Handbook of Molecular Gastronomy
Scientific Foundations, Educational Practices, and Culinary Applications
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Roasting

Publicaton details
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Published online on: 09 Jun 2021

How to cite :- Laura Febvay, Hervé This vo Kientza. 09 Jun 2021, Roasting from: Handbook of Molecular Gastronomy, Scientific Foundations, Educational Practices, and Culinary Applications CRC Press
Accessed on: 11 Oct 2023
In the kitchen, many food ingredients are “roasted”, i.e., thermally processed without addition of a liquid. The most common are coffee, chocolate, nuts, almonds, flour and spices. The various chemical changes due to this process are discussed in this chapter. As the same tissues from various plants often have the same overall chemical composition, one example (the seeds of Coffea) is analysed more thoroughly.

In the kitchen, the roasting process is defined as “the action of cooking something in an oven or over an open fire” (Oxford Dictionaries, 2018). This is what has been done for the seeds of Coffea and also for the beans of the cocoa tree Theobroma cacao (“chocolate beans”), various seeds such hazelnut (from Corylus avellana), sesame (Sesum indicum), and also wheat flour (the ground seed of plants of the genus Triticum). However for all these culinary ingredients, roasting is performed in more ways than described by the dictionary: sometimes it is performed in an oven, but it can also be in a frying pan, and the “open fire” is today replaced by modern heating systems (gas, electric heating plates, induction systems, electric oven, etc.).

**The Particular Example of Coffee**

For coffee, the green seeds (also called “green beans”) of Coffea are harvested in producing countries and then sent to roasters, who operate a thermal treatment during which the coffee seeds get new organoleptic properties: a brown colour and a specific flavour. This process increases the value of the coffee seeds by 100–300% compared with the green seeds (Yeretzian et al., 2002). For a long time, coffee was simply roasted in a frying pan (Kurti and Kurti, 1997), but the need to treat all parts of the surface of the seeds led to the introduction of small rotating drum roasters, in particular for large-scale production.

In the coffee industry, roasting is performed by putting the seeds in a heated vessel (“roaster”) at temperatures between 160 °C and 250 °C for a time between 8 and 20 min, depending on the final desired organoleptic properties (Fabbri et al., 2011; Münchow, 2016). In the roaster, the coffee seeds are heated by conduction, radiation and convection, but depending on the design of the roasting equipment, the proportion of heat received through each transfer mechanism can vary (Eggers and Pietsch, 2001). For instance, in fluidized bed roasters, coffee seeds are exposed to fast-moving hot air that simultaneously heats and tumbles individual seeds in the roast chamber; convective heating is the main mode of heat transfer.

In drum roasters, conduction tends to dominate (Baggenstoss et al., 2008).

Based on the phenomena triggered by heat, the roasting process can be divided into five steps: drying, yellowing, first crack, development and second crack (Figure 70.1). Then the roasted beans are cooled (Hoffmann, 2014).

These various steps can be observed by colour changes of seeds. Figure 70.2 shows these changes (Vosloo, 2017).

1. Drying: when the green seeds are introduced into the preheated roaster, the temperature of the vessel drops. But because more energy is provided, the system temperature stops dropping and increases again after a “turning point”. When the temperature inside the seeds
reaches the temperature of water vaporization, the water inside cells becomes gaseous: this is the drying step, during which the water content is reduced from 12% to 2% (Fadai et al., 2017), making the seeds expand. This is the longest step in roasting, as it takes some time for the seeds to absorb enough energy before evaporation.

2. Yellowing: when the seeds absorb more energy, volatiles are released, and the colour of the seeds turns to yellow (Franca et al., 2005); the seeds then have an odour similar to that of bread (Franca et al., 2009; Putranto and Chen, 2012). In this step, as in the first one, the walls of the seeds remain firm, and little steam escapes from the seeds, so that the pressure increases; the seeds expand and lose their “chaff” (Hoffmann, 2014; Vosloo, 2017). During the roasting process, these coffee chaffs are often recovered using an air flux inside the roaster in order to avoid the formation of flames.

The two first steps are important for roasting, as if an insufficient quantity of water is released, the external part will roast correctly, but the inside of the seeds will remain “raw”, with an undesirable bitter flavour (Hoffmann, 2014).

3. First crack: then some chemical reactions take place, releasing a large quantity of gases (5–12 L/kg, mainly carbon dioxide (CO₂)) (Münchow, 2016). The temperature in the seeds increases rapidly, and the gas production increases the volume of seeds even more, until the breaking point (Schwartzberg, 2002; Wang and Lim, 2014). This is the first crack, associated with a soft noise, as for popcorn. This occurs generally at a temperature between 175 °C and 185 °C (Gloess et al., 2014), with about 2 min elapsing from the time when the sound appears for the first seeds until all seeds have cracked. At this step, the volume of the seeds is twice the initial volume.

4. Development: after the first crack, odorant compounds are generated by many chemical reactions. This step lasts for 20–25% of the total roasting time (Münchow, 2016), and roasters base their decision on roasting time on the colour associated with these processes. Indeed, technicians decide the development time by choosing a balance between acidity and bitterness of the final product; more precisely, during development, the acidity decreases, whereas bitterness increases (Hoffmann, 2014).

5. Second crack: after the colour turns browner and odorant compounds accumulate, a second crack can occur because of CO₂ accumulation, but this second sound is softer (like snapping fingers) than the first crack, and it occurs during a shorter time than for the first. This happens when the temperature reaches 200 °C, where the seeds become darker (Gloess et al., 2014; Hoffmann, 2014). Industrial roasting processes
generally end between the first and the second crack. Before the first crack, the odour and flavour of coffee are not yet fully developed, and after the second crack, the beans are considered burnt; favourable odorant and taste compounds are lost, and unwanted odours are generated (Münchow, 2016).

6. Cooling: when the final roasting stage is reached, the seeds are transferred into another drum for cooling. Often, liquid water is added in order to stop the roasting, but some roasters also use cold air (Franca et al., 2005).

As a whole, roasting remains empirical, because the various times depend on a number of parameters, such as the physical and chemical characteristics of the seeds (density and water content), size, volume of batches, room temperature, etc. The goal of the roaster is to choose the seeds and decide on the roasting parameters in order to “maximize the flavour” (Illy and Viani, 2005): a strange expression, because the appreciation is either personal or cultural and is hard to measure. They follow the process using thermocouples inserted inside the roaster at the level of the seeds. Most roasters use the temperature development curve in order to observe the kinetics of the process.

The chemical changes involved have been studied, as will be discussed later.

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**Some Modifications of Coffee Seeds during Roasting**

Colour changes are the most obvious change in seeds during roasting. In large-scale industrial applications, the roasting degree is even evaluated through the colour changes (Münchow, 2016), but this is not a proper choice, because different chemical compositions of roasted seeds can be associated with the same colour (Febvay, 2019). Roasting triggers a multitude of chemical reactions (Clarke, 1987; Clarke and Vitzthum, 2017), generating new compounds, with sensorial, nutritional and toxicological effects (Buffo and Cardelli-Freire, 2004; Baggenstoss et al., 2008).

Of course, the chemical reactions are many, and include in particular pyrolysis, glycation reactions (including Schiff, Fischer, Maillard and Strecker reactions), hexose dehydration, oxidations, and degradation of polysaccharides, chlorogenic acids, proteins and trigonelline [1] (Franca et al., 2009b; Putranto and Chen, 2012; Sunarharum et al., 2014).

As a result, the main changes are:

- loss of water
- decrease in polysaccharides, loss of oligomers and monosaccharides
- changes in quantities of aliphatic acids
- loss of chlorogenic acids
- decrease in proteins and amino acids
- disappearance of trigonelline
- formation of melanoidins

Some of these will now be considered.

1. Saccharides: polysaccharides undergo degradation, depolymerization and structural modification (Redgwell et al., 2002). Monosaccharides such as galactose [2], mannose [3], arabinose [4] and ribose [5] are released (Moreira et al., 2012; Moreira et al., 2015; Oosterveld et al., 2003; Nunes et al., 2012). The oligosaccharides and monosaccharides produced are then transformed into degradation products (Oosterveld et al., 2003).

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[1] Trigonelline


[4] Arabinose

[5] Ribose
Arabinogalactans and galactomannans undergo many chemical modifications, including a reduction of the polymerization and branching degree, which can lead to a reduced solubility in water (Moreira et al., 2012; Nunes and Coimbra, 2001). Arabinogalactans are particularly prone to thermal processing compared with other polysaccharides of coffee. They are depolymerized after a mild roasting through galactan backbone fission and a loss of arabinose [4] by lateral chains.

Only a fraction of the oligomers or monomers in green seeds is found in the roasted seeds, showing that they are rapidly modified (Oosterveld et al., 2003). Modelling (Ginz et al., 2000) shows that the sucrose [6] content decreases, becoming too low to be detected after strong roasting (at temperatures more than 280 °C). When sucrose is added to seeds during roasting, fructose [7] and glucose [8] are formed, showing that these sugars are produced by degradation of sucrose.

The acidity appearing during roasting is primarily due to the formation of four aliphatic acids: formic [18], acetic [19], glycolic [20] and lactic [21] acids (Verardo et al., 2002). Their main precursor is sucrose [6], which is at a concentration between 3% and 8% in green seeds. Arabinose [4], erythrose [22] and 1,6-anhydroglucose [23] are also produced by the thermal degradation of sucrose [6] and are precursors for acid formation.

3. Chlorogenic acids: during roasting, the chlorogenic acids undergo many transformations, the first being a dehydration generating a lactone (Figure 70.3).

When the roasting process continues, the chlorogenic acids are degraded and react with sugars. Typically, 60% of chlorogenic acids are modified, being transformed into 30 lactones through the loss of water and quinic acid [24] and the formation of an intramolecular ester (Bennat et al., 1994; Farah et al., 2005). Of these lactones, seven were identified in roasted coffee (Farah et al., 2005): 3-caffeoylquinic-1,5-lactone (3-CQL, the most abundant) [25], 4-caffeoylquinic-1,5-lactone (4-CQL) [26], 3-coumaroylquinic-1,5-lactone (3-pCoQL) [27], 4-coumaroylquinic-1,5-lactone (4-pCoQL) [28], 3-feruloylquinic-1,5-lactone (3-FQL) [29], 4-feruloylquinic-1,5-lactone (4-FQL) [30], and 3,4-dicaffeoylquinic-1,5-lactone (3,4-diCQL) [31]. With a prolonged roasting, the chlorogenic acids are degraded into phenolic compounds through the hydrolysis of caffeic [32] and quinic [24] acids, forming new phenolic compounds such as pyrogallol [33] or catechol [34], and also caffeic acid [35] and hydroquinone [36] (Clifford, 1985; Müller et al., 2006).
[15] Succinic acid  
[16] Fumaric acid  
[17] Maleic acid

[18] Formic acid  
[19] Acetic acid  
[20] Glycolic acid

[21] Lactic acid  
[22] Erythrose  
[23] 1,6-anhydroglucose

[24] Quinic acid  
[25] 3-caffeoylquinic-1,5-lactone (3-CQL)

[26] 4-caffeoylquinic-1,5-lactone (4-CQL)
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[27] 3-coumaroylquinic-1,5-lactone (3-pCoQL)

[28] 4-coumaroylquinic-1,5-lactone (4-pCoQL)

[29] 3-feruloylquinic-1,5-lactone (3-FQL)

[30] 4-feruloylquinic-1,5-lactone (4-FQL)
[31] 3,4-dicaffeoylquinic-1,5-lactone (3,4-diCQL)

[32] Caffeic acid

[33] Pyrogallol

[34] Catechol

[35] Caffeinic acid

[36] Hydroquinone

[37] Arginine
4. Formation of melanoidins: melanoidins are polymers that are present in many transformed food products. In roasted coffee, they are nitrogen-containing compounds of large size, with a molar mass between 3,000 and 22,000 (Ledl and Schleicher 1990; Nunes et al., 2012). Melanoidins include residues of sugars, proteins and phenolics (Nunes and Coimbra, 2001; Borrelli et al., 2002; Bekedam et al., 2006; Nunes and Coimbra, 2007; Bekedam et al., 2008; Gniechwitz et al., 2008; Nunes and Coimbra, 2010; Silván et al., 2010; Moreira et al., 2012; Nunes et al., 2012; Coelho et al., 2014; Moreira et al., 2015). Because of the poor characterization of melanoidins to date, their quantity is difficult to assess and their formation is difficult to follow. It has been reported that polymerization of phenols and glycation processes contribute to the formation of melanoidins in coffee (Borrelli et al., 2002; Montavon et al., 2003).

5. Degradation of proteins: roasting denatures proteins but also makes them insoluble. Depending on the intensity of roasting, the loss of amino acid residues can reach 20–40%. Some amino acids, such as arginine [37], cysteine [38], lysine [39], methionine [40], threonine [41] and serine [42], are lost partially or entirely (Moreira et al., 2012a; Parliment, 2000; Clarke, 1987; Spiller, 1997). Amino acids with hydroxyl (-OH), thiol (-SH) and amino (-NH2) groups participate in odour formation.

6. Disappearance of nitrogenous compounds: caffeine [43] does not appear to be modified during roasting (Farah et al., 2005), but other xanthines, such as adenine [44], guanine [45] and hypoxanthine [46], are destroyed. Trigonelline [11] is changed into nicotinic acid [47], pyridine [48] and aromatic substances (such as furanes, pyrazines or pyrroles) (Ky, 2001). In particular, N-methylpyridinium [49] is produced (Taguchi et al., 1985; Stadler et al., 2002).

7. Volatiles: volatile compounds are absent in green seeds, but they make up about 0.1% of the dry matter of roasted seeds. Their appearance during roasting is largely due to sucrose [6] degradation through caramelization (Ginz et al., 2000; De Maria et al., 1996). Volatile compounds such as aldehydes, ketones, thiols, furans, pyroles, pyrazines and guaiacols derive from degradation or fragmentation of sucrose, amino acids, trigonelline and chlorogenic acids, as well as from pyrolysis of arabinogalactans.

Roasted coffee contains more than 600 volatile compounds; only about 10% of these contribute to odour. Furfurylic alcohol [50] plays a particular role, because green seeds contain more of it (418 µg/g) compared with other roasted seeds in the same conditions (up to 132 µg/g). Its production resembles that of other compounds such as hydroxymethylfurfural (HMF) [51] or acrylamide [52]. However, the quantity of furfurylic acid [53] in roasted coffee does not correspond to the quantity produced during roasting.

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[38] Cysteine

![Cysteine](image)

[39] Lysine

![Lysine](image)

[40] Methionine

![Methionine](image)

[41] Threonine

![Threonine](image)

[42] Serine

![Serine](image)

[43] Caffeine

![Caffeine](image)
8. Lipids are not much transformed during roasting; the lipid fraction tends to be stable and survive the roasting process with only minor changes. Linoleic [54] and palmitic [55] acids are the predominant fatty acid residues in coffee. The most important modification is the reduction of diterpenes in dehydrocafestol [56] and dehydrokahweol [57]. Cafestol [58] and kahweol [59] are diterpenes that are degraded by the roasting process.

As a whole, for culinary purposes, it is worth observing that not only are the temperature of roasting and the duration of the thermal process important, but also the different time-temperature profiles during roasting develop different flavours (Buffo and Cardelli-Freire, 2004; Febvay et al., 2019). The effects of time-temperature profile on coffee odorant properties have been reported by Lyman et al. (2003), who observed that the medium roasted process (6.5 min to the onset of the first crack and 1.0 min to the onset of the second crack) resulted in “good balance” of taste and odour. However, the “sweated process” (4.5 min to the first crack and 6.5 min to the second crack) resulted in non-uniform bean colour, and the coffee was “sour, grassy, and underdeveloped”. Reducing the heating rate further by using the “baked process” (11 min to the first crack and 18 min to the second crack) produced coffee that was “flat, woody with low brightness and acidity” (Lyman et al., 2003). In another study, Schenker et al. (2002) reported that processes for which temperature increases from low to high (150 to 240 °C for 270 s; 240 °C for 55 s) resulted in the formation of the highest quantities of odorant volatiles, while the long-time low-temperature approach (isothermal heating at 220 °C for 600 s) generated the lowest odorant volatiles. Moreover, the distribution of the 13 volatile compounds monitored differed considerably depending on the roasting profiles used.
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[54] Linoleic acid

[55] Palmitic acid

[56] Dehydrocafestol

[57] Dehydrokahweol

R = fatty acid
Other Seeds

Roasting is also performed for other food ingredients than coffee beans. The process has been less well studied, but many results have been obtained. Some are given here, providing complementary information that can sometimes hold as well for coffee.

1. Cocoa: One other important (in terms of mass treated) product that is roasted is cocoa, for which roasting also develops unique flavour (Zzaman et al., 2017). Roasting temperatures are often between 150 °C and 250 °C, and roasting times are in the interval 10–50 min. As for coffee, the concentration of total reducing sugars is also reduced to 60–85% with increased roasting temperature. The hydrophobic amino acids or amino acid residues are reduced by as much as 30–49% with increased roasting temperature after 50 min processing. A number of pyrazines, esters, aldehydes, alcohols, ketones, carboxylic acids and hydrocarbons appear in all the samples at different concentration ranges. The most flavour-active compounds, pyrazines, were formed at the highest concentration (2.96 mg/kg) at 200 °C for 10 min.

2. Carob: Other plant materials give analogous results. For example, carob pod powder (Ceratonia siliqua L.) roasted at different roasting temperatures become darker, and the average moisture content, water activity, oil content and sweetness values decrease at higher temperatures (Boublenza et al., 2017). Here, the total content of phenolics (and the antioxidant activity) increases with increasing roasted temperature. Oleic acid [60], linoleic acid [54] and palmitic acid [55] are the main fatty acid residues present in carob oil. Results showed that the roasted carob pod powders are sweeter and have a more caramel-like taste and a more cacao-like aroma at lower roasting temperatures but have a more astringent taste, coffee-like aroma and roasted aroma at higher roasting temperatures.

3. Walnut: For walnut flour (Santos et al., 2017), the changes in lipids were thoroughly followed in one study. The goal was to evaluate the composition and the antioxidant properties of walnut flours submitted to different roasting protocols (50, 100 and 150 °C for 30, 60 and 120 min). All walnut flours contained about 42% of protein and a significant amount of dietary fibre (17%), which was affected by the roasting process. Nonetheless, the fat content increased around 50% in walnut flours subjected to longer and higher roasting temperatures (150 °C). The lipid fraction showed good nutritional quality with a high vitamin E content (mainly γ-tocopherol [61]) and a fatty acid profile rich in linoleic [54] and linolenic acids [62]. The high phenolic content also provides great antioxidant capacity to the flours. Mild roasting of the walnuts did not affect the quality of the flours, which could be used as a functional ingredient in the food industry.

4. Sesame seeds: For sesame, Kahyaoglu and Kaya (2006) modelled moisture, colour and texture changes in sesame seeds during roasting. Experiments were performed at 120, 150 and 180 °C for 120 min. As for other roasting processes, seeds became browner, but the interest of this study was to simulate the changes in the moisture content, colour values (L*, a* and b*) and textural properties (hardness and fracturability) using exponential, kinetic and polynomial models. The variations in the colour parameters of sesame seeds during conventional roasting were adequately simulated by cubic polynomials. The zero-order kinetic model satisfactorily described the reduction in the hardness and fracturability of sesame seeds. The temperature dependence of moisture and colour models was described by a linear function relationship, but an Arrhenius-type relationship was used for textural models. The activation energy for sesame seeds was estimated to be 6.9 and 9.8 kJ/mol for hardness and
fracturability changes, respectively, over the temperature range of the study.

The effect of roasting treatment on the chemical composition of sesame oil was also studied (Ji et al., 2019). They reported that with roasting, the peroxide value and colour development of oils were obviously elevated, while the total tocopherols and sesamolin decreased steadily. The acid values in the current experiment were expected to grow as the roasting time increased at the same temperature, and the acid value decreased in the first 30 min of roasting at 160 °C. Increased roasting temperature or time facilitates sesamol formation in sesame oil. The fatty acid profiles are almost independent of roasting conditions.

[60] Oleic acid

[61] γ-tocopherol

[62] Linolenic acid
5. Wheat: Of course, the case of wheat flour and bread is important, as baking bread is related to roasting, with the same range of temperature and time of thermal processing. Bread making leads to the generation of a lot of odorant compounds, but these can be attributed to either fermentation or roasting (Gassenmeier and Schieberle, 1995). The most important odorants in the crumbs of wheat breads (French-type) prepared according to two different dough recipes using pre-fermentation (crumb I: liquid pre-ferment, containing 0.25% yeast and 1.5% yeast in the final dough; crumb II: soft dough pre-ferment containing 15% yeast and 4.6% yeast in the final dough) were evaluated on the basis of aroma extract dilution analyses. In crumb I, exhibiting the more typical flavour, comparatively higher flavour dilution (FD) factors were found especially for 2-phenylethanol (2-PE) [63] and 3-methyl-butanol (3-MB) [64], while in crumb II, the FD factors of methional [65], 1-octen-3-one [66], 4-hydroxy-2,5-dimethyl-3(2H)-furanone [67], butanoic acid [68] and 2-methylbutanoic acid [69] and 3-methylbutanoic acid [70] were higher than in crumb I. Quantitative studies (stable isotope dilution assays) of 2-PE and 3-MB formation in the liquid pre-ferments containing low yeast concentrations (0.25%) revealed that anaerobic conditions and a fermentation temperature of 35 °C favoured the production of both odorants. Model studies, in which either the 3-MB precursors L-leucine [71] and 3-methylbutanal [72] or the 2-PE precursors L-phenylalanine [73] and phenylacetaldehyde [74] had been added to the pre-ferments, indicated that baker’s yeast significantly (15–55%) converted these precursors into the respective odorants.

[63] 2-phenylethanol (2-PE)

![Image of 2-phenylethanol](image)

[64] 3-methyl-butanol (3-MB)

![Image of 3-methyl-butanol](image)

[65] Methional

![Image of Methional](image)

[66] 1-octen-3-one

![Image of 1-octen-3-one](image)

[67] 4-hydroxy-2,5-dimethyl-3(2H)-furanone

![Image of 4-hydroxy-2,5-dimethyl-3(2H)-furanone](image)

[68] Butanoic acid

![Image of Butanoic acid](image)

[69] 2-methylbutanoic acid

![Image of 2-methylbutanoic acid](image)

[70] 3-methylbutanoic acid

![Image of 3-methylbutanoic acid](image)

[71] L-leucine

![Image of L-leucine](image)
Roasting gives a different perspective on the same kind of process with the same kind of raw material (Rychlik and Grosch, 1996): slices of wheat bread were toasted until a distinct intensity of brown colour was attained. Potent odourants formed were evaluated by odorant extract dilution analysis and gas chromatography/olfactometry of headspace samples. Compounds showing high dilution factors were quantified, and their odorant activity values (OAV, ratio of concentration to odour threshold) were calculated on the basis of their odour thresholds in starch. The roasty smell of 2-acetyl-1-pyrroline showed the highest OAV, followed by (E)-2-nonenal, 3-methylbutyric acid, 4-hydroxy-2,5-dimethyl-3 (2H)-furanone, methional and 2,3-butanedione. Formation of nine odorants was measured in relation to the intensity of the brown colour. It was found that at the beginning of toasting, [72] increased more rapidly in the bread slices than [77], which was mainly produced at medium browning.

Conclusions

Plant materials share a common basic composition, with water, polysaccharides, amino acids, proteins, etc. Seeds in particular include lipids because of the biological significance of these compounds for young plant development (Bergfeld et al., 1978). It is not surprising that the thermal processing of these products is accompanied by the same kind of chemical reaction, with the same colour changes, and the same products being formed in the same range of time and temperature. Of course, particular plant tissues with a particular raw composition (a lot of starch for flour, caffeine in coffee or chocolate, etc.) can have particular reactions, alone or in combination, but this is not to say that all these plant tissues will have the same flavour in the end, because it is well known that changes in the particular composition of odorants can have drastic consequences for the odour, and hence the flavour, of food products.

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