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Review Article

Coffee Metabolomics, Bioassays, and Sensory Profiles: A Critical Review

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ABSTRACT

Coffee is a chemically rich beverage whose sensory quality and bioactivity are shaped by cultivar, post-harvest processing, roasting, and brewing. Comprehensive metabolomic and targeted analyses identify chlorogenic acids, caffeine, trigonelline, diterpenes, simple phenolic acids, melanoidins, and numerous Maillard- and lipid-derived volatiles as recurring families. This critical review synthesizes chemical profiling (LC-MS, HR-MS, NMR, and GC-MS), antimicrobial and antifungal bioassays, and sensory science to map structure–function relationships, highlight isomer-specific roles in acidity and aroma formation, and evaluate reported biological activities. While many coffee constituents show *in vitro* antimicrobial, antibiofilm, and metabolic-modulating effects, reported MIC/IC_{50} values vary widely across studies and sample matrices, and most bioassays lack essential validation and microbial authentication. Likewise, untargeted metabolomics frequently omits quantitative validation and orthogonal confirmation of isomers, limiting confidence in compositional–functional links. Therefore, routine reporting of validation metrics (selectivity, linearity, accuracy, precision, and LOD/LOQ), authenticated strains, and cell lines is recommended. Implementing these practices will strengthen the connection between verified compound concentrations, sensory outcomes, and translational bioactivity, while prioritizing specific coffee metabolites and processing steps for future sensory optimization and clinical validation.

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Content

1. Introduction
2. Metabolomic Profiling of Coffee
3. Coffee Compounds as Antimicrobial Agents
4. Coffee Compounds as Non-Microbial Agents
5. Effect of Coffee Compounds on Coffee Specialty
6. Coffee Compounds with Dual Bioactivity and Flavor Functions
7. Conclusion

1. Introduction

Coffee is one of the world's most chemically complex and widely studied beverages, whose rich composition dictates both its distinctive flavor profile and immense potential for health-related properties [1]. As the second most traded commodity globally after petroleum [2], global coffee consumption continues its robust ascent, with recent figures for 2023-2024 showing production reaching 178 million bags [3]. Within this market, the rapidly growing sector of specialty coffee is highly prized, valued not only for its refined sensory attributes—acidity, sweetness, and complex aroma—but also for the diverse array of bioactive compounds that influence taste and biological activity [4]. The complete metabolomic fingerprint of coffee, comprising hundreds of volatile and non-volatile compounds, is the chemical foundation of this duality. Key chemical families, including chlorogenic acids (CGAs), caffeine, trigonelline, and diterpenes, are dynamically altered by varietal choice, post-harvest fermentation, and roasting degree, which directly links specific molecules and their isomer distributions to sensory and functional outcomes [5]. Beyond sensory quality, the profound influence of the coffee metabolome on human health is well documented. Coffee bioactives modulate critical

physiological pathways, contributing to benefits such as improved glucose homeostasis through CGA action [6,7], protective effects like antioxidant and antihypertensive actions [8,9], and notable *in vitro* antimicrobial activity against pathogens [10,11]. However, a pervasive problem exists: the literature is characterized by significant variability in reported bioactivity parameters, such as IC_{50} and MIC values, a phenomenon heavily influenced by heterogeneous extraction solvents, assay formats, and sample stability [12]. While previous literature has successfully illuminated several key aspects of coffee science—including the application of metabolomics for quality control [13], the systematic documentation of bioactive compound changes during processing [14], the comprehensive cataloging of health benefits [15], and the specific role of coffee in antimicrobial applications [11]—none of these works offers the integrated, methodologically critical framework proposed here. These existing reviews are largely descriptive and compilatory; they tell us what has been found. In contrast, the central novelty of this review is its meta critical focus—it is the first to systematically and rigorously challenge the methodological integrity underlying the reported bioactivity claims. This work uniquely integrates the sensory science of specialty coffee with translational bioactivity by demanding evidence for three non-negotiable pillars of reliability. First, analytical validation: compound identity and quantitation require orthogonal, validated techniques (*e.g.,* HPLC UV/MS, GC MS, and NMR) with MS/MS confirmation and reporting of identification confidence [16], method performance characteristics (specificity, linearity, LOD/LOQ, accuracy, precision, and stability) per USP/ICH/AOAC guidance, and standardized reporting of retention times, ion ratios and spectral matches [17]. Second, bioassay validation and biosystem authentication: *in vitro* and microbial assays must demonstrate assay quality (Z′/signal window), reproducible EC50/CC50 estimates with appropriate replicates and controls, extract stability over assay times, and authenticated biological reagents (STR profiling for human cell lines; MLST/WGS and mycoplasma/sterility checks for microbes) to avoid false positives from contamination or cell line drift [18,19]. Third, contextual and regulatory rigor: studies intended to inform product development or clinical translation must follow compendial and regulatory expectations [20-22], include orthogonal confirmation of active constituents and schedule re authentication at key milestones (receipt, pre critical experiments, after passaging, and prior to distribution) to preserve master stock integrity and traceability [20]. Implementing these standards—multimodal chemical fingerprinting with method validation for complex extracts [23], rigorous bioassay qualification with transparent effect size and uncertainty reporting, and mandatory authentication of biological materials [19, 24]—will reduce irreproducibility, increase comparability across studies, and clarify which coffee constituents genuinely warrant further preclinical and clinical investment.

2. Metabolomic Profiling of Coffee

Coffee's metabolite composition is remarkably diverse, encompassing a wide range of primary and secondary metabolites that contribute to its sensory complexity and bioactive potential. Advanced metabolomic techniques such as LC-ESI (±)-LTQ-MS^n and ^{1}H-NMR profiling have revealed over 60 polar compounds in green and roasted Coffea arabica beans [25,26]. Among the most prominent are CGAs, including mono- and di-caffeoylquinic acids (3-CQA, 4-CQA, 5-CQA, and diCQA), feruloylquinic acids, and p-coumaroylquinic acids, which are abundant in green beans and undergo significant transformation during roasting. Alkaloids such as caffeine and trigonelline are consistently detected across bean types and processing stages, with caffeine contributing to bitterness and stimulation, and trigonelline serving as a precursor to aroma-active compounds like N-methyl-pyridinium and nicotinic acid. Amino acids including tryptophan, tyrosine,

phenylalanine, and γ-aminobutyric acid (GABA) are present in varying concentrations, with GABA particularly enriched in beans from Nameur and Cimulek regions [27]. Cinnamoyl-amino acid conjugates—such as caffeoyl tryptophan and p-coumaroyl tyrosine—suggest metabolic cross-talk between phenolic and protein biosynthesis pathways. In roasted beans, additional compounds emerge due to Maillard reactions and thermal degradation. These include quinic acid, γ-quinide, organic acids (citric, malic, lactic, acetic, and salicylic), sugars (sucrose, mannose, arabinose, and galactose), and volatile furans like 2-furyl-methanol and 5-(hydroxymethyl)furfural [28]. The presence and relative abundance of these metabolites are influenced by species, geographic origin, altitude, maturity stage, and post-harvest processing, underscoring the complexity and uniqueness of coffee's chemical fingerprint.

Table 1 confirms that coffee metabolomics benefits from a rich suite of orthogonal analytical platforms—primarily LC-based high-resolution and tandem mass spectrometry, supported by UHPLC-TOF, GC-MS for volatiles and ^{1}H-NMR for polar metabolites—which together enable broad coverage of chlorogenic acid isomers, methylxanthines, sugars, amino acids and numerous minor phenolics across green and roasted beans [25,29-31]. High-resolution MS and MSn workflows repeatedly show strength in resolving isomeric CQAs and di-/tri-acylquinic derivatives, while NMR and GC-MS provide orthogonal structural and volatile-profile confirmation that increases assignment confidence when reported [32-34]. Despite broad analytical capability, the table reveals uneven application and reporting of validation metrics: several studies document only basic repeatability or MS2/MS3-based selectivity [25,29,35] a subset reports full quantitative validation (linearity, accuracy, precision, LOD/LOQ) that supports comparability [31,36,37], and multiple high-coverage HRMS reports omit validation details altogether, leaving concentration claims and isomer assignments difficult to evaluate [32,38,39]. Where structure-diagnosis schemes [40], selectivity and specificity evaluation, and retention-time matches or authentic-standard comparisons are provided, annotation confidence is noticeably stronger [37].

The study of coffee metabolites suffers from a serious lack of validation methods, making it hard to compare results across different research papers. The main issue is that many studies fail to report essential validation details, such as those related to accuracy or detection limits. For instance, while some papers confirm the structure of compounds using advanced techniques (like MS^2 or MS^3), only the quantitative studies provide a full set of necessary quality controls. A second major problem is that most researchers rely solely on one type of analysis (like LC-MS), rarely using a

Table 1. Identified compounds, analytical approach, and validation parameters

Compounds identified /Quantified	Method used	Method validation	Ref.
Identifying 60 compounds, including: chlorogenic acids, caffeoylquinic acids, feruloylquinic acids, di-*O*-caffeoylquinic acids, quinic acid, sucrose, hexoses, valine, phenylalanine, *gamma*-aminobutyric acid, caffeine, trigonelline, atractylosides, carboxyatractylosides, and quercetin 3-*O*-glucoside	LC-MS	Selectivity/Specificity through MS^2 and MS^3 analysis	[25]

Performed targeted and untargeted metabolomics, including: Caffeine, CGAs, CQA isomers, including 5-CQA, 4-CQA, and 3-CQA, caffeoylshikimic acid, a glucopyranosyl-CQA, FQA isomers, mangiferin, neomangiferin, homomangiferin, isomangiferin, a tetrahydroxyxanthone-C-hexoside dimer, garcimangosone D (2-benzoyl-3,5-dihydroxyphenyl beta-*D*-glucopyranoside), an iriflophenone-di-*O*, C-hexoside isomer. The quantitative analysis of caffeine, CQA isomers, and mangiferin	LC-(HR)MS	Repeatability (n=5)	[29]
Identified 18 compound classes in green beans and 20 compound classes in roasted beans (caffeine, trigonelline, caffeoyl tyrosine, quinic acid, and cinnamic acids)	LC-MS/MS	Repeatability (n=3)	[35]
Identified: caffeine, trigonelline, xanthine, kahweol, elaidic acid, chlorogenic acid lactones, (*E*)-octadec-9-enoic acid, caffeoyl shikimic acid, caffeic acid, *N*-methylpyridinium, myo-inositol, difurfuryl ether, fumaric acid, lactic acid, sucrose, quinic acid, and malic acid	UPLC-MS, SPME-GC-MS	Repeatability (n=3)	[41]
Quantified and identified chlorogenic acids, caffeine, caffeoylquinic acid, di-caffeoylquinic acid, feruloylquinic acid, coumaroylquinic acid, mozambioside, mascaroside, mozambioside aglycone, caffeic acid (CA), and ferulic acid (FA)	UHPLC-PDA-ESI-TOF/MS	Repeatability (n=3)	[33]
The structural characterization and identification of 69 CGAs including esters of quinic acid and various cinnamic acids: Sinapoylquinic acids, 3-, 4-, and 5-sinapoylquinic acid, sinapoyl-caffeoylquinic acids, sinapoyl-feruloylquinic acids, trimethoxycinnamoylquinic acids (TQA), and triacyl quinic acids (TriCQAs)	HR-LC-MS	Not reported	[32]
Identified and quantified eight specific metabolites: Lactic acid, acetic acid, formic acid, caffeine, and CQA isomers (3-CQA, 4-CQA, and 5-CQA)	^{1}H-NMR spectroscopy	Linearity, accuracy, precision, LOD, and LOQ	[31]
The identified/quantified chlorogenic acids, caffeoylquinic acids (*e.g.,* 5-CQA, 3-CQA, 4-CQA), di-O-caffeoylquinic acids (*e.g.,* 3,5-diCQA), FQA, and coumaroylquinic acids (CoQA), caffeine, sucrose, glucose, and fructose, rhamnose, arabinose, galactose, mannose, and glucose	LC-ESI-MS/MS and LTQ-Orbitrap XL	Not reported	[38]

Identifying 219 compounds, the major classes and key compounds identified include: CGAs, caffeoylvaleroylquinic acid (CVQA), caffeoylquinic acid, feruloylquinic acid, coumaroylquinic acid, and caffeoylshikimic acid, caffeine, trigonelline, carboxyatractyligenin, and noncarboxyatractyligenin	LC-MS/MS	Not reported	[30]
The quantification of several major bioactive constituents, including: chlorogenic acids, 3-CQA, 4-CQA, 5-CQA, caffeine, trigonelline, and caffeic acid	LC-DAD	Selectivity, specificity, linearity, accuracy, precision, LOD, and LOQ	[36]
Quantifying 28 individual phenolic compounds and methylxanthines including caffeine, theophylline, chlorogenic Acids, 3-FQA, 5-FQA, 4-FQA, 3,4-diCQA, 3-caffeoyl-5-feruloylquinic acid, 3-caffeoyl-4-feruloylquinic acid, 3-*p*-coumaroyl-4-caffeoylquinic acid, 3-caffeoyl-4-dimethoxycinnamoylquinic acid, 3-caffeoyl-5-dimethoxycinnamoylquinic acid, 3-dimethoxycinnamoyl-5-feruloylquinic acid, *p*-coumaroyl-*N*-tryptophan, feruloyl-*N*-tryptophan, caffeoyl-*N*-tryptophan, *p*-coumaroyl-*N*-tyrosine, caffeoyl-*N*-phenylalanine, and caffeoyl-*N*-tyrosine, caffeic acid, and dimethoxycinnamic acid	LC-DAD	Sensitivity and specificity	[37]
Characterization of 28 compounds including CGAs, caffeoylquinic acids, feruloylquinic acids, *p*-coumaroylquinic acid, dicaffeoylquinic acids, feruloyl-caffeoylquinic acids, *p*-coumaroyl-caffeoylquinic acids, diferuloylquinic acids, dimethoxycinnamoyl-caffeoylquinic acids, and dimethoxycinnamoyl-feruloylquinic acids, caffeine, theobromine, theophylline, caffeic acid, ferulic acid, and dimethoxycinnamic acid, cinnamoyl-amino acid conjugates, and cinnamoyl glycosides	LC-DAD	A structure diagnosis scheme was provided for identification	[40]
Identified 24 volatile aroma compounds including: Pyrazines, furans, and sulfur compounds	GC-MS	Repeatability (n=4)	[34]
Identified 11 major chemical compounds/classes: CGAs, 5-CQA and 3-feruloylquinic acid (3-FQA), caffeine, trigonelline, *N*-methylpyridinium, quinic Acid, caffeic acid, and ferulic acid	LC-HRMS	Not reported	[39]
Qualitative profiling and quantified caffeine, trigonelline, sucrose, myo-inositol, quinic acid, and mannose, arginine, alanine, threonine, proline, phenylalanine, malic acid, citric acid, acetic acid, and formic acid, and quinic acid	NMR	Not reported	[42]

different technique (an "orthogonal confirmation") such as ^{1}H-NMR to double-check compound identities, especially for hard-to-distinguish isomers. This overall inconsistency means that scientists cannot fully trust the structural or quantitative accuracy of all published data, highlighting an urgent need for mandatory minimum reporting standards in the field.

3. Coffee Compounds as Antimicrobial Agents

Antibacterial activity: Coffea-derived alkaloids and polyphenols exhibit broad antibacterial and antibiofilm activity through complementary mechanisms—membrane disruption, inhibition of DNA/protein synthesis and key enzymes, oxidative stress induction, quorum-sensing interference, and disruption of metal-ion homeostasis—making them promising leads for natural preservatives, dental formulations, and adjunctive therapies [43-45]. Caffeine shows activity against *Salmonella*, *S. mutans*, *E. coli*, *Shigella*, and *MRSA* and can act synergistically with antibiotics [46,47], while trigonelline and theobromine contribute strain-dependent antibacterial and oral-health benefits that depend on extraction and formulation [10,48,49]. Major phenolics—chlorogenic acid (including 5-CQA), caffeic and protocatechuic acids—often outperform other constituents against enteric and oral pathogens, with activity influenced by organism and extraction method [43,50,51]. Glycosylated derivatives such as caffeic acid-O-hexoside and (epi)catechin monoglucosides retain potency while improving solubility and bioavailability, inhibiting adhesion, and biofilm formation, and showing low MICs in the micromolar to submilligram per milliliter range [52-55]. (+)-Catechin/(−)-epicatechin and procyanidin trimers disrupt membranes, impair metabolic and iron-acquisition pathways, and inhibit biofilms with MICs reported from approximately 25 μg/mL to 1 mg/mL, depending on compound and species [11,56,57]. Quinic acid has modest direct antibacterial effects but potentiates phenolics and can attenuate *P. aeruginosa* virulence and biofilm formation, especially in combination with antibiotics [50,58]. Roasting-derived α-dicarbonyls (glyoxal, methylglyoxal, and diacetyl) contribute strong antimicrobial activity via protein cross-linking and membrane damage and may act synergistically with caffeine, though their cytotoxicity necessitates safety evaluation [59]. Despite this promising bioactivity, pervasive methodological shortcomings—particularly poor strain authentication and inconsistent validation—require adoption of a standardized polyphasic quality framework to ensure reproducibility and reliable translation of these findings. **Table 2** summarizes inhibitory effects of primary coffee constituents against a range of bacterial species, highlighting the broad-spectrum potential of these compounds, particularly against foodborne and oral pathogens. The data provide compelling evidence that coffee-derived molecules possess diverse and potent antimicrobial and antibiofilm activities.

Table 2. Antibacterial activity and bioassay validation of coffee compounds

Compound /Class	Antimicrobial activity	Bioassay validation; authentication of the microbial strain	Positive control	Ref.
Caffeine	*S. enterica* (IC_{50} = 2.6 ± 0.2 μg/mL); *S. aureus*, *E. coli*, *C. albicans*, *P. aeruginosa* (MIC values ranged from 0.5 to 2.0 mg/mL depending on strain)	Repeatability (SD, n=3); gram staining test	Chloramphenicol and amphotericin B	[43]

	E. coli K-12 (wild-type and DNA repair mutants: recA-, uvrA-, and umuC-) Sub-lethal alone; potentiates DNA damage with Methyl methanesulfonate (MMS) in repair-deficient strains	Repeatability (SD, n=3); not reported	Not reported	[44]
	Caffeine alone showed weak antimicrobial activity: MIC for *A. baumannii*, *K. pneumoniae*, *S. aureus* strains: 4 mg/mL, 16 mg/mL, and >16 mg/mL (most isolates). Caffeine potentiated the activity of several antibiotics (Ticarcillin, Cefepime, Gentamycin, Azithromycin, and Novobiocin), the MIC reductions of 2- to 16-fold were observed in combination	Repeatability (SD, n=3); not reported	Not reported	[47]
	Caffeine standard: MIC: 62.5–125 µg/mL, most potent against *E. coli* and *S. aureus*. Robusta coffee extract: MIC: 187–375 µg/mL, most effective against *P. aeruginosa* and *B. subtilis*	Repeatability (SD, n=3); not reported	Tetracycline	[60]
Trigonelline	*S. enterica* (IC_{50} = 2.2 ± 0.5 µg/mL)	Repeatability (SD, n=3); gram staining test	Chloramphenicol	[43]
	S. mutans (MIC = 0.8 mg/mL). Trigonelline had stronger inhibitory effect than caffeic acid and 5-CQA	Repeatability (SD, n=3); not reported	Chlorhexidine	[48]
	S. parasanguinis (MIC = 1.28–2.56 mg/mL); *L. rhamnosus* (MIC = 2.56 mg/mL); *P. gingivalis* (MIC = 1.28–2.56 mg/mL; MBC = 2.56 mg/mL); *F. nucleatum* (MIC = 5.12 mg/mL); *P. intermedia* (MIC = 1.28–2.56 mg/mL); *P. nigrescens* (MIC = 2.56 mg/mL)	Repeatability (SD, n=3); not reported	Chlorhexidine digluconate	[61]
Theobromine	At 2.0 mM, TB significantly reduced colony-forming units (CFU) of *S. mutans* compared to control	Repeatability (SD, n=3); not reported	Epigallocatechin gallate (EGCG)	[62]

	All three treatment groups - 1450 ppm sodium fluoride, 300 ppm theobromine, and the combination of 150 ppm theobromine with 725 ppm fluoride - produced significantly lower bacterial counts of *S. mutans* and *Actinomyces naeslundii* compared to the control group	Repeatability (SD, n=3); not reported	Sodium fluoride	[63]
	Zone inhibition using a 2–4% theobromine toothpaste formulation: *S. mutans*: 16.83 ± 1.33 mm (significantly higher than fluoride-based controls), *L. acidophilus*: Mean rank = 15.50 (statistically significant inhibition), *E. faecalis*: Mean rank = 15.42 (strong antimicrobial effect)	Repeatability (SD, n=3); not reported	Fluoride toothpastes	[64]
Chlorogenic acid (CGA)	*S. enterica* (IC_{50} = 4.8 ± 0.9 mg/mL)	Repeatability (SD, n=3); gram staining test	Chloramphenicol	[43]
	coffee extracts containing CGA: *L. casei* (MIC = 50 mg/mL); *P. gingivalis* (MIC = 100–200 mg/mL depending on coffee type); *S. mutans* (MIC = 240 mg/mL)	Repeatability (SD, n=3); not reported	Amoxicillin	[65]
	V. cholerae N16961 (MIC = 0.5 mg/mL). Time-kill assay showed CGA did not achieve ≥ 3 $\log_{10}$ CFU/mL reduction even at 8× MIC — indicating bacteriostatic	Repeatability (SD, n=3), multiple resistant strains tested	Tetracycline	[12]
Caffeic acid (CA)	*S. enterica* (IC_{50} = 6.6 ± 0.2 µg/mL). *S. mutans* (MIC = 0.8 mg/mL), *E. coli* (MIC = 2500 µg/mL), *Vibrio cholerae* (MIC = 1 µg /mL), Bacillus subtilis (MIC = 1.18 - 3.12 µg/mL)	Repeatability (SD, n=3); gram staining test	Chloramphenicol	[43]
	Vibrio cholerae (MIC = 1 mg/mL). Time–kill kinetics showed CA reduced *V. cholerae* counts by ~3 $\log_{10}$ CFU/mL within 1 h at 8 mg/mL (8× MIC)	Repeatability (SD, n=3), multiple resistant strains tested	Tetracycline	[12]

	Evaluated 23 compound of caffeic acid amides against *B. subtilis*. Most potent activity is (*E*)-3-(3,4-dihydroxyphenyl)-*N*-*p*-tolylacrylamide : MIC = 1.18 µg/mL	Repeatability (SD, n=3); not reported	Kanamycin and penicillin	[66]
Protocatechuic acid	*E. coli* (MIC=550 µg/mL), *P. aeruginosa* (MIC=300 µg/mL), *S. aureus* (MIC=450 µg/mL)	Repeatability (SD, n=3); not reported	Ciprofloxacin	[67]
	S. enterica (IC_{50} = 1.2± 0.2 µg/mL). PCA as one of the most potent coffee-derived compounds against *S. marcescens and E. cloacae*	Repeatability (SD, n=3); gram staining test	Chloramphenicol	[43]
5-Caffeoylquinic acid	Inhibitory effect (MIC80 = 10 mg/mL) toward *S. aureus*, *E. faecium*, *E. coli*, *P. vulgaris*, *P. aeruginosa*, and *C. albicans*. The strongest antimicrobial activity was observed against *K. pneumonia* (MIC_{80} = 5 mg/mL)	Repeatability (SD, n=2-3); not reported	Not reported	[68]
	E. coli (MIC 2.5 mg/mL), Bacillus sp. S. epidermidis, and *S. pyogenes* (MIC >2.5mg/mL)	Repeatability (SD, n=3); not reported	Ampicillin and kanamycin	[69]
	S. enterica (IC_{50} = 4.8 ± 0.9 mg/mL)	Repeatability (SD, n=3); gram staining test	Chloramphenicol	[43]
Hydroxycinnamic acids	Hydroxycinnamic acid derivatives — specifically 16 caffeic acid ester derivatives were tested. The lowest MIC values were 0.20–0.23 µM for *E. coli* (propyl caffeate, butyl caffeate, pentyl caffeate, and di-(4-chlorobenzyl) caffeate), and 0.21 µM for *S. aureus* (butyl caffeate)	Repeatability (SD, n=3); not reported	Chloramphenicol	[52],

	Seven hydroxycinnamic acid compounds were tested against six Gram-negative and four Gram-positive bacteria. Sinapic acid was the most active overall, producing inhibition zones of 9–27 mm and MICs of 18–72 mg/mL across the tested strains. 4-Hydroxybenzoic acid showed moderate activity with inhibition zones of 9–16 mm and MICs of 36–72 mg/mL	Repeatability (SD, n=3); not reported	Gentamicin	[70]
Quinic acid	Quinic acid was the standout antibiofilm agent. At very low sub-MIC levels (1/128 MIC), more effectively than CA itself. Its MIC against *P. aeruginosa* was relatively high (2 mg/mL), so its strength is not in killing planktonic cells but in disrupting biofilm structure and quorum sensing	Repeatability (SD, n=3); not reported	Levofloxacin	[58]
	The activity of quinic acid at 10 mM, against *E. coli* caused a log reduction of ~0.55 (CFUs/mL), indicating mild bactericidal effect	Repeatability (SD, n=3), multiple stress conditions; not reported	Not reported	[50]
(+)-Catechin	Catechins, including (+)-catechin and (−)-epicatechin, exhibit consistent antimicrobial potency across both Gram-positive and Gram-negative bacteria. Specifically, (−)-epicatechin was shown to inhibit Helicobacter pylori at MIC 0.6 mg/mL	Repeatability (SD, n=3); not reported	Not reported	[56]
Melanoidin	*Staphylococcus aureus*, *Bacillus cereus*were more sensitive (MIC 2.0–2.5 mg/mL), *Proteus mirabilis*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, *Escherichia coli* generally required higher concentrations (MIC 4.0–8.0 mg/mL), and siderophore-producing strains *E. coli*, *P. aeruginosa* had the highest MICs (7.0–8.0 mg/mL)	Repeatability (SD, n=3); not reported	Not reported	[71]

Gloxal, methylgloxal, diacetyl	Glyoxal was the most potent overall, with MIC values of 88.3 µg/mL for *S. aureus* and just 11.8 µg/mL for *S. mutans*. Methylglyoxal followed closely, showing MICs of 110.2 µg/mL and 14.7 µg/mL, respectively. Diacetyl was slightly less active, with MICs of 114.2 µg/mL for *S. aureus* and 34.3 µg/mL for *S. mutans*. These results indicate that all three α-dicarbonyl compounds are particularly effective against *S. mutans*, with much lower MIC values compared to *S. aureus*.	Repeatability (SD, n=3), gram staining, morphology, and biochemical tests	Not reported	[59]

However, the source literature reveals a pervasive methodological shortcoming in microbial quality control, with frequent absence of transparent strain authentication and validation.

This widespread deficit in quality management underscores the urgent need for a standardized polyphasic validation framework to ensure the credibility, reproducibility, and generalizability of future research in this field.

Antifungal activity: Caffeine and coffee-derived phenolics show reproducible, concentration-dependent antifungal activity with variable potency by compound, organism and extraction matrix. Caffeine preferentially suppresses phytopathogens over mycoparasitic *Trichoderma* spp., exhibiting minimal effect at ~0.01% (0.5 mM), substantial suppression at ~0.1% (5 mM; ~35–69% for several pathogens) and complete inhibition of sensitive filamentous species at ~1% (50 mM) [72]. It is fungistatic to planktonic *Candida albicans* (MIC ≈ 12.5 mM) while reducing adhesion and biofilm formation at 12.5–25 mM [73], with additional reports of antidermatophytic activity and ultrastructural cell-wall perturbation against *Trichophyton mentagrophytes* [74]. The plant polyphenol chlorogenic acid exerts antifungal effects mediated by membrane and metabolic disruption but is generally less potent than clinical agents (yeast MICs often ≈ 40–80 $\mu g \cdot mL^{-1}$ versus amphotericin B at 2.5–10 $\mu g \cdot mL^{-1}$) [75]. Coffee processing streams and roasted beans yield extracts rich in caffeine, chlorogenic derivatives, and other phenolics that produce measurable antifungal activity: ethanolic spent coffee ground (SCG) extracts profiled by HPLC-DAD-MS inhibited *Candida* spp. and dermatophytes with MICs in the low–mid hundreds $\mu g \cdot mL^{-1}$ [76]; parchment extracts incorporated into gellan-gum films inhibited *Fusarium* and *Colletotrichum* at 4–8 $mg \cdot cm^{-2}$ [77]; methanol fractions of pulp produced mycelial IC_{50}s of 0.09–0.31 $g \cdot mL^{-1}$ against several phytopathogens [78]; and lipophilized 5-CQA esters show chain-length–dependent potency gains (octyl esters with MIC_{50} ≈ 0.5–0.75 $mg \cdot mL^{-1}$) consistent with enhanced membrane partitioning [79]. Broader surveys of coffee husk, wet coffee waste and Soxhlet green-coffee extracts confirm activity against food-spoiling and clinical fungi (Penicillium, Aspergillus, *Botrytis*, *Rhizopus*, *Fusarium*, and *Candida*), but reported potencies span orders of magnitude—from crude husk effects at $g \cdot L^{-1}$ to enriched fractions active at low $mg \cdot mL^{-1}$ or hundreds $\mu g \cdot mL^{-1}$—reflecting solvent, fractionation, assay format and strain differences [80-83]. Recent *in silico* and *in vitro* work on Coffea canephora husk sterols, caffeine and chlorogenic derivatives supports antifungal potential and possible multi-target mechanisms but often lacks full validation metrics [84]. **Table 3** provides research on the efficacy of coffee-derived compounds and extracts against a broad range of fungal pathogens and

demonstrates clear antifungal potential. It highlights promising antifungal activity of coffee components while simultaneously underlining the urgent need for standardized authentication and quality control frameworks to ensure credible, reproducible, and interpretable results in future research. Most studies do not report the microbial authentication. Without mandatory confirmation of strain identity and stability using high-resolution methods such as whole-genome sequencing or equivalent polyphasic approaches, it is impossible to rule out genetic drift or phenotypic change influencing reported outcomes. Only one study reported a specific differentiation test for *Candida albicans*, a solitary example that falls far short of current standards requiring authenticated, low-passage strains and rigorous quality management.

Antimalarial activity: Alkaloid-rich Coffea arabica leaf extracts display selective antiplasmodial activity against Plasmodium falciparum (IC_{50} ≈ 7–10 µg/mL for Pf3D7/PfDd2) with favorable cytotoxicity margins in Vero and RAW cells, supporting further mechanistic and *in vivo* evaluations [85]. **Table 3** shows that coffee compounds exhibit diverse, mechanistically plausible non-microbial activities, but the evidence base is weakened by inconsistent validation and limited translational readiness. To advance from hypothesis to application, future work should prioritize standardized extracts or purified compounds, authenticated bioassays with appropriate positive controls, full concentration–response reporting, and early toxicity and ADME assessments.

Table 3. Antifungal activity and bioassay validation of coffee compounds

Sample used, compound(s) identified	Fungal targets	Activity values	Bioassay validation, Authentication of the microbial strain	Positive control	Ref.
Caffeine	*Candida* spp.	MIC: 12.5–20 mM	Repeatability (n=3); not reported	Not reported	[72]
Caffeine	*Candida* spp.	MIC: 12.5–25 mM; adhesion/biofilm inhibition	Repeatability (n=3); not reported	Fluconazole	[73]
Caffeine	*Trichophyton mentagrophytes*	MIC = 8 mM	Repeatability (n=3); not reported	Not reported	[74]
Chlorogenic acid	*C. albicans*, *M. furfur*, and *T. beigelii*	MIC: 40–80 µg/mL	Repeatability (n=3); not reported	Amphoteric in B	[75]

Ethanolic extracts of spent coffee grounds, Caffeoylquinic acid, Feruloylquinic acid, and Caffeoylshikimic acid	*Candida krusei*, *Candida parapsilosis*, *Trichophyton mentagrophytes*, *Trichophyton rubrum*	MIC: 250–1,000 µg/mL (strain-dependent)	Repeatability (n=3); not reported	Itraconazole	[76]
Coffee parchment ethanolic extract, Gallic, Chlorogenic, p-Coumaric, and Sinapic acids	*Fusarium verticillioides*, *Colletotrichum gloeosporioides*	The coffee parchment extract (8 mg cm^{-2}) gave the greatest inhibition (65%-89%) for all fungi tested	Repeatability (n=3); not reported	Nystatin	[77]
Coffea arabica pulp extract, Caffeic acid, Epigallocatechin gallate, and poliphenols	*Alternaria brassicicola*, *Pestalotiopsis sp.*, *Paramyrothecium breviseta*	Inhibition increased with extract concentration; at 0.5 g/mL, inhibition reached 62%-78 %	Repeatability (n=3); not reported	Not reported	[78]
Isolated from Coffea canephora husk, cholestane steroid (coffeacanol A, ergosterol peroxide, cerevisterol, gramisterol, caffeine, methyl 5-*O*-caffeoylquinate, and chlorogenic acid	*Candida albicans*, *Trichophyton mentagrophytes and Trichophyton rubrum*	(chlorogenic acid) showed the strongest antifungal activity against Candida albicans with MIC = 25 µM	Repeatability (n=3); not reported	Fluconazole	[84]
5-CQA and alkyl esters	5 toxigenic *Aspergillus* spp.	MIC_{50}: 0.5–0.75 mg/mL (octyl most active)	Repeatability (n=3); not reported	Not reported	[79]
Green Coffea arabica beans, CGA, and DCGA	*A. flavus*, *A. ochraceus*	Growth/mycotoxin reduction 35% (A. flavus), 74% (A. ochaceus)	Repeatability (n=3); not reported	Not reported	[86]
Methanol extract of coffee husk	*Penicillium camemberti*, *P. expansum*, *P. roqueforti*, *Aspergillus flavus*, and *A. niger*	Most sensitive strain: *P. expansum* MIC: 6.3–25 g/L. *P. expansum*, *A. niger F. oxysporum* stopped growing at 6 g/L, 10 g/L, and 8 g/L of coffee husk extract, respectively	Repeatability (n=3); not reported	Not reported	[80]

Ethanolic extract from *Coffea arabica*	*A. niger*, *B. cinerea*, and *R. stolonifer*	The extract often matched or exceeded carbendazim's performance, especially against *A. niger* and *B. cinerea*. The strongest inhibition halos and mycelial suppression were at 2,000 µg/mL	Repeatability (n=3); not reported	Carbendazim	[81]
Methanolic extract of green coffee beans (Coffea arabica)	*C. albicans*	IC_{50} at 160 mg/mL	Repeatability (n=3); not reported	Not reported	[82]
Ethanolic extract of C. arabica grounds coffee	*C. albicans*	Disc-diffusion inhibitory zone diameters at extract concentrations of 80% is 4.53 mm	Repeatability (n=3); differentiation test to confirm their identity as *C.albicans*	Ketoconazole	[87]
Isopropanol extract of spent coffee grounds	*Aspergillus*, *Fusarium*, *Penicillium*, and *Candida* spp.	Zones, growth reduction, and mycotoxin suppression	Repeatability (n=3); not reported	Synthetic antifungal (unnamed)	[83]
Coffee silverskin extract	Plant-pathogenic fungi	Mycelial growth inhibition	Repeatability (n=3); not reported	Not reported	[88]

4. Coffee Compounds as Non-Microbial Agents

Antidiabetic activity: Chlorogenic acid (CGA) and related coffee polyphenols activate adenosine monophosphate–activated protein kinase (AMPK) to promote glucose transporter type 4 (GLUT4) translocation and increase muscle glucose uptake in cellular and rodent models [89]. Acute human crossover trials report that CGA and trigonelline reduce early postprandial glucose and insulin responses, whereas whole caffeinated coffee can acutely impair insulin sensitivity, implicating caffeine as a modifying factor [90,91]. Coffee polyphenols inhibit intestinal glucose transport—more strongly affecting GLUT2 than SGLT1—and can suppress postprandial incretin (GIP) release, contributing to lower glycemia after meals [7,92]. Extracts rich in CGA, caffeic acid and related metabolites inhibit α-glucosidase/α-amylase and improve antioxidant status, and preclinical work shows synergistic interactions with metformin, supporting multitarget antiglycemic effects [93,94].

Antiurolithic activity: Methanolic extracts of Coffea arabica, especially ethyl-acetate fractions, inhibit calcium oxalate nucleation and growth, favor formation of the more soluble COD form, and exhibit mild diuretic effects in crystal assays comparable with standard antiurolithic agents [95].

Antigenotoxic activity: Coffee constituents (CGA, caffeic acid, cafestol, kahweol, trigonelline, and melanoidins) protect genomic integrity by scavenging ROS, inducing Nrf2/phase II defenses, and suppressing CYP-mediated

pro-mutagen activation [9,51,96]. *In vivo* studies using freeze-dried Coffea arabica (100 mg/kg) reduced micronucleus formation after mutagen exposure and showed enhanced protection when combined with dietary antioxidants [8]. Cafestol and kahweol reduce AFB1–DNA adduct formation through CYP suppression and GST induction in rodent and liver-cell models [9,97].

Antihypertensive activity: CGAs improve endothelial function by enhancing nitric oxide bioavailability and reducing oxidative stress and vascular inflammation, mechanisms that support modest blood-pressure lowering [98]. Peptides derived from enzymatic hydrolysis of spent-coffee-ground proteins inhibit angiotensin-converting enzyme in vitro, indicating an additional ACE-dependent antihypertensive mechanism [99]. However, acute randomized trials in medicated hypertensive patients found no immediate blood-pressure benefit from single coffee doses, so clinical effects likely depend on habitual intake, preparation, roast degree, and concurrent medications [100,101]. **Table 4** shows that coffee compounds exhibit diverse, mechanistically plausible non-microbial activities, but the evidence base is weakened by inconsistent validation and limited translational readiness. To advance from hypothesis to application, future work should prioritize standardized extracts or purified compounds, authenticated bioassays with appropriate positive controls, full concentration–response reporting, and early toxicity and ADME assessments.

Table 4. Coffee compounds as non-microbial agents

Compound / Extract	Activity	Mechanism of action	Validation of method/Bioassay; authentication of cell line	Positive control	Ref.
Chlorogenic acid (CGA)	Antidiabetic	Inhibits glucose-6-phosphatase; delays intestinal glucose absorption; suppresses GIP secretion; and activates AMPK	Not reported and not reported	2% meat hydrosylate	[7]
Caffeic acid, chlorogenic acids derivate and *p*-coumaric acid	Antidiabetic	Inhibit intestinal glucose transport (GLUT2 > SGLT1); enhance insulin sensitivity via PI3K and GLUT2 signaling	Validated using Transepithelial Electrical Resistance (TEER) measurements	Not reported	[92]
Brazilian coffee extract	Antidiabetic	Inhibits *α*-glucosidase and *α*-amylase	Repeatability (n=3) *in vitro* anti-diabetic assays	Acarbose	[102]
Natural-processed *C. arabica* beans (Thailand)	Antidiabetic	Inhibit α-amylase	Repeatability (n=3) *in vitro* anti-diabetic assays	Acarbose	[103]
East African coffee beans extract	Antidiabetic	Inhibit α-glucosidase and *α*-amylase and enhance glucose uptake by Yeast cells	Repeatability (n=3) *in vitro* anti-diabetic assays	Acarbose and metformin	[94]

Ethyl acetate subfraction of *C. arabica* beans	Antiurolithic	Inhibition and dissolution of calcium oxalate crystallization	Repeatability (n=3) *in vitro* crystallization assay	Cystone	[95]
Cafestol and kahweol	Antigenotoxic	Promotion of Detoxification; reduced production of the ultimate carcinogen	Repeatability (n=3-5) *in vitro* assays	Not reported	[9]
Green coffee extract (GCE)	Cardiometabolic and gut microbiota-modulating	Improves insulin sensitivity; reduces hepatic triglycerides and inflammatory markers	Not reported	Not reported	[104]
Proteins isolated from spent coffee grounds	Antihypertensive	Inhibit ACE	Repeatability (n=3) *in vitro* assay	Not reported	[99]
Alkaloid-rich *C. arabica* leaf extract	Antimalarial	Inhibits *Plasmodium falciparum* growth (Pf3D7, PfDd2); selective toxicity	Not reported	Not reported	[85]

5. Effect of Coffee Compounds on Coffee Specialty

The defining specialty of high-quality coffee is a sensory experience rooted in the precise balance and transformation of its chemical components, which number over a thousand and are generally categorized as non-volatile taste compounds and volatile aroma compounds. The foundation of the complex flavor profile begins with the non-volatile fraction: the characteristic acidity so prized in specialty coffee stems from precursors like Chlorogenic Acids (CGA), Quinic Acid, and Caffeic Acid [105], with the CGA content directly influencing the pH level and sour taste, peaking at medium-light roasts before thermal degradation occurs [106]. Crucial for elevating the cup are Trigonelline and Sucrose, whose increased accumulation in commercial Arabica varieties provides enhanced sweetness and overall flavor complexity [107]. While both Caffeine and Trigonelline contribute to the brew's inherent bitterness [105,108,109], the palatability is actively improved by the chlorogenic acid derivatives 4- and 5-Caffeoylquinic Acids and 2-O-β-D-glucopyranosyl-atractyligenin, which function as proven bitterness suppressors [110]. Furthermore, non-volatile diterpenes, like Cafestol and Kahweol, contribute to the desired body and mouthfeel [111,112]. The most intricate characteristics, however, are delivered by the volatile compounds: the signature fine fruity and floral aromas of elite varieties like Geisha are driven by high concentrations of the monoterpene Limonene [113], while other fruity notes are attributed to fermentation products such as 2-Phenylethanol and Isoamyl Acetate [105,114]. Maintaining specialty quality is challenged by chemical degradation, whereby phenolic breakdown products act as scavengers, irreversibly reacting with and removing crucial odor-active thiols (like 2-furfurylthiol), leading directly to flavor staling [115]. The specialty status is ultimately validated by integrating chemical quantification, using techniques like GC/MS for volatiles and LC-MS/HPLC for non-volatiles, and correlating this data with the comprehensive human evaluation provided by the industry-standard Professional Cupping Test.

Table 5. Coffee compounds and their flavor contributions

Compound/Class	Contribution to specialty coffee flavor	Ref.
Caffeine	Main contributor to bitterness and body. High concentrations can negatively correlate with overall quality	[105,109,116-118]
Chlorogenic acids	Impart acidity and mild bitterness. Influence bitterness and astringency upon degradation. High concentrations tend to show a negative correlation with overall quality	[105,106,116,119]
Sucrose & Sugars	Vital for sweetness and overall flavor complexity. High levels in the green bean positively correlate with better Flavor and Overall Quality scores	[105,107,116,119]
Trigonelline	Vital for sweetness and overall flavor complexity. Contributes to its characteristic undue bitterness. Increased accumulation is associated with improved flavor in commercial varieties	[105,107,108]
Quinic acid and caffeic acid	Primary precursors that impart acidity and mild bitterness. Their degradation during roasting produces many of the final aroma compounds	[105,120]
Diterpenes (cafestol/kahweol)	Primarily determine the brew's mouthfeel or body (in unfiltered preparations) and contribute to bitterness. Kahweol is a marker for Arabica	[111,112]
4-CQA and 5-CQA	Compounds that actively suppress the perceived bitterness of coffee brew, contributing positively to the overall flavor profile	[110]
L-lactic acid	Exhibits the strongest correlation with measured bitterness intensity	[121]
Melanoidin	Tactile sensation of astringency	[122]
2-Phenylethanol	Desirable floral and fruity aromas, often produced during fermentation. Its successful transfer into the bean produces desirable fruity and floral notes characteristic of high-quality coffee	[105,114]
Limonene	Characteristic fine fruity and floral aromas, notably in specialty varieties like Geisha	[105,113]
Isoamyl acetate	Desirable floral and fruity aromas, often produced during fermentation. Its successful transfer into the bean produces desirable fruity and floral notes	[105,114]
Pyrazines	Key to developing roasted, nutty, and earthy notes, especially in darker roasts.	[105,119]
Furans/Furfuryl alcohol	Associated with desirable sweet and nutty aromas (2,5-dimethylfuran) and caramel/sweet notes (Furfuryl alcohol)	[119,120]
Volatile thiols	Responsible for the fresh, roasty coffee aroma. Their loss due to reaction with phenolic breakdown products leads to flavor staling	[115]

6. Coffee Compounds with Dual Bioactivity and Flavor Functions

The integrated evidence from **Tables 2–5** shows that coffee is a chemically rich matrix in which many compounds perform dual roles as sensory drivers of specialty coffee and as bioactive agents *in vitro*; however, their functional relevance in the brewed cup depends critically on concentration, processing, and matrix effects. Alkaloids (notably caffeine, trigonelline, and theobromine) and phenolic families (chlorogenic acids, caffeic acid and related hydroxycinnamates, protocatechuic acid, and quinic acid) display the most consistent antimicrobial and metabolic activities in laboratory assays, with some molecules (for example, trigonelline and quinic

acid) showing targeted actions such as inhibition of oral streptococci or antibiofilm activity. Many reported MICs and IC_{50}s, however, occur at concentrations higher than those typically present in a serving of brewed coffee. Thermal and biochemical transformations during fermentation and roasting—Maillard reactions that produce melanoidins, α-dicarbonyls, pyrazines, furans, and other volatiles—both modulate bioactive precursor levels and generate the volatile and non-volatile compounds that define acidity, bitterness, body, and aromatic nuance in specialty profiles. This coupling creates practical trade-offs: optimizing extracts or by-products for bioactivity (for example, spent grounds or silverskin) can yield valuable antimicrobial or antifungal ingredients for non-cup applications but may produce sensory penalties if incorporated into beverage formulations. For researchers and developers, priorities are clear: provide rigorous contextualization by reporting validated bioassays with strain authentication and repeatability, quantify compound levels across processing conditions and in brewed coffee, and relate bioactive thresholds to sensory impact so that flavor integrity and functional claims can be balanced in scientific interpretation and product design. **Figure 1** and **Table 6** illustrate the key coffee compounds that serve dual functions as both sensory drivers of specialty coffee and bioactive agents in laboratory assays. The chemical richness of coffee includes alkaloids (like caffeine and trigonelline) and phenolic families (like chlorogenic acids). **Table 6** synthesizes these compounds, detailing their primary bioactivities (*e.g.,* antimicrobial, antifungal, stimulant) and their contribution to specialty flavor (*e.g.,* bitterness, acidity, and body).

Table 6. Coffee compounds having a dual function (flavor and bioactivity)

Compound / Class	Main bioactivity	Contribution to specialty coffee flavor	Notes
Caffeine	Antimicrobial and stimulant	Bitterness and body	Higher in Robusta; brewed concentrations often below many reported MICs
Trigonelline	Antimicrobial (oral) and flavor precursor	Sweetness/complexity (after roasting: pyridines and nicotinic acid)	Decreases with roast; active vs. oral *Streptococci in vitro*
Chlorogenic acids (CGA and 5-CQA)	Antimicrobial; antifungal; and metabolic effects	Acidity; mild bitterness; fruity notes preserved in light roasts	Concentration and roast strongly modulate effects
Caffeic acid	Antimicrobial; antifungal	Acidity; contributes to brightness	Derivatives can increase antimicrobial potency
Protocatechuic acid	Antimicrobial	Minor phenolic bitterness contributor	Notable antibacterial potency in some assays
Quinic acid	Antibiofilm and quorum sensing disruption	Minor mouthfeel contributor; precursor in flavor chemistry	Strong antibiofilm at sub-MIC levels; weak planktonic killing
Melanoidins	Weak–moderate antimicrobial	Atringency; deep roasted flavors	Formed by Maillard reactions; dominant in dark roasts
Cafestol and Kahweol	Antigenotoxic; metabolic modulation	Enhanced body and mouthfeel	Lipid-soluble diterpenes; content varies with species and brew

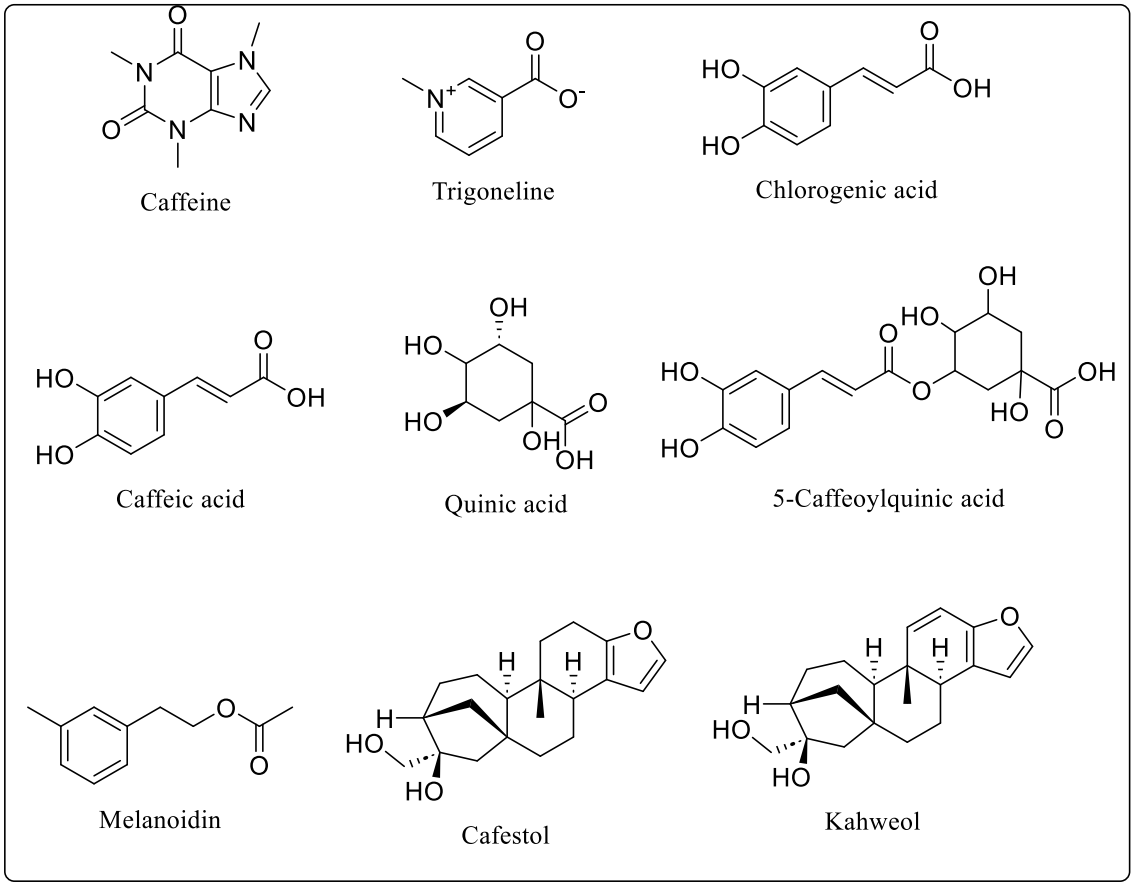

Figure 1. The molecular structures of coffee compounds that have dual functions in bioactivity and flavor

Thermal reactions during roasting create compounds like melanoidins (deep roasted flavors) and modulate the levels of bioactive precursors. While these compounds show consistent antimicrobial activity in assays, many required concentrations (MIC and IC_{50} values) are often higher than those typically found in a brewed cup of coffee. Therefore, understanding the relationship between bioactive thresholds and sensory impact is crucial for balancing flavor integrity and functional claims.

7. Conclusion

Coffee is a chemically diverse beverage whose sensory attributes and potential health-related effects are shaped by a complex matrix of bioactive compounds, including chlorogenic acids, caffeine, trigonelline, melanoidins, and various polyphenols. These constituents exhibit a dual function —contributing to coffee's distinctive flavor and aroma while also exhibiting a range of experimentally observed biological activities, such as antioxidant, antimicrobial, antidiabetic, anti-inflammatory, and antigenotoxic effects, primarily demonstrated *in vitro* or in animal models. Mechanistic insights suggest their roles in enzyme inhibition, oxidative stress modulation, membrane integrity disruption, and signaling pathway regulation; however, their translational relevance to human health remains an area of ongoing investigation. Crucially, chemical transformations during roasting and processing significantly modulate both sensory quality and bioactivity, often yielding optimized profiles in specialty coffee. Given the complex nature of the coffee matrix, priorities for researchers are clear: they must provide rigorous contextualization by reporting

validated bioassays with strain authentication and repeatability, quantify compound levels across processing conditions and in brewed coffee, and relate bioactive thresholds to sensory impact. This rigorous approach is necessary so that flavor integrity and functional claims can be balanced in scientific interpretation and product design. Overall, coffee's evolving characterization as a functional beverage invites further interdisciplinary research—bridging analytical chemistry, sensory science, and nutritional biochemistry—to clarify its role in food innovation, preventive health strategies, and sustainable product development.

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Conflict of Interest

The authors declare no conflict of interest.

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