



Acrylamide in Coffee:

Impact of Bean Selection, Roasting, Storage,
Brewing and Strategies for Mitigation

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Abstract

Coffee is one of the major dietary sources of acrylamide (AA), a heat-induced contaminant classified as probably carcinogenic to humans. This literature study investigates how coffee bean variety, roasting, storage and brewing influence AA formation and extraction while also evaluating potential mitigation strategies. The findings show that Robusta generally contains higher levels of the precursor asparagine and consequently higher AA concentrations than Arabica. Roasting degree strongly affects AA levels with light roasted coffee consequently containing the highest concentration and dark roast the lowest due to thermal degradation of AA during prolonged roasting. Storage further reduces AA levels over time, particularly at elevated temperatures although prolonged storage negatively affects sensory qualities. Brewing parameters such as coffee-to-water ratio, brewing time, temperature and extraction method significantly influence the amount of AA transferred to the beverage. Different brewing methods and coffee consumption habits intersect with deeply rooted regional and cultural consumer preferences, expecting individuals to alter their drinking habits is impractical. Therefore, mitigation efforts must focus on upstream, industrial solutions. The most viable approaches include sorting out defective green beans, optimizing roasting time-temperature profiles, utilizing advanced technologies like vacuum roasting, and implementing enzymatic asparaginase pretreatments to ensure public health without compromising sensory quality.

Keywords: Coffee, Acrylamide, Roasting, Brewing, Coffee species, Storage, Mitigation strategies, Arabica, Robusta, Asparaginase

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Abbreviations

Abbreviation	Description
AA	Acrylamide
BMDL ₁₀	Benchmark dose lower confidence limit 10%
B.W.	Body weight
EFSA	European Food Safety Authority
GA	Glycidamide
HMF	Hydroxymethylfurfural
LB	Lower bound
MOE	Margin of Exposure
PAH	Polycyclic aromatic hydrocarbons
R.T.	Room temperature
TDI	Tolerable daily intake
TDS	Total dissolved solids
UB	Upper bound

1. Introduction

Coffee is one of the most consumed beverages worldwide. To transform the coffee cherries to the final beverage the beans must go through several steps including fermentation, drying, roasting and finally brewing it into a cup of coffee (Zhang et al. 2019). The aroma and taste in the coffee that is appreciated by so many is mostly generated during the roasting process. Depending on the colour, the roasted coffee beans are classified into three categories, light, medium and dark roast (Vignoli et al. 2014). The different degrees of roasting generally reflect different styles of coffee and are preferred by different consumers. Dark roast is usually preferred by southern Europe for espresso whilst North Europe and America prefer a lighter roast (Schouten et al. 2021).

Green coffee beans consist of carbohydrates, lipids, proteins, peptides, free amino acids, sucrose, minerals along with bioactive compounds and other small biochemical compounds (Dong et al. 2023). *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta) are two most used coffee tree species. Arabica accounts for 70% of the green coffee beans used worldwide and Robusta for 30% (Bastian et al. 2021). The two coffee beans display different sensory properties. Arabica is usually sweeter, softer with aromas of fruit and berries while Robusta has a stronger, harsher, more grain like flavour (da Costa et al. 2023). While the roasting of green coffee beans is essential for developing desired physicochemical characters and sensory profiles that develop, the process simultaneously triggers the formation of undesirable heat-induced contaminants, such as furans, hydroxymethylfurfural (HMF) and acrylamide (AA) (Strocchi et al. 2022).

Acrylamide (C₃H₅NO, 2-propenamide), Figure 1, is a polar, water-soluble organic compound primarily synthesized via the Maillard reaction (Schouten et al. 2021). This complex non-enzymatic browning reaction involves interaction between amino compounds and the carbonyl on reducing sugars such as fructose or glucose (Shakoor et al. 2022). The reaction typically occurs at temperatures above 120°C and results in hundreds of compounds, many of them generate the characteristic aromas and flavours associated with cooked food while others are

harmful byproducts. Specifically, when the amino acid asparagine is the primary precursor the reaction results in the formation of AA (Shakoor et al. 2022).

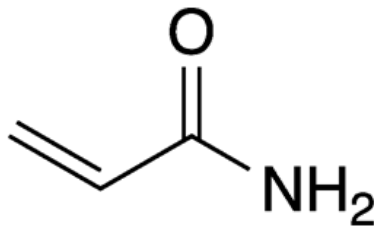


Figure 1. Structural formula of Acrylamide.

Coffee is usually roasted at temperatures above 150 °C and green coffee beans contains the necessary precursors to form AA during the roasting process (Bertuzzi et al. 2020). In coffee beans the main sugar is sucrose, despite it not being a reducing sugar, it plays an important role in the formation of AA. In the initial steps of the roasting process the sucrose decomposes. It will partly hydrolyse into the reducing sugars, fructose and glucose, and it will also form other carbonyl compounds like HMF that can react with asparagine to form AA (Kocadağlı et al. 2012). Beyond the Maillard reaction, AA can also be synthesized via the acrolein pathway (Bonilla et al. 2025). The acrolein pathway is the second most contributing pathway in AA formation. In this route the thermal oxidation of polyunsaturated fatty acids, specifically linoleic acid is transformed into acrolein. Acrolein is a reactive carbonyl that can react with asparagine to form AA (Kocadağlı et al. 2012). As coffee beans contain around 8-18% lipids this oxidative pathway is the second most contributing pathway to the total AA levels in coffee (Bonilla et al. 2025).

After roasting the coffee beans are ground to a coarse powder, then it is time for brewing. The preferred brewing method is influenced by cultural traditions, geographical origin, lifestyle, habits and economic aspects (Schouten et al. 2021). There are four main methods; the Italian method using high pressure making Espresso, the northern European and American method of pouring hot water over ground coffee followed by filtration, the Turkish method where the coffee grounds are boiled without filtration and cold brewing where coffee grounds are steeped in cold water.

Acrylamide is a compound that displays neurotoxic, genotoxic, carcinogenic and reproductive toxicity in animal cells and culture experiments (Peivasteh-Roudsari et al. 2024). International Agency for Research on Cancer (IARC) classified AA as “probably carcinogenic to humans” in 1994 (Mousavi Khaneghah et al. 2022).

Due to its low molecular weight and high-water solubility AA is rapidly absorbed and distributed in the tissue after digestion. AA is then metabolized into glycidamide (GA) in the liver (Peivasteh-Roudsari et al. 2024). GA is a genotoxic mutagen that forms adducts with DNA and proteins, that can cause mutations and cancer (Yan et al. 2023). Other possible pathways for inducing gene mutations are through oxidative DNA damage and reactive oxygen species (EFSA 2015). Prolonged AA exposure will lead to neurological damage in humans, both in the central and the peripheral nervous system (Nematollahi et al. 2020). The highly reactivity α,β -unsaturated double bond on AA form adducts with neuroproteins, causing neurological damage (Yoshioka et al. 2020).

In 2002 it was confirmed by the Swedish National Food Authority that AA can be found in certain heat- treated food products like bread, coffee and fried potato products (Mousavi Khaneghah et al. 2022). According to the European Food Safety Authority (EFSA 2015) coffee accounts for approximately 34% of the dietary AA exposure among adults and elderly making it a primary dietary contributor. EFSA concluded that while potential adverse effects on the nervous system, development and effects on male reproduction are not a significant concern at current dietary exposure levels, the carcinogenic effect remains a public health concern across all age groups. Because both AA and its metabolite GA are genotoxic, a tolerable daily intake (TDI) cannot be established. Theoretically, even a single molecule can cause DNA damage that leads to tumor development, meaning no completely safe exposure limit exists. Because human epidemiological data is limited, a benchmark dose lower confidence limit 10% (BMDL₁₀) of 0,17 mg/ kg body weight (b.w.) per day for neoplastic effects in animals serves as the reference point.

For adolescents, adults and elderly the current human dietary exposure of AA ranges from 0,6 $\mu\text{g}/\text{kg}$ b.w. per day to 2,0 $\mu\text{g}/\text{kg}$ b.w. per day (EFSA 2015). Comparing this human exposure data to the BMDL₁₀ reference point yields Margin of Exposure (MOE) values between 89 (maximum UB) and 425 (minimum LB). MOE is a risk assessment tool to characterize chemical exposure risks by calculating the ratio between the BMDL₁₀ and the estimated human exposure (Benford et al. 2010). The MOE indicates the size of the safety buffer between the actual exposure and potential toxic effects; a larger MOE signifies a lower concern while a smaller MOE indicates greater risk. For substances that are both genotoxic and carcinogenic EFSA consider an MOE of 10,000 or greater to be of low public health concern. Because calculated MOEs for dietary AA are substantially lower than 10,000 EFSA concluded that current exposure indicates a legitimate concern regarding neoplastic effects. Based on the risk assessment from EFSA the European Union announced in 2017 that AA in food products needs to be monitored and mitigation measures for AA reduction needs to be implemented

by food business operators (EU 2017). Commission Regulation 2017/2158 establishes the benchmark level in roasted coffee to be 400 µg/kg and 850 µg/kg in instant coffee. These benchmarks are not maximum legal safety thresholds, but rather operational performance indicators used to verify the effectiveness of commercial mitigation strategies and to ensure that AA levels remain as low as reasonably achievable.

The amount of AA in coffee is affected by numerous factors along the process (Strocchi et al. 2022; Li et al. 2023; Bonilla et al. 2025). The aim of this paper is to assess how the amount of AA is affected by the coffee bean variety selection, roasting, storage and brewing. Also investigate potential mitigation strategies for AA reduction.

2. Method

This literature study was carried out searching and analysing studies concerning acrylamide in coffee. The data collection focused on the following factors: raw material, degree of roasting, storage degradation, the effect of brewing and potential mitigation by asparaginase and roasting conditions.

Searches were performed in the PubMed and Web of Science databases using the following search strings: Acrylamide AND coffee, Acrylamide AND (Arabica or Robusta), Acrylamide AND coffee species, Acrylamide AND coffee beans, Acrylamide AND roasting* AND coffee, Acrylamide AND storage AND coffee, Acrylamide AND brewing, Acrylamide AND coffee AND mitigation, Acrylamide AND mitigation, Acrylamide AND asparaginase, Acrylamide AND reduction.

The initial database search yielded a total of 227 search results. A selection process was applied. First articles were screened based on their titles. Potentially relevant studies then underwent abstract screening, followed by a full-text review to assess relevance. Additionally, the reference list of the selected articles was manually searched. The selection criteria prioritized research published from 2020 and onwards to ensure the latest information. In instances where recent data was limited, older studies were included to provide a comprehensive overview. This was particularly necessary for the storage degradation section where not enough new research was published. Only papers published in English were considered. Ultimately, a total of 52 articles was included in this study. Of these, 36 were original research articles used to compile the results, the rest were review articles and other articles used for background information and utilized for the introduction.

3. Results and discussion

3.1 Factors Affecting Acrylamide in Coffee

Acrylamide is formed during thermal processing of the coffee beans and given the chemical precursors present in the green beans the formation is inevitable. The following section details how raw material selection, thermal processing, storage and brewing determine the final AA concentration.

3.1.1 Raw Material

Arabica and Robusta are the two most used coffee varieties, displaying both different sensory properties and chemical composition (Kocadağlı et al. 2012; Bastian et al. 2021). During roasting, AA is primarily formed via the Maillard reaction, a chemical reaction between the amino acid asparagine and reactive carbonyl compound (Shakoor et al. 2022). Because the availability of these compounds dictates how much AA can form, several researchers have identified asparagine as the limiting precursor in coffee beans (Strocchi et al. 2022; Li et al. 2023; Bonilla et al. 2025).

Asparagine and Sucrose Variations

The concentration of asparagine differs between the two green bean varieties, see Table 1. Green arabica beans contain between 486 and 658 mg/kg whereas Robusta beans exhibit notably higher levels, ranging from 797 to 1026 mg/kg. The difference reported within the same variety are generally attributed to different environmental cultivation methods, geographical origin and post-harvest techniques, such as wet versus dry processing, methods for removing the pulp from the coffee cherries either before or after drying (Bastian et al. 2021; Li et al. 2023).

Table 1. Studies on the amount of asparagine in Arabica and Robusta green beans together with the level of AA formed during roasting.

Coffee bean variety	Asparagine (mg/kg)	AA level (µg/kg)	References
<i>Arabica</i>	658 ± 40	286	(Bertuzzi et al. 2020)
<i>Arabica</i>	540 ± 40	230–270	(Schouten et al. 2021)
<i>Arabica</i>	535 ± 29	NA	(Hamzalıoğlu & Gökmen 2020)
<i>Arabica</i>	486 ± 97	374 ± 86	(Bagdonaite et al. 2008)

<i>Arabica</i>	NA	154 ± 52 – 348 ± 71	(Esposito et al. 2020)
<i>Robusta</i>	1026 ± 43	298	(Bertuzzi et al. 2020)
<i>Robusta</i>	800 ± 50	330 – 370	(Schouten et al. 2021)
<i>Robusta</i>	797 ± 23	708 ± 77	(Bagdonaite et al. 2008)
<i>Robusta</i>	NA	224 ± 49 – 495 ± 72	(Esposito et al. 2020)

Sugars also play a critical role during roasting. Generally, green Arabica beans feature higher levels of sucrose than Robusta beans (Bagdonaite et al. 2008; Schouten et al. 2021). While sucrose itself is a non-reducing sugar and cannot directly participate in the Maillard reaction, is it hydrolysed into the reducing sugars glucose and fructose during roasting. Interestingly elevated sucrose levels often correlate with lower final amounts of AA in roasted coffee, as sucrose accelerate the kinetics of AA formation leading to both faster formation and degradation of AA (Kocadağlı et al. 2012). However, literature on sugar concentration is not entirely uniform. Contrary to the standard trend, Bertuzzi et al. (2020) observed a significantly higher sucrose content in Robusta beans (8,75%) compared to Arabica beans (7,05%). These conflicting observations are largely driven by differences in the cultivation conditions, the origin and post-harvest treatment of the green beans.

Impact on Acrylamide Formation

When comparing the AA levels in the two roasted bean varieties, the scientific consensus largely indicates that Robusta beans yield higher levels of AA compared to Arabica. Alves et al. (2010), Esposito et al. (2020) and Bagdonaite et al. (2008) all found AA levels to be significantly higher in Robusta beans at all three roasting degrees compared to Arabica. This trend is further supported by Esposito et al. (2020) who demonstrated that the final AA content climbs proportionally with an increasing percentage of Robusta beans in commercial blends. Roasting duration does play an important role, Schouten et al. (2021) confirmed that Robusta maintained higher AA concentrations in light and medium roasts, though the difference between the two varieties became negligible during dark roasting.

This trend reflects the chemical compositions of the green beans, where Robusta contains much higher concentrations of asparagine compared to Arabica. This reinforces the theory that asparagine functions as the primary limiting precursor (Bagdonaite et al. 2008; Schouten et al. 2021). This chemical difference directly impacts the consumer exposure as well. Alves et al. (2010) tracked AA levels in

brewed beverages made from medium roasted beans and discovered that an espresso cup brewed from Arabica contained significantly less acrylamide (0.87-1,52 μg / cup) than a cup brewed from Robusta (1,71 – 2,92 μg /cup).

Despite the strong academic consensus pointing to Robusta forming higher AA levels, notable conflicting research exists. Bertuzzi et al. (2020) conducted a study within a large-scale industrial coffee roasting plant and reported conflicting data. In the final roasted beans, they observed no statistically significant differences in AA levels between the two varieties, with both showing levels around 300 $\mu\text{g}/\text{kg}$. Even more surprisingly Arabica demonstrated a much higher peak level, the highest AA concentration reached during roasting, during the intermediate stages of roasting compared to Robusta 1045 $\mu\text{g}/\text{kg}$ and 795 $\mu\text{g}/\text{kg}$ respectively.

The authors suspected that this was due to the higher levels of sucrose present in Robusta. The unusually high sucrose levels in Robusta resulted in Arabica having higher AA concentrations when the opposite is usually observed. The lower concentration of sucrose leads to a slower kinetic process, resulting in less AA degradation in the early stages resulting in a higher peak accumulation before degradation begins. By the end of the industrial roasting both beans displayed similar AA content, the levels not that different from other reported concentrations. The finding highlights the impact from sucrose on AA formation during roasting. The impact of the industrial roaster should be evaluated as much other research is performed on a laboratory scale roasters, more research is needed on the impact of the unique thermodynamics, air flow and heat transfer profiles found in industrial plants. Ultimately, low asparagine content remains the most reliable baseline predictor for potential AA formation across most literature the sucrose content plays an important role as well.

3.1.2 Degree of roasting

Green beans are roasted at temperatures exceeding 150 °C to develop the desired sensory characteristics (Bonilla et al. 2025). The relation between roasting time and temperature will result in different roasting degrees light, medium or dark. The absolute concentration of AA in different degrees of roasting varies substantially across different publications, see Table 2. The variance is due to the many other factors affecting AA levels difference in raw material, moisture content, agricultural practices, geographical origin, pH and different time and temperature used within the same roasting degree (Bonilla et al. 2025).

Table 2. Studies of the acrylamide content at different degrees of roasting. All values converted to ($\mu\text{g}/\text{kg}$).

Coffee bean variety	Light	Medium	Dark	References
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<i>Arabica</i>	650–700	230–270	110 – 140	(Schouten et al. 2021)
<i>Arabica</i>	NA	298	NA	(Bertuzzi et al. 2020)
<i>Arabica</i>	348 ± 71	243 ± 43	154 ± 52	(Esposito et al. 2020)
<i>Arabica</i>	1243 ± 67– 783 ± 34	279 ± 4– 183 ± 8	186 ± 1– 132 ± 6	(Alves et al. 2010)
<i>Robusta</i>	495 ± 72	311 ± 50	224 ± 49	(Esposito et al. 2020)
<i>Robusta</i>	1050 – 1100	330 – 370	100–130	(Schouten et al. 2021)
<i>Robusta</i>	NA	286	NA	(Bertuzzi et al. 2020)
<i>Robusta</i>	2191 ± 20– 1385 ± 69	455 ± 2–564 ± 25	442 ± 6– 383 ± 19	(Alves et al. 2010)

Despite the discrepancies in baseline values between separate studies, a universal trend is observed across the literature: light > medium > dark. While certain studies observe no statistically significant difference exclusively between medium and dark roasts the progressive decline from the initial roasting stages remains constant (Bolka & Emire 2020).

This trend successfully transitions from the roasted bean into the final beverage. Santanatoglia et al. (2023) evaluated eight different brewing methods and found the highest AA concentrations in light roasted coffee (93,273 ng/ mL), followed by medium (90,202 ng/ mL) and dark roast (53,105 ng/ mL). Similarly, Bolka & Emire (2020) reported a significant positive correlation ($p < 0,001$) between light roast and final AA concentrations in brewed samples.

Time and temperature serve as the primary determinants of AA kinetics during thermal processing. Unlike many starch-based foods where AA accumulates continuously coffee exhibits a rapid spike in AA generation during the initial

minutes of roasting, followed by a progressive decline as roasting time extends (Badoud et al. 2020). The reduction is due to the depletion of precursors and thermal degradation of the formed AA (Esposito et al. 2020). The asparagine, the limiting precursor, present in the green beans is completely consumed within the first minutes of processing. Consequently, a total depletion of free asparagine is typically observed after approximately five minutes of roasting hindering further AA synthesis (Kocadağlı et al. 2012). The AA already generated undergoes rapid degradation due to the high reactivity of its electrophilic acryl group which reacts with coffee constituents to form stable derivatives. This explains why light-roasted coffee contain the highest AA concentrations and prolonged roasting leads to lower AA levels.

3.1.3 Storage

AA has a highly reactive acrylic group, and research indicates that AA is not stable during storage in packaged coffee, see Table 3. Hoenicke and Gatermann (2005) observed that AA levels in ground coffee dropped from 305 µg/kg to 210 µg/kg after three month storage at 10-12 °C, with whole beans showing a similar reduction. After 6 months they noticed a 40-65% decrease in AA concentration. Lantz et al (2006) also reported a substantial reduction of AA in samples stored for 12 months. Their findings highlighted a temperature-dependant reduction, samples stored at ranges from –18 °C to 37 °C, the most substantial degradation occurred at the highest temperature. Baum et al. (2008) utilized ¹⁴C-labelled AA to track reduction during storage, finding that after 48 weeks of room temperature storage the AA transferred to the final brew was 40% lower than in fresh samples. In research by Yoshioka et al. (2020) samples of black coffee and coffee with milk were stored at 4°C, r,t, and 37°C for up to 10 months. They concluded that the reduction of AA increased with increasing storage time and increasing temperature. The biggest reduction was coffee stored at 37 °C, coffee with milk displayed 75,3 % AA loss after 4 month storage. Very little decrease was observed in coffee stored at 4 °C.

Table 3. Studies on decrease of Acrylamide level during storage in roasted beans, instant coffee and coffee beverages.

Coffee type	Storage condition	AA loss	References
Whole roasted and ground beans	3 months at 10-12 °C	31 – 30 %	(Hoenicke & Gatermann 2005)
Roasted and ground coffee	12 months, r,t & 37 °C	40 – 65 %	(Lantz et al. 2006)

Roasted and ground coffee	48 weeks at r.t	40 %	(Baum et al. 2008)
Instant coffee	12 months at 25 °C	33 %	(Michalak et al. 2016)
Canned coffee beverage with and without milk	4 months at 37 °C	75,3% (coffee with milk)	(Yoshioka et al. 2020)

Duration and temperature are clearly two important factors for AA reduction in packaged coffee during storage. The reduction is linked to coffee-typical constituents. AA acts as an electrophile that has high reactivity towards nucleophilic food components in peptides, proteins and melanoidins (Hoenicke & Gatermann 2005). In coffee, amino acids containing ϵ -NH₂ and SH are involved in the degradation of AA (Michalak et al. 2016). Sulphur and other nucleophiles can react with the electrophilic α,β -unsaturated carbonyl group of AA and undergo Micheal addition reaction to form stable AA adducts. AA is more stable in cereal based products as they do not contain the same nucleophiles (Hoenicke & Gatermann 2005; Michalak et al. 2016). A decrease in AA is desirable, but the prolonged storage will cause degradation of volatile compounds in coffee impacting the aromas and flavours of the ground coffee negatively (Gantner et al. 2024). Consequently, while prolonged storage particularly at 37 °C effectively reduces AA concentration it simultaneously degrades the cup quality and sensory attributes of the coffee.

3.1.4 Brewing

Brewing parameters

Because dietary exposure to AA depends strictly on the amount transferred into the final beverage, evaluating how extraction mechanics vary across brewing methods is critical. Due to its high polarity and water solubility AA is easily extracted from the ground coffee beans to the final beverage (Schouten et al. 2021). The efficiency of AA is highly sensitive to the fluid dynamics and water volume characteristics of specific brewing methods. Alves et al. (2010) demonstrated that increasing the brew volume from 20 mL to 70 mL accelerated the extraction efficiency from approximately 60% to nearly 99%, a standard shot of espresso is generally 30 mL. Lantz et al. (2006) observed that espresso preparation yielded a 25% lower overall extraction efficiency compared to filter coffee. This lower efficiency is primarily due to the brief contact time between water and the packed coffee grounds together with the low amount of water passing through the ground preventing extraction of the total AA content.

There is a critical distinction between extraction efficiency, percentage of total AA content removed from the grounds and the final concentration in the cup. Methods utilizing larger water volumes prolong the contact time and enabling near complete extraction of the available AA into the liquid. This yields high total extraction efficiency but can dilute the concentration depending on the initial amount. In contrast the high coffee-to-water ratio, like in espresso, ensures that despite incomplete total extraction the resulting beverage maintains high concentration of AA per volume. This aligns with the findings of Santanatoglia et al. (2023) who evaluated eight brewing methods and determined that the highest final AA concentrations positively correlated with high coffee-to-water ratios and high total dissolved solids percentages (TDS%).

Two other factors influencing the AA levels in the beverage are brewing temperature and contact time. Kang et al. (2020) compared cold and hot brewing techniques noting that despite lower temperatures cold brew variants exhibited significantly higher final AA levels. This is explained by extended contact time, the cold brew requires prolonged immersion period allowing for steady extraction over time despite low thermal energy. This positive correlation between extended contact times and elevated AA recovery is supported by other literature as well (Santanatoglia et al. 2023).

Temperature shows a clear correlation with AA concentration. Kang et al. (2020) demonstrated that when comparing multiple hot or cold brew treatments against each other, samples processed at higher temperatures consistently yielded elevated AA concentrations. This direct correlation between thermal energy and accelerated mass transfer was further supported by Basaran et al. (2026) who highlighted water temperature as a primary factor in AA extraction velocity.

Han et al. (2020) evaluated cold brew variations across temperature range of 5 °C to 20 °C and determined that AA concentration increased with increasing extraction duration regardless of temperature. Furthermore, they noted that because of the highly hydrophilic profile of AA, steeping (immersion) methods generally yield higher final AA levels than dynamic drip systems. This difference occurs because immersion has constant contact between the water and the ground coffee, facilitating uninterrupted mass transfer.

Brewing methods

Isolating the independent effect of different brewing styles remains challenging because the AA content in the ground beans varies significantly based on agricultural variety, pre-roasting processing, roasting degree and storage time. Consequently, the current literature exhibits substantial variability and a lack of

standardized data. Across published studies, AA levels in final beverages range from 3,5 ng/mL to 122,03 ng/mL as presented in Table 4.

The elevated concentration observed in Moka pot 122,03 ng/mL are driven by a combination of high-to-medium coffee-to-water ratios and elevated pressure and boiling temperatures. The Turkish coffee also displays elevated concentrations of 81,9 ng/mL due to a combination of high temperature and immersion technique. Espresso generally shows higher concentrations compared to filter coffee and pour over the absolute exposure from a single shot of espresso may be lower than that of a much larger serving of filter coffee.

Table 4. Studies on AA levels in coffee beverages utilizing different brewing methods.

Brewing method / type of coffee	Coffee to water ratio	Brewing temperature (°C)	AA level (ng/mL)	References
Espresso	1:4,6	NA	32,8 – 50,8	(Alves et al. 2010)
Espresso	NA	NA	25,5	(Basaran et al. 2026)
Espresso	NA	NA	20,6	(Mesías & Morales 2016)
Americano	NA	NA	19,5	(Basaran et al. 2026)
Moka	1:10	boiling	122,03	(Santanatoglia et al. 2023)
Turkish coffee	1:10	boiling	81,9	(Santanatoglia et al. 2023)
Filter coffee	NA	NA	16,8	(Basaran et al. 2026)
Pour over (Chemex)	1:15	93	61,6	(Santanatoglia et al. 2023)
Pour over	1:20	80	3,5	(Kang et al. 2019)
Pour over	1:20	95	4,3	(Kang et al. 2019)
French press	1:15	93	28,5	(Santanatoglia et al. 2023)

Cold brew	1:20	5 – 20	3,9 – 5,4	(Han et al. 2020)
Cold brew	1:20	5 – 20	4,1 – 5,4	(Kang et al. 2019)
Instant coffee	1:100	NA	47,4	(Basaran et al. 2026)

Instant or soluble coffee is one of the most consumed variants of coffee. The European Union has established significantly higher benchmark threshold for soluble coffee (850 µg/kg) than for standard ground coffee (EU 2017). In an analysis of 41 commercial products, Basaran et al. (2026) confirmed that instant coffee beverages contained markedly higher AA concentrations than alternative preparation methods. This is directly linked to industrial manufacturing methods. Soluble coffee is primarily extracted using highly pressurized water at elevated temperatures, allowing large amounts of highly soluble compounds like AA to transfer from the raw material (Mussatto et al. 2011). Subsequent industrial evaporation and dehydration processes remove water to create the soluble powder, concentrating the non-volatile AA fraction in the final product. When preparing the beverage, the instant coffee powder is completely dissolved in the water giving it a 100% extraction efficiency, no AA is remaining in the coffee grounds. Therefore, the combination of industrial concentration and total dissolution makes instant coffee a high contributor to dietary AA exposure per gram of soluble coffee powder used.

From an extraction standpoint, minimizing AA concentration in a coffee beverage is favoured by a low coffee-to-water ratio, low TDS%, short brewing duration and reduced water temperatures. However, because consumers generally select their preferred brewing technique based on deeply ingrained cultural habits and sensory preferences rather than chemical profiles, focusing strictly on extraction variables has practical limitations. Ultimately a consumer's total daily volumetric intake of coffee exerts a far greater impact on dietary AA exposure than the adjustments made to individual brewing configurations.

3.2 Mitigation

EU commission Regulation 2017/2158 establishes the benchmark level of roasted coffee to be 400 µg/kg and 850 µg/kg in instant coffee (EU 2017). If the level of AA exceed the benchmark the food business operators need to review their mitigation measures and adjust their processes to reduce the level of AA to as low as reasonably achievable below the benchmark. In this section possible mitigation strategies to reduce the AA levels will be discussed.

3.2.1 Bean selection

Despite the inconclusive results from Bertuzzi et al. (2020) showing that Arabica beans contain higher levels of AA compared to Robusta, contrasting several studies that identify Robusta as the bean variety resulting in the highest AA levels. Selecting raw materials based on beans variety is a viable mitigation strategy for reducing AA formation, favouring Arabica over Robusta. This being due to the higher asparagine content in Robusta and asparagine being identified as the limiting precursor in AA formation. The EU Commission Regulation presents this as a potential mitigation strategy as well (EU 2017). However, because Arabica and Robusta possess distinct flavour and aroma profiles altering the coffee bean ratio or totally interchanging the beans will modify the sensory characteristics of the final cup. Post-harvest quality control presents a non-disruptive mitigation strategy, where removal of unripe and defective beans prevents elevated AA formation as these contain significantly higher amounts of asparagine (Kocadağlı et al. 2012). Further research could be conducted on the potential of cultivation of coffee beans strains that might have a lower asparagine content, thus reducing AA formation.

3.2.2 Roasting

Roasting represents the most critical stage influencing AA formation, where different time and temperature determine both the roasting degree and the final AA concentration. Consequently, choosing different roasting degrees serves as a potential mitigation strategy. Multiple studies confirm that light roasted coffee frequently exceeds the EU benchmark threshold of 400 µg/kg (Alves et al. 2010; Esposito et al. 2020; Schouten et al. 2021). On the other hand, prolonging the roasting to a dark roast successfully keeps the AA levels below benchmark. However, mitigation is not entirely guaranteed at intermediate stages, as Esposito et al. (2020) also identified several medium roast samples that exceeds the benchmark. Furthermore, while dark roasting effectively mitigates AA levels, it may lead to an increase in other heat-induced contaminants such as polycyclic aromatic hydrocarbons (PAHs) and furans (da Costa et al. 2023). Additionally, prolonged roasting simultaneously breaks down beneficial compounds like antioxidants (Schouten et al. 2021).

Beyond simply choosing dark roast, optimizing the roasting conditions, such as time, temperature, air velocity, humidity and atmospheric pressure can be an effective way to mitigate AA in coffee. There are several studies on finding the optimal roasting conditions to limit the AA formation, though these do not usually consider the desirability of achieving different roasting degrees and desired sensory profiles (Endeshaw & Belay 2020; Hu et al. 2021; Kim et al. 2022). Esposito et al. (2020) optimized the roasting conditions at each roasting degree to

achieve the desired taste and aroma as well as reduce the AA content. The researchers concluded that with the right time and temperature combination it was possible to achieve a 6 – 38% reduction in AA levels. The optimal roasting parameters varied significantly across coffee species and geographical origins, highlighting the complexity of the mitigation process but the result also shows that reduction is achievable whilst still maintaining sensory quality.

Beyond conventional roasting, innovative techniques such as vacuum and superheated steam roasting offers significant potential for AA mitigation. Anese et al. (2014) showed that vacuum roasting Arabica beans to a medium degree reduced AA by 50% without compromising sensory quality, the dark roast did however exhibit lower odour intensity compared to conventional roasted coffee. Similarly superheated steam roasting has proven effective in AA reduction by replacing oxygen with steam to inhibit lipid oxidation thereby limiting the AA formation. Alafeef et al. (2020) reported AA reduction of 14,8% in Arabica and 32,4% in Robusta using this method. Rattanarat et al. (2021) confirmed that the superheated steam reduced AA in medium and dark roasted coffee. The superheated steam roasting does however impact the flavour of the coffee beans, in Robusta the flavour becomes sweeter and more citrus like acidity is formed (Chindapan et al. 2019).

Other variables such as air velocity and humidity also play a critical role. Budryn et al. (2015) found that AA levels in Robusta decreased with higher air velocities across all temperatures and decreased with increasing humidity at high temperatures. Despite this trend they identified the optimal roasting conditions at 203 °C with low air flow and low humidity (Budryn et al. 2015).

Mitigation of AA must be weighed against the potential increase of other heat-induced contaminants. The coffee producers must find the chemical balance between reducing the amount of AA together with limiting the production of other heat induced contaminants in order not to breach the safety guidelines of these compounds, this will most likely be somewhere closer to a medium roast rather than a dark roast coffee. Together with the heat induced contaminants and the negative influence on bioactive compound and antioxidants the health impact of dark roasted coffee might be lower than of the medium roast coffee. While alternative roasting methods show promising potential, the industrial adaptation faces several problems. The sustainability and investment required for completely new roasting apparatus is a significant challenge for industrial- scale implementation.

3.2.3 Enzymatic treatment

Since asparagine is the primary limiting precursor in AA formation, extensive research has been carried out on the possibility to reduce asparagine content in green beans prior to roasting (Strocchi et al. 2022). This is achieved through application of the enzyme asparaginase, which catalyses the hydrolysis of L-asparagine into L-aspartic acid and ammonium, compounds that do not contribute to AA synthesis (Lubkowski & Wlodawer 2021).

A significant obstacle to enzyme treatment is the compact, dense structure of green beans which hinders the homogenous distribution and penetration of the enzyme (Abedi et al. 2023). To overcome this, pre-treatment of the beans is necessary to increase bean porosity. Steam treatment, blanching or soaking are used to swell the bean matrix and facilitate enzyme diffusion. Porto et al. 2019 demonstrated that steam pre-treatment reduced asparagine content by 60% in Arabica and 35% in Robusta.

Recent studies highlight the potential of this method without compromising quality. Corrêa et al. (2021) reported a 59% reduction of AA in roasted Arabica coffee, noting that the treatment did not interfere with the major bioactive compounds. Furthermore, Vieira-Porto et al. (2024) found that combining steam pre-treatment with asparaginase resulted in AA reduction up to 56% in Arabica and 60% in Robusta with no negative impact on the sensory profile. While Cunha et al. (2019) corroborate that the treatment preserves the nutritional and organoleptic properties of food the industry remain cautious. Food and Drink Europe (2019) do not currently recommend enzymatic treatment as a commercial mitigation strategy due to the concern of maintaining adequate sensory profile across diverse coffee blends. The EU commission Regulation 2017/2158 does however suggest it as a mitigation strategy to achieve AA levels below benchmark level (EU 2017).

Despite successful laboratory and pilot trails, upscaling remains a challenge. The integration of the enzymatic treatment requires additional processing steps such as soaking and then drying which significantly increases production cost and necessitates specialized facilities. Further research is required to optimize these processes for commercial adaptation and to ensure the sensory integrity of the coffee is maintained when used on large scale.

4. Conclusion

This literature review demonstrates that AA content in coffee is determined by a complex interplay of factors. The baseline is established by precursor levels in green coffee beans, with Arabica varieties generally resulting in lower AA levels than Robusta. During roasting, AA is first formed and then degrades. Because of the degradation during prolonged roasting dark roast ultimately contain significantly lower AA levels than light roast. Furthermore, AA levels continue to decrease during storage and the final concentration in the beverage is dependent on the specific brewing parameters.

Given that coffee is a primary dietary source of AA in high consuming countries and considering the genotoxic and carcinogenic nature of this compound limiting its formation is critical. The European Food Safety Authority has concluded that current dietary exposure to AA poses a public health concern. However, addressing this risk is complicated by the fact that human dietary exposure is driven by deeply rooted consumer habits, cultural preferences and lifestyle choices of volume consumed each day rather than beverage concentration alone. For example, in southern Europe where consumer favour dark roasted espresso. Although the concentration of AA per millilitre may be high the small beverage volume combined with the low AA content of dark roast results in a lower overall dietary exposure even if multiple shots are consumed. Comparing this to northern Europe where consumers traditionally prefer large volumes of light-to-medium roasted filter coffee. Because the light-medium roasted beans retain more AA and filter coffee is consumed in larger cups, a single serving can result in substantial higher total AA exposure compared to multiple espressos.

Because changing these regional, culturally ingrained consumer behaviours is difficult, mitigation efforts should focus on upstream industrial solutions rather than relying on the consumers to alter their brewing or drinking habits. The most promising industrial strategies include; simple quality control of sorting out defective beans, tailoring the roasting time and temperature profile to minimize AA formation, developing innovative roasting methods and utilizing asparaginase to reduce the precursor asparagine.

Ultimately, future mitigation strategies require the balance between multiple variables: reducing AA, preventing the formation of other heat-induced contaminants, preserving natural antioxidants, maintaining the sensory profile, ensuring economic viability and achieving industrial scalability. Additional research is essential to develop these practical scalable solutions that do not compromise public health and still maintain the final cup quality.

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