COMBINED INFLUENCE OF ROASTING DEGREE AND BREWING METHOD ON CHLOROGENIC ACIDS, TRIGONELLINE, CAFFEINE, AND MELANOIDINS IN COFFEE BEVERAGES – A REVIEW

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Abstract

This review critically examines the influence of roasting degree and brewing method on chlorogenic acids, trigonelline, caffeine, melanoidins, and the antioxidant activity of coffee through a comparative synthesis of the scientific literature. The available evidence indicates that increasing roasting intensity promotes the degradation of chlorogenic acids and trigonelline, whereas caffeine shows relatively greater stability. At the same time, the formation of melanoidins and other compounds generated during roasting contributes to antioxidant activity, which therefore does not necessarily follow the changes in chlorogenic acid content. Brewing method further influences the final composition through extraction conditions such as temperature, contact time, pressure, and grind size. The integrated analysis highlights the heterogeneity of the reported findings, the limited number of factorial comparisons between roasting degree and brewing method, and the need for a more standardized characterization of roasting degree.

Key words: *coffee; roasting degree; brewing methods; bioactive compounds; antioxidant activity*

INTRODUCTION

The biological value of a cup of coffee results from two successive technological stages, roasting and brewing [1,2]. Roasting profoundly alters the composition of green beans: chlorogenic acids (CGA) are degraded by 92–95% between green beans and dark roast [3], trigonelline follows a similar trend [4], caffeine remains relatively stable [4,5], and melanoidins are formed and accumulate as roasting progresses [6]. The brewing method then determines which fraction of this composition reaches the beverage, through water temperature, contact time, pressure, grind size and the coffee-to-water ratio [1,7].

The two factors have mostly been studied separately. Of the 32 studies on the caffeine content of beverages analysed in a recent synthesis, only 25% included at least two roasting degrees, and the classification of roasting degree is not standardized [8]. The few available factorial studies show that the effects are not simply additive: antioxidant capacity decreases with roasting intensity in cold extraction but remains constant in hot extraction [9], and for caffeine and total polyphenols the brewing method and species had a significant influence, unlike roasting degree [10]. Moreover, antioxidant activity does not necessarily follow the decrease in CGA,

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because roasting generates melanoidins and new phenolic compounds with their own activity [11,12].

This review aims to critically analyse the combined influence of roasting degree and brewing method on CGA, trigonelline, caffeine, melanoidins and the antioxidant activity of the coffee beverage. The working hypothesis is that the effect of roasting cannot be interpreted independently of extraction conditions and that the direction of this effect differs from one compound to another.

MATERIAL AND METHOD

Type of study and search strategy

The work was designed as a critical, narrative-comparative review based on a structured search of the scientific literature. This format was preferred to a systematic review with meta-analysis because of the nature of the available data: studies on the effects of roasting and brewing differ considerably in experimental design, raw material and the way results are expressed, and statistical pooling of the values would have led to conclusions without real support.

The literature search was carried out in September–October 2026. The scientific literature was queried using combinations of the following English terms: “coffee”, “roasting degree”, “roast level”, “brewing method”, “espresso”, “filter coffee”, “French press”, “moka”, “cold brew”, “extraction”, “chlorogenic acids”, “5-caffeoylquinic acid”, “trigonelline”, “caffeine”, “melanoidins” and “antioxidant activity”. Each identified paper was confirmed on the publisher’s platform or in a bibliographic database (ScienceDirect, MDPI, SpringerLink, Wiley Online Library, Royal Society of Chemistry, Frontiers, Nature Portfolio, Oxford Academic, SciELO, PubMed), and the bibliographic metadata were verified through the DOI.

Eligibility criteria

Papers were included if they simultaneously met four conditions: (i) they were published in peer-reviewed scientific journals or conference proceedings; (ii) they investigated roasted coffee from *Coffea arabica* and/or *Coffea canephora*; (iii) they assessed the effect of roasting degree, brewing method or extraction parameters (temperature, contact time, pressure, grind size, coffee-to-water ratio, flow rate); (iv) they reported quantitative data for at least one of the target compounds or for antioxidant activity. Review papers presenting quantitative values or ranges were also accepted. Studies limited to green coffee, papers dealing with the valorisation of spent coffee grounds or with extracts used as supplements, papers without accessible numerical data, and one article retracted by the publisher were excluded.

Data extraction and verification

For each paper, the following were extracted into a data matrix built in Microsoft Excel: coffee species and origin; the definition of roasting degree (temperature and time, mass loss, colorimetric parameters or instrumental scales); the brewing method and its parameters; the analytical method (HPLC-DAD, LC-MS, spectrophotometry); the antioxidant assays (DPPH, ABTS, FRAP, TEAC); and the reported values, together with the unit of measurement and the basis of expression (per millilitre of beverage, per serving, per gram of dry weight or per gram of extract). Values were taken exclusively from the text, tables or abstract of the papers and were re-checked in the primary source; when a value appeared only in figures or could not be confirmed, the paper was used only for the qualitative trend.

Data organization and interpretation

The papers were grouped into six categories: (1) effect of roasting degree; (2) effect of brewing method; (3) roasting × brewing factorial studies; (4) effect of extraction parameters; (5) antioxidant activity, including after *in vitro* digestion; (6) review papers with quantitative data.

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Because the units of expression were highly heterogeneous, the values were neither converted to a common basis nor statistically pooled. Comparisons were made primarily within the same study, through relative changes calculated from the published values (for example, the percentage decrease of a compound between light and dark roast); across studies, only trends and the ranking of methods were compared. Roasting degree was kept in the authors' terminology, without reclassification. The final corpus comprised 59 papers published between 2005 and 2026, of which 49 (83%) appeared after 2015; 54 are experimental studies and 5 are review papers (four reviews and one meta-analysis).

RESULTS AND DISCUSSION

Effect of roasting degree on bioactive compounds

Comparable data from within the same studies confirm a consistent pattern, but with different magnitudes from one compound to another (Table 1). CGA degradation is the most pronounced. In beans roasted at 200°C, total CGA decreased from 4661 to 234 mg/100 g d.w. in Arabica and from 4946 to 377 mg/100 g d.w. in Canephora between green beans and dark roast, i.e., by 95% and 92%, respectively [3]. For 5-caffeoylquinic acid (5-CQA), the major isomer, the decrease between light and dark roast was 85% in Arabica and 95% in Robusta [4], and in a recent study the 5-CQA content decreased from 48.27 to 0.99 mg/g between green beans and the most intense roast [13]. Part of this loss is not actual destruction but redistribution among isomers: the proportion of 5-CQA decreases from approximately 49–64% in green coffee to 33–41% after roasting, partly through isomerization to 4-CQA and 3-CQA [14]. The decrease in CGA with roasting intensity was also observed in espresso coffee, both in the powder and in the beverage [15], and bean colour (L*, a*, h°) correlated strongly with CGA content [16], which supports the use of colorimetric parameters to characterize roasting degree.

Trigonelline follows the same direction, but with a smaller magnitude: −68% in Arabica and −83% in Robusta between light and dark roast [4], and −40% (29–54%) after traditional roasting of Ethiopian coffee, compared with −81% for CGA in the same samples [5]. However, trigonelline degradation is not merely a nutritional loss, because it generates bioactive products such as nicotinic acid and N-methylpyridinium [17], and nicotinic acid has even allowed the roasting degree of commercial coffees to be characterized [18]. Caffeine proved to be the most stable compound: values remained between 1.33 and 1.36 g/100 g d.w. in Arabica and between 2.10 and 2.25 g/100 g d.w. in Robusta across the three roasting degrees [4], and the difference after traditional roasting was not statistically significant [5]. The apparent increase in caffeine reported on a dry-weight basis (e.g., from 1110 to 1222–1255 mg/100 g d.w. in Arabica) [3] most likely reflects the mass loss during roasting rather than caffeine synthesis. Nevertheless, decreases in extractable caffeine have also been reported at high roasting temperatures [19], and the review by Olechno et al. shows inconsistent results regarding the effect of roasting degree on beverage caffeine [20].

Melanoidins evolve in the opposite direction. In Arabica beans roasted for espresso, their content increased from 0.12 to 0.14 mmol/g d.w. between light and dark roast [6], and in Canephora coffees from the Amazon values ranged between 10.0 and 17.9 g/100 g, of the same order of magnitude as total CGA (3.93–6.37 g/100 g) in the same samples [21]. The difference between species is also maintained in the beverage: in cold extraction, Canephora provided more CGA, caffeine and melanoidins than Arabica [22].

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Table 1. Changes in bioactive compounds with roasting degree within the same study (data from roasted beans)

Source	Material and roasting definition	Compound	Reported values	Change*
[3]	Arabica and Canephora; 200 °C, 7/10/12 min	Σ CGA	Arabica 4661 → 234; Canephora 4946 → 377 mg/100 g d.w. (green → dark)	−95%; −92%
[3]	idem	Caffeine	Arabica 1110 → 1192–1255; Canephora 1486 → 1698–1884 mg/100 g d.w.	apparent increase
[4]	Arabica and Robusta; 230 °C, mass loss 13/17/20%	5-CQA	Arabica 1.786 → 0.263; Robusta 2.015 → 0.094 g/100 g d.w.	−85%; −95%
[4]	idem	Trigonelline	Arabica 0.928 → 0.297; Robusta 0.683 → 0.119 g/100 g d.w.	−68%; −83%
[4]	idem	Caffeine	Arabica 1.33–1.36; Robusta 2.10–2.25 g/100 g d.w.	stable
[13]	Arabica; green → "Italian" roast	5-CQA	48.27 → 0.99 mg/g	−98%
[5]	Ethiopian Arabica, 5 regions; traditional roasting	CGA / trigonelline / caffeine	mean decrease 81% / 40% / not significant	−81%; −40%
[6]	Specialty Arabica; 3 espresso roasting profiles	Melanoidins	0.12 → 0.13 → 0.14 mmol/g d.w.	+17%

** Change calculated by the authors of this review from the published values (last degree versus first). d.w. – dry weight; Σ CGA – sum of chlorogenic acid isomers; 5-CQA – 5-O-caffeoylquinic acid. Values refer to beans, not to the beverage.*

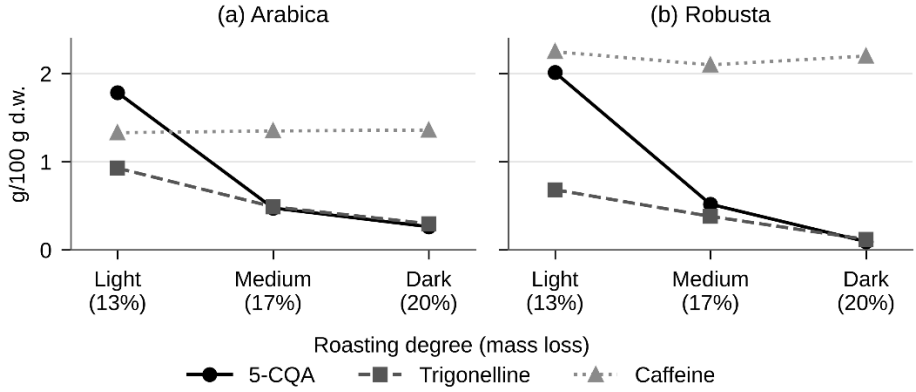


Fig. 1. Changes in 5-CQA, trigonelline and caffeine in Arabica (a) and Robusta (b) beans with roasting degree (g/100 g d.w.); data from [4], Table 2

Effect of brewing method and extraction parameters

The comparison of brewing methods depends decisively on the basis of expression (Table 2). In the most comprehensive study using a single Arabica batch, espresso had the highest concentration of caffeine (4.10–4.20 mg/mL) and 5-CQA (4.46–4.80 mg/mL), approximately eight to nine times higher than French press (0.52 and 0.53 mg/mL) [23]. Per serving, however, the ranking changed: cold brew provided the highest amount of caffeine (149.52 mg in 120 mL), followed by classic espresso (122.40 mg in 30 mL), while specialty espresso, served in 18 mL, dropped to 75.51 mg [23] (Fig. 2). A similar picture emerged from the comparison of nine methods, in which caffeine ranged between 4.7 and 21.0 mg/10 mL and 5-CQA between 0.78 and 2.8 mg/10 mL [24]. The high

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concentration of espresso was confirmed in comparisons with moka and Neapolitan coffee [25,26], and espressos prepared from Arabica of different origins contained 393.3–489.3 mg caffeine and 284.1–311.3 mg trigonelline/100 mL [27].

Variability becomes even greater under real consumption conditions. In commercial espressos, caffeine content ranged between 51 and 322 mg/serving and caffeoylquinic acids between 24 and 422 mg/serving [28]; in Italian espressos, caffeine ranged between 54 and 150 mg/serving [29]. These ranges show that the name of the method does not, by itself, define the ingested dose, which depends on the amount of coffee, the serving volume and the brewing practice.

Comparisons between hot and cold extraction are not unequivocal. When the coffee-to-water ratio was identical (1:18), the differences between boiling, pour-over, cold brew and ultrasound-assisted extraction were small: caffeine 0.56–0.68 mg/mL, CGA 1.25–1.53 mg/mL and trigonelline 0.31–0.54 mg/mL [30]. In the same direction, metabolomic analysis revealed no significant differences in caffeine, chlorogenic acid and trigonelline between hot and cold beverages [31], and caffeine values for cold brew and filter coffee were similar (0.74–0.80 mg/mL) [32]. In contrast, when recipes differ, the differences increase: caffeine ranged from 217.57 mg/L (V60) to 939.28 mg/L (cold brew) [33], and in another study cold brew contained 96.3–120.4 mg caffeine/100 mL, compared with 47.3–53.5 mg/100 mL for espresso [34]. These differences largely reflect the coffee-to-water ratio and dilution, not only water temperature. Nevertheless, for the same type of immersion, cold brew had a higher pH (5.38 vs. 5.18), lower titratable acidity (0.86 vs. 0.97 g/L) and fewer polyphenols (3.40 vs. 4.08 g/L) than hot French press [7].

Extraction parameters explain an important part of these differences. Technical guidelines recommend water temperatures of 88–93 °C, a pressure of 9 bar for espresso and an extraction yield of 18–22% [1]. In espresso, flow rate had the strongest effect on the mass of compounds in the cup, its increase reducing the content of trigonelline, caffeine and 5-CQA, whereas temperature alone had a small effect [35]. For cold brew, usual practice involves 50–100 g coffee/L and brewing times of 14–26 h [36], but low temperature and coarse grind size limit extraction [37].

Table 2. Bioactive compounds in beverages obtained by different methods, with the basis of expression

Source	Design	Compound	Reported values	Basis
[23]	8 methods, same Arabica batch	Caffeine	French press 0.52 → specialty espresso 4.20	mg/mL
[23]	idem	Caffeine	Caffè Firenze 42.78 → cold brew 149.52	mg/serving
[23]	idem	5-CQA	French press 0.53 → specialty espresso 4.80	mg/mL
[24]	9 extraction methods	Caffeine; 5-CQA	4.7–21.0; 0.78–2.8	mg/10 mL
[30]	5 methods, fixed ratio 1:18	Caffeine; CGA; trigonelline	0.56–0.68; 1.25–1.53; 0.31–0.54	mg/mL
[34]	cold brew, French press, AeroPress, espresso	Caffeine	96.3–120.4; 55.4–77.0; 49.8–62.9; 47.3–53.5	mg/100 mL
[33]	V60 vs. cold brew (different ratios)	Caffeine	217.57; 939.28	mg/L
[27]	espresso, 3 Arabica origins	Caffeine; trigonelline	393.3–489.3; 284.1–311.3	mg/100 mL
[28]	commercial espressos	Caffeine; CQA	51–322; 24–422	mg/serving

CGA – chlorogenic acids; CQA – caffeoylquinic acids; 5-CQA – 5-O-caffeoylquinic acid. Values are not comparable between rows, because the bases of expression and the recipes differ.

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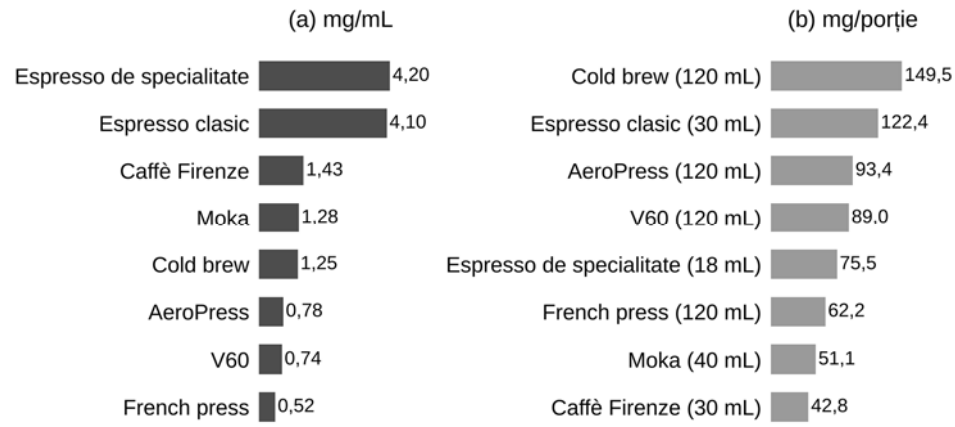


Fig. 2. Caffeine in eight beverages prepared from the same Arabica batch: (a) concentration, mg/mL; (b) amount per serving, mg; data from [23], Tables 3 and 5

Roasting × brewing interaction

Studies that simultaneously varied roasting degree and brewing method are few, but they support the working hypothesis (Table 3). In hot and cold extraction of three roasting degrees, CGA decreased with roasting in both variants, caffeine remained comparable, and total antioxidant capacity remained constant in hot extraction but decreased with roasting intensity in cold extraction [9]. A plausible explanation is the weaker cold extraction of compounds formed during roasting, including melanoidins, which, in hot extraction, may compensate for the loss of CGA. In a design with four methods, three roasting degrees and two species, method and species significantly influenced caffeine and total polyphenols, whereas roasting degree had no significant effect ($p = 0.784$) [10]; espresso was the richest per 100 mL but provided the lowest amount of caffeine per serving [10], which reproduces, in a different context, the reversal observed by Angeloni et al. [23].

For cold brew, the effect of roasting depends on extraction conditions. CGA reached a maximum of 996 mg/L for the roasting profile with a final temperature of 210 °C and 6 h of extraction, while caffeine ranged between 430 and 631 mg/L, with the maximum for the 220 °C profile [38]. The HTST roasting profile combined with cold drip extraction led to the highest values of soluble solids, caffeine, trigonelline and 4- and 5-CQA [39]. For filter coffee, the maximum extraction yield was obtained at a roasting mass loss of approximately 12–14%, and maximum caffeine at 14–16% [40], indicating an intermediate optimum rather than a monotonic relationship. The interaction also appears in the ranking of methods: at light roast, moka contained more caffeine than the Turkish ibrik (2903.14 vs. 2055.95 mg/L), but at dark roast the order was reversed (2342.32 vs. 2551.03 mg/L) [41].

Other studies complete the picture. Moka extracted more than 85% of phenolic compounds, compared with 64–74% for espresso, and the effect of roasting on antioxidant activity was uneven, depending on the method and the assay [42]. In ultrasound-assisted extraction, maximum caffeine (27.65 mg/g extract) was obtained at medium roast, and maximum CGA (16.67 mg/g extract) at light roast [43]. Medium roast retained more CGA than dark roast in Turkish coffee [44], and in home brewing the highest CGA values were obtained by combining medium roast, fine grinding and three pours of hot water [45].

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Table 3. Roasting × brewing factorial studies: design and key results

Source	Design	Key result
[9]	3 roasting degrees × hot (100 °C, 6 min) / cold (7 h) extraction; 20 g/200 mL	CGA decrease with roasting in both methods; caffeine comparable; antioxidant capacity constant in hot extraction, decreasing with roasting in cold extraction
[10]	4 methods × 3 roasting degrees × 2 species	Method and species significantly influence caffeine and total polyphenols; roasting degree does not ($p = 0.784$)
[38]	Cold brew: 3 roasting profiles (210–230 °C) × 3 temperatures × 3 times	Maximum CGA 996 mg/L (210 °C, 6 h); caffeine 430–631 mg/L, highest at 220 °C
[39]	Roasting profiles × cold brew methods (immersion, drip) and hot brewing	HTST + cold drip: highest values of caffeine, trigonelline and 4-, 5-CQA
[41]	8 preparations × 3 roasting degrees	The moka / ibrik ranking for caffeine is reversed between light and dark roast
[40]	Roasting degrees × extraction yield (filter)	Maximum yield at 12–14% mass loss; maximum caffeine at 14–16%
[42]	Roasting degrees × brewing methods	Moka > 85% of phenolics extracted, espresso 64–74%; uneven effect of roasting on antioxidant activity

CGA – chlorogenic acids; CQA – caffeoylquinic acids; HTST – high-temperature, short-time roasting. In most studies, values for each combination appear only in figures; the table reports the results stated explicitly in the text.

Antioxidant activity

The relationship between roasting degree and antioxidant activity is less linear than that of CGA. The available meta-analysis shows that light roast has the highest antioxidant activity (FRAP, DPPH), significantly higher than dark roast and comparable to medium roast [46]. Individual results support this trend: the effective concentration EC50 increased from 63.69 to 84.11 µg/mL between light and dark roast in conilon coffee, indicating weaker activity [47], and the maximum inhibition of guaiacol oxidation (43.79%) was obtained at light roast [48]. On the other hand, in beans of different origins antioxidant activity (63.9–92.0 mg TE/g d.w.) did not correlate with roasting degree, whereas new phenolic compounds such as gallic acid, pyrogallol and purpurogallin, absent in green coffee, increased at darker roasts [11]; non-linear trends have also been reported for the polyphenols of some Arabica varieties [49].

In the beverage, the contribution of CGA remains dominant: chlorogenic acids accounted for more than 84% of the total antioxidant potential of the beverages analysed by Sęk et al. [33]. Nevertheless, antioxidant capacity correlated directly with the degree of melanoidin extraction in capsule espresso [12], and the disappearance of the roasting effect in hot but not in cold extraction [9] suggests that melanoidins partly compensate for the loss of CGA when they are efficiently extracted. Hot extraction resulted in higher antioxidant activity than cold extraction [50], and DPPH values ranged between 31% (espresso) and 42% (AeroPress) [51]. An often overlooked aspect is bioaccessibility: after *in vitro* gastrointestinal digestion, polyphenol bioaccessibility was 45.9–62.9%, and antioxidant activity increased, especially in the colonic phase [52]. Therefore, the values measured in the beverage do not fully describe the biological value of coffee.

Data heterogeneity and methodological limitations

The critical analysis revealed four main sources of heterogeneity. The first is the lack of a standardized definition of roasting degree, expressed either as temperature and time or as

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mass loss, colour or instrumental scales [8,16]. The second is the basis of expression: the same beverages can be ranked differently per millilitre and per serving [10,23], and coffee-to-water ratios differ considerably between methods, from approximately 1:31 to 1:13.3 within the same study [33]. The third is the analysed matrix: an important part of the data on the effect of roasting comes from beans or analytical extracts, not from the consumed beverage [3,4,6]. The fourth concerns reporting quality: values presented only in figures [9,10], ambiguous or unusual units [51,53], ranges that combine different types of samples [32] and internal inconsistencies between text and tables [23,28]. For these reasons, the quantitative comparisons in this review were limited to changes within the same study, and the results should be interpreted as trends rather than reference values.

From the perspective of future research, complete factorial studies are needed that combine at least three roasting degrees, characterized instrumentally (mass loss and colorimetric parameters), with brewing methods standardized by coffee-to-water ratio, temperature and time, and that report results both per millilitre and per serving. Including melanoidins and *in vitro* bioaccessibility would allow a more complete assessment of the biological value of the beverage.

CONCLUSIONS

Roasting degree determines the potential composition of coffee: chlorogenic acids and trigonelline decrease sharply as roasting intensifies, caffeine remains relatively stable, and melanoidins accumulate. The brewing method determines how much of this composition reaches the cup, and the ranking of methods depends on whether results are expressed per millilitre or per serving.

The two factors interact: the effect of roasting on antioxidant capacity and on the extraction of bioactive compounds differs according to extraction temperature and time, so that antioxidant activity does not necessarily follow the changes in chlorogenic acids. For food engineering, this means that optimizing the biological value of the beverage should be achieved through the combined choice of roasting profile and extraction parameters, rather than by optimizing each stage separately.

Methodological heterogeneity and the small number of factorial studies limit quantitative comparisons between papers. A standardized characterization of roasting degree and the reporting of results on comparable bases are needed.

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