to the buildup of AGEs in addition to promoting the development of flavour and colour. At the same time, lipoxidation takes place when unsaturated fats break down, particularly when oils are heated repeatedly during pan- or deep-frying. This results in the production of reactive carbonyl compounds, which contribute to the formation of AGE. Similar to glycooxidation, which is the oxidative breakdown of sugars, reactive dicarbonyl intermediates such as methylglyoxal and glyoxal are produced. These react easily with proteins or lipids to generate AGEs. Because of these overlapping chemical pathways, foods that are exposed to dry heat, such roasted nuts, baked goods, fried meats, and processed snacks, often have higher amounts of AGE.

7.2.1 Use of moist heat cooking methods

Incorporating moist heat cooking methods into your culinary practices is a practical strategy for managing AGE intake and promoting healthier eating. These methods, including steaming, boiling, poaching, and sous vide cooking, involve cooking food at lower temperatures in the presence of moisture, thus minimizing the formation of AGEs. Slow cooking and braising also fall into this category, offering tender and flavorful results without excessive AGE production. Marinating proteins in acidic solutions before cooking can further reduce AGE formation (Uribarri *et al.*, 2010). Regularly cleaning cooking equipment to prevent residue buildup is essential for maintaining AGE-conscious cooking practices. By embracing these moist heat cooking techniques, individuals can savor delicious meals while proactively managing AGE intake, contributing to their long-term health and well-being (Bekhit *et al.*, 2019).

7.2.2 Reducing cooking time and temperature

High-temperature cooking accelerates Maillard reactions and lipid oxidation, leading to increased AGE formation. Table 1 highlights the impact of various cooking methods on AGE levels. To manage intake, reducing both cooking time and temperature is key. Gentle techniques like simmering and moderate baking help minimize AGEs while preserving nutrients (Uribarri *et al.*, 2010). Efficient alternatives such as microwaving, pressure cooking, and sous vide cooking further limit AGE formation (Bekhit *et al.*, 2019). Additionally, avoiding excessive browning, using non-stick cookware, and opting for alternative ingredients can further reduce AGE exposure (Goldberg *et al.*, 2004; Uribarri *et al.*, 2010). By embracing these strategies, individuals can enjoy flavorful, nutritious meals while promoting long-term health and well-being.

7.2.3 Adding antioxidant-rich ingredients

Incorporating antioxidant-rich ingredients into your diet is a strategic approach for managing AGE intake and promoting better overall health. Herbs and spices like rosemary, thyme, and turmeric, known for their antioxidant properties, can be used to enhance flavors while mitigating the effects of AGEs (Matsuura *et al.*, 2003). Colorful vegetables, berries, and citrus fruits, abundant in antioxidants like vitamins A, C, and E, serve as powerful allies in neutralizing free radicals generated by AGEs. Additionally, nuts, seeds, and fatty fish provide a dose of antioxidants such as vitamin E and omega-3 fatty acids, offering a double benefit of protection against AGE-related damage and supporting overall well-being (Amarowiczand Pegg, 2001). By incorporating these antioxidant-rich ingredients into your daily meals, you not only enhance the nutritional quality of your diet but also reduce the negative impact of AGEs on your health (Purwidiani *et al.,* 2019).

7.3 Food additives and supplements

7.3.1 AGE inhibitors

One strategic approach for managing AGE intake involves the incorporation of AGE inhibitors into your diet. These inhibitors are substances capable of mitigating or decelerating the production of AGEs within the body. Certain amino acids such as carnosine and pyridoxamine, along with particular dietary fibers, serve as natural AGE inhibitors. Carnosine, for example, has shown effectiveness in hindering AGE formation by capturing and neutralizing reactive sugar compounds (Brownlee, 2005).

7.3.2 Antioxidants

Another vital strategy for managing AGE intake involves incorporating antioxidants into your diet. Antioxidants are compounds that can help combat oxidative stress and reduce the damage caused by AGEs. Vitamins C and E, as well as phytochemicals like flavonoids and polyphenols found in fruits, vegetables, and tea, act as potent antioxidants. By consuming a diet rich in antioxidant-containing foods, individuals can help protect their cells and tissues from the harmful effects of AGE promote overall health (Shahidi, 2000).

8. Detection methods

Table 3 provides an overview of various analytical methods used to detect and quantify AGEs, focusing on their specificity, non-destructiveness, and ability to identify individual AGE molecules.

Fluorescence spectroscopy is commonly used for detecting fluorescent AGEs like pentosidine due to its high sensitivity, selectivity, and reproducibility, though it only reacts to fluorescent AGEs (Chen and Smith, 2015). Ultra-performance liquid chromatography-tandem mass spectrometry (UPLC-MS/MS) is effective for quantifying AGEs in various foods, including dairy products, beverages, seasonings, almonds, meats, and cereals. UPLC operates at low flow rates (0.2 ml/min) and withstands high pressures (103-124 MPa) (Aalaei *et al.,* 2017; Li *et al.,* 2015; He *et al.,* 2014).

ELISA is particularly useful for detecting high concentrations of CML/AGEs and has been used to develop preliminary AGE databases. LC-MS/MS is a highly sensitive method for measuring CML and CEL without requiring derivatization, making it superior to UV or fluorescence-based methods. Gas chromatography (GC), unlike liquid chromatography (LC), uses gas as the mobile phase, allowing for rapid sample transfer and broad applicability of stationary phases (Milkovska-Stamenova *et al.,* 2015).

9. Conclusion

AGEs in food represent major health hazards since they contribute to oxidative stress, inflammation, and chronic diseases such as diabetes, cardiovascular disease, and neurodegenerative ailments. To help prevent AGE production, dietary changes that reduce AGE consumption include eating foods high in antioxidants, such as fruits, vegetables, and whole grains. Cooking procedures are important; moist-heat methods, such as steaming and boiling, produce a lot fewer AGEs than dry-heat ones, such as grilling, roasting, and frying. AGE development is further inhibited by lower cooking temperatures. Potential AGE inhibitors including pyridoxamine and aminoguanidine, as well as regular exercise and enough hydration, may help prevent AGE buildup in addition to diet. Despite these strategies, there are still research gaps about the bioavailability and metabolic destiny of dietary AGEs. Future research should aim to standardize how we measure AGEs, create functional foods that help reduce AGE levels, and delve into how our gut microbiota may influence AGE metabolism. A well-rounded approach, combining smart dietary choices, healthy lifestyle habits, and potential pharmacological interventions, can significantly reduce AGE exposure, ultimately supporting better long-term health and preventing chronic diseases.

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Conflict of interest

The authors declare no conflict of interest relevant to this article.

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