Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal

Cite this: DOI: 10.1039/d5fb00768b

Green coffee extracts: advances in green extraction, bioactivity, and food applications with emphasis on sustainable processing

Dian Shofinita, *[ab] Amarthya Benigna Achmadi,[b] Jason Thamleonard Tjahjadi,[a] Rediana Adelia Azizah[a] and Reisa Nopianti[a]

Green coffee extract (GCE) has become a topic of interest due to its rich bioactive compound content and potential health benefits. This article presents a comprehensive review covering the composition of green coffee, coffee bean processing, extraction methods, health benefits, GCE microencapsulation and applications in food products. Green coffee beans contain substantially higher levels of chlorogenic acids (CGA) than roasted beans, with reported values of 543.23 ± 8.92 mg L^{-1} in green coffee compared with 90.53 ± 12.97 to 270.93 ± 10.76 mg L^{-1} after roasting, reflecting the well-documented degradation of CGA during thermal processing. Among the extraction approaches evaluated, microwave-assisted extraction (MAE) consistently provides the highest yields, producing extracts containing 34.08–40.06% caffeine and 46.41–61.87% CGA. Evidence from clinical studies indicates that GCE supplementation (10–6000 mg per day for 4–12 weeks) in overweight and obese individuals is associated with reductions in BMI and circulating insulin levels. In addition, microencapsulation by spray drying using a combination of agave fructans and gum arabic as wall materials resulted in an encapsulation efficiency of 94.36%. As a food ingredient, GCE has been applied at levels of 0.025–12%, contributing to improved oxidative stability during storage for up to 90 days, enhanced antioxidant capacity, and better acceptance in terms of aroma and texture. These various study results indicate that GCE has promising prospects due to its numerous benefits in the fields of food and health, making this review a useful reference for future studies, even though *in vivo* clinical trials on GCE have not yet been conducted.

Received 29th October 2025
Accepted 18th May 2026

DOI: 10.1039/d5fb00768b

rsc.li/susfoodtech

Sustainability spotlight

This study underscores the sustainability potential of green coffee extracts through the adoption of environmentally friendly extraction technologies and responsible use of natural resources. By comparing advanced green extraction and conventional methods, the work highlights techniques that reduce solvent consumption, lower energy demands, and enhance process efficiency. Microwave, NADES-ultrasound, and enzyme-assisted extraction utilize green solvents and require 5, 30, and 60 minutes, respectively, whereas conventional extraction requires 25 hours and uses some toxic solvents. Furthermore, the review emphasizes sustainable microencapsulation techniques, utilizing biodegradable and food-grade carriers to protect bioactive compounds. These combined approaches support the Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), SDG 3 (Good Health and Well-being), and SDG 9 (Industry, Innovation, and Infrastructure).

1. Background

Coffee, belonging to the Rubiaceae family, is globally renowned as the second most traded commodity after petroleum.[1] While most commercial coffee products are derived from roasted beans, unroasted green coffee beans have attracted increasing interest due to their high content of chlorogenic acids (CGA) and other phenolic compounds.[2] These compounds have been strongly associated with multiple health-related benefits, including antioxidant, anti-inflammatory, and antihypertensive activities.[3]

Scientific interest in green coffee processing as a novel food ingredient has substantially spiked over the past two decades (see Fig. 1). These studies have mostly addressed several select aspects of green coffee extracts (GCE), including processing techniques, phytochemical profiles, and biological activities.[4] However, comparative evaluation of extraction techniques from a processing sustainability perspective remains limited, making it difficult to identify environmentally preferable and scalable routes for producing GCE. Therefore, an updated review is

[a]Faculty of Industrial Technology, Food Engineering Department, Bandung Institute of Technology, Jl. Let. Jen. Purn. Dr (HC). Mashudi No. 1/Jalan Raya Jatinangor KM 20, 75, Sumedang 45363, Indonesia. E-mail: shofi1988@itb.ac.id

[b]Faculty of Industrial Technology, Chemical Engineering Department, Bandung Institute of Technology, Jl. Ganesa No. 10, Bandung 40132, Indonesia

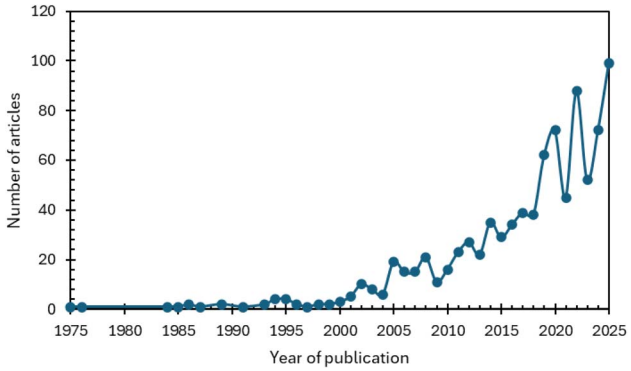

Fig. 1 Number of scientific publications on green coffee processing in Scopus under the subarea of agricultural science and process engineering.

needed to consolidate evidence and guide the development of greener and more sustainable GCE extraction strategies.

Furthermore, current literature lacks systematic mapping of health evidence and critical evaluation of quality across study types such as randomized controlled trials (RCTs), meta-analyses, and animal studies. Variations in study design, GCE dosage, intervention duration, and reported outcomes complicate interpretation. For example, a randomized clinical trial on the effect of GCE on weight loss under certain conditions reported limited sample size and relatively short study duration,[5] suggesting that a new review that compares multiple types of evidence on the health effects of GCE would provide deeper insight.

In addition, many studies discussing GCE applications in food products remain conceptual and have not been synthesized in a comparative and application-oriented manner. One such example is the application of microencapsulation as a promising strategy to improve the stability, bioavailability, and sensory compatibility of GCE-derived antioxidants. Existing literature on microencapsulation of coffee antioxidants emphasizes that effective delivery systems must preserve phenolic integrity during processing and storage, minimize undesirable sensory impacts, and maintain effectivity under digestive conditions such that absorption remains high. However, existing discussions on microencapsulation are often method-specific and insufficiently connected to formulation requirements or end-use applications. A more systematic synthesis is needed to compare encapsulation techniques, wall materials, and performance outcomes in relation to food matrix compatibility and digestive stability.

As a response to these gaps, this review offers a new perspective by integrating four interrelated topics that are typically discussed separately, namely (i) the bioactive compound composition of GCE as the basis for raw material selection and processing conditions for green coffee beans, (ii) a comparative, sustainability-oriented evaluation of extraction methods for green coffee beans, (iii) microencapsulation as a strategy to enhance stability and delivery, and (iv) applications in food matrices with emphasis on feasibility and practical formulation challenges. By incorporating environmental sustainability into the evaluation, this review moves beyond descriptive summarization of existing findings, but also proposes a more practical and forward-looking roadmap for the sustainable development of GCE as a functional food ingredient.

2. Chemical composition of green coffee: bioactives, variability, and processing effects

2.1 Major bioactive compounds in green coffee

Green coffee contains a broad spectrum of bioactive constituents spanning primary and secondary metabolites. The secondary metabolite fraction includes polyphenols, terpenoids, flavonoids, and alkaloids such as caffeine, as well as saponins and bioactive peptides.[6] Moreover, when classified by pharmacological activity, certain amino acids, vitamins, and pigments may also be considered bioactive constituents in green coffee.[7,8] Among these compounds, three are widely regarded as key chemical markers of green coffee, namely caffeine, chlorogenic acids (CGA), and trigonelline. These compounds are usually used for coffee species characterization[9] and act as important aroma precursors, which makes them highly relevant to the coffee industry due to their substantial contribution to overall coffee quality.[10–12] The contents of caffeine, CGA, and trigonelline were determined in three different green coffee extract (GCE) samples using a UV-Vis method,[13] as summarized in Table 1.

Variations in the levels of these three compounds in green coffee are primarily driven by genetic factors, most notably differences between species and, to a lesser extent, between varieties.[14] Caffeine (1,3,7-trimethylxanthine) (Fig. 2) is an alkaloid belonging to the methylxanthine family and is present in foods, beverages, and pharmaceuticals, with major natural sources including coffee, tea, and other plants.[15] It is readily soluble in organic solvents.[16] In brewed coffee, caffeine is a principal contributor to bitterness.[11] Beyond its sensory role, caffeine is functionally significant as a central nervous system stimulant. Its primary mechanism involves antagonism of adenosine receptors, thereby counteracting sleep-promoting signaling and enhancing alertness. This effect may also be accompanied by increased release of hormones such as cortisol and adrenaline, contributing to improved focus and perceived energy. However, higher caffeine intake may induce adverse effects in some individuals, including arrhythmias, although such risks can be mitigated through the use of decaffeination processes.[17]

CGA ($C_{16}H_{18}O_9$) (Fig. 3) represents the predominant polyphenolic group in green coffee and is well known for its strong antioxidant and antimicrobial properties, with reported anti inflammatory and cardiometabolic benefits.[18] Structurally, CGA comprises a group of related esters commonly referred to as its isomeric forms, including caffeoylquinic acids (CQA), dicaffeoylquinic acids (diCQA), and feruloylquinic acids (FQA).[19] In addition, CGA contributes to the acidity, flavor, aroma, and characteristic green color of coffee beans, making it a functional

Table 1 Summary of bioactive compound ranges in green coffee extract

Sample of coffee	Caffeine (% w/w)	CGA (% w/w)	CGA (mg L^{-1})	Reference
A	1.06 ± 0.08	8.50 ± 0.26	0.71 ± 0.04	13
B	1.05 ± 0.09	8.59 ± 0.59	0.90 ± 0.05	
C	1.21 ± 0.11	8.92 ± 0.54	1.04 ± 0.10	

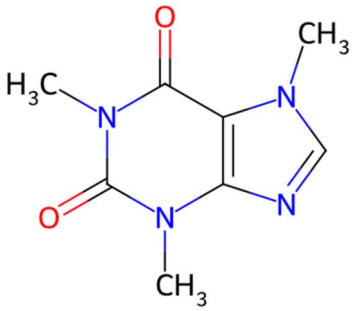

Fig. 2 Chemical structure of caffeine.

component that can be utilized to enhance sensory attributes, particularly color and aroma, in food and beverage applications.[20]

Trigonelline ($C_7H_7NO_2$) (Fig. 4) is a pyridine alkaloid and a niacin related compound naturally present in green coffee beans. It has a bitter taste and has been used as a food additive to enhance coffee like aroma and flavor in food products.[21] Owing to its hydrophilic and polar nature, trigonelline is readily formulated in aqueous systems for food and pharmaceutical applications. Commercially, trigonelline is largely obtained from plant sources and can contribute nutritional value because it may degrade to niacin during baking or thermal processing.[22] In addition, trigonelline has been reported to exhibit diverse biological activities, including antimigraine, anticancer, antidiabetic, neuroprotective, and hypocholesterolemic effects.[23]

2.2 Variability in chemical composition

Green coffee is composed of insoluble polysaccharides (comprising around 50% w/w), with small amounts of sucrose, fructose, glucose, galactose, and arabinose. Additionally, green coffee contains oils and waxes (8–18% w/w), proteins (9–12% w/w), and minerals (3–5% w/w). In addition, several compounds that fall within the broader chlorogenic acids (CGA) family are present in green coffee, including caffeic acid, caffeoylquinic acids, and dicaffeoylquinic acids.

In a recent study by Bojórquez-Quintal *et al.*,[6] the content of individual mineral elements in green coffee was determined using energy-dispersive X-ray spectroscopy (EDS), with the highest mineral level reported being potassium (3.37 ± 0.03%) and calcium (0.45 ± 0.04%), which are minerals that play multiple roles in biological function.[24] The mineral composition can vary among green coffee types and is influenced by several factors, including the geographical region where coffee is cultivated, agronomic practices, and postharvest bean processing.[6]

2.3 Effect of processing

Moisture content is a key quality attribute of green coffee and reflects both origin and postharvest handling. Arabica green coffee beans have been reported not to exceed 12.5% moisture regardless of geographical origin,[25] although some samples, particularly from Africa, exhibited low moisture contents below 7%. Moisture contents between 8.0% and 12.5% are generally considered optimal to maintain bean quality.[25] Wet processing typically results in moisture contents of 9.83–11.75%,[26–28] and beans with higher moisture can be redried using solar or mechanical methods.[29]

After postharvest handling, processing steps such as steaming and roasting determine subsequent physicochemical changes. Steaming of green coffee beans has been reported to have a minimal impact on caffeine content, with only a slight decrease of 0.4%. Roasting, in contrast, induces substantial transformations and is commonly described as two consecutive stages: dehydration and roasting.

During dehydration, the moisture content decreases from 10–12% in green beans to approximately 2.5% in roasted beans.[30] Moisture loss will facilitate heat transfer and prepares the matrix for subsequent reactions during roasting. In the

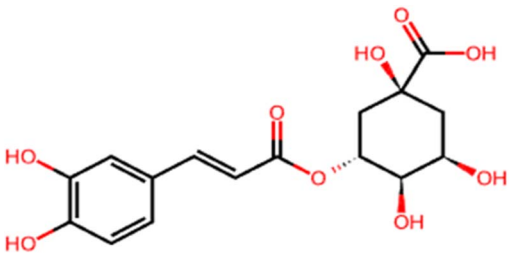

Fig. 3 Chemical structure of CGA.

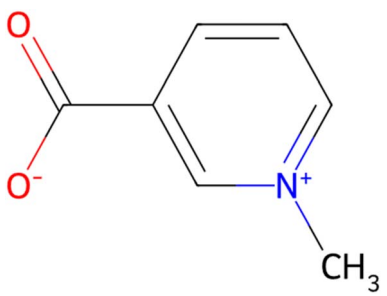

Fig. 4 Chemical structure of trigonelline.

Table 2 The effect of roasting temperature differences on caffeine and CGA concentrations

Roasting degree	Roasting temperature (°C)	Caffeine (mg L^{-1})	CGA (mg L^{-1})	Reference
Green coffee	—	166.72 ± 5.08	543.23 ± 8.92	42
Light roast	155–165	196.35 ± 6.67	270.93 ± 10.76	
Medium roast	175–185	203.63 ± 3.16	187.45 ± 9.05	
Dark roast	205–215	189.85 ± 5.81	90.53 ± 12.97	

roasting stage, beans are heated in air, and roasting degree is typically monitored by bean color, namely light, medium, and dark.[31] These visual changes coincide with marked physical modifications, including an almost twofold increase in volume, a weight loss of 15–25%, and continuous color development.[32] At higher temperatures (up to 300 °C), oil migration may occur; breakage of oleosomes allows lipids to leak out and contribute to desirable aromas.[33] However, overroasting may result in structural cracking, swelling, and undesirable sensory properties.

Notably, while beans are roasted in air, the internal conditions are effectively pyrolytic because substantial carbon dioxide is released. This CO_2, produced through decarboxylation of organic acids, helps protect volatile flavors formed during roasting by limiting oxidative degradation, thereby supporting flavor preservation. The final flavor profile is therefore determined not only by roasting degree but also by CO_2 dynamics within the bean matrix.

Roasting also drives major compositional shifts, particularly within the phenolic fraction. Polyphenols, including chlorogenic acids (CGA), are closely linked to the antioxidant properties of coffee, and the ability to inhibit oxidation as a commonly cited health-related attribute has been attributed to CGA and other polyphenolic compounds such as ferulic acid, caffeic acid, and *n*-coumaric acid. Longer roasting times have been associated with a significant decline in polyphenol levels, reported to range from 7.3% to 32.1% across roasting stages.[34] CGA can initially decompose into caffeic and chianaic acids, which may further generate phenolic compounds such as phenol, dihydroxybenzenes, guaiacol, 4-vinylguaiacol, and 4-ethylguaiacol.

The CGA content in green coffee has been reported to vary between 6% and 10% on a dry matter basis,[35] and yet appreciable amounts of CGA can still be detected in coffee brews and commercial coffee powders after conventional roasting. As roasting progresses, CGA and quinic acid generally decrease, while several phenolic compounds, including caffeic acid, gallic acid, pyrogallol, and purpurogallin, increase.[36] In line with this trend, light-roasted coffee is often associated with high total phenolic content, with TPC decreasing from green coffee toward the dark roast stage, whereas dark-roasted coffee has been reported to show higher flavonoid content and condensed tannins.[37]

Beyond roasting, fermentation can further modulate phenolic composition. Fermentation of green coffee using *Aspergillus oryzae* for 24 h has been reported to increase phenolic content by up to 68%.[38] Accordingly, the relationship between roasting degree and antioxidant capacity is not fully uniform across studies. Alnsour *et al.*[39] reported that antioxidant levels in arabica ground coffee correlated with roasting degree and were highest in green coffee beans, whereas Cho *et al.*[40] observed the highest antioxidant levels in light-roasted coffee followed by a pronounced loss (40–80%) with further roasting, which they attributed to Maillard reaction products responsible for brown pigment formation. Other findings indicate that antioxidant activity does not always decline in parallel with CGA depletion, Chindapan *et al.*[41] reported that despite a significant decrease in CGA with increasing roasting degree, antioxidant properties did not significantly decrease, potentially due to the formation of melanoidins or low-molecular-weight compounds with antioxidant activity. From a nutritional standpoint, light- to medium-roasted coffee is often considered preferable because these conditions may retain the highest overall antioxidant properties.

Caffeine exhibits its own roasting-dependent behavior. While steaming causes only a minor decrease, caffeine content has been reported to increase with roasting degree up to light and medium roasting, likely due to mass loss and concentration effects, before declining in dark roasting where thermal degradation is likely to occur.[42] This pattern is consistent with Tsai and Jioe,[43] who similarly reported an increase in caffeine content after roasting.

Collectively, roasting transforms the bioactive profile of coffee through interconnected mechanisms such as moisture loss, physical structure change, thermal degradation, Maillard reaction, and volatile formation. To translate these qualitative mechanisms into comparable evidence, Table 2 compiles quantitative changes in caffeine, CGA, and phenolic-related metrics across roasting degrees, enabling direct comparison of how roasting intensity modulates the bioactive profile of green coffee and its derived products.

3. Effects of GCE on human health

Human clinical evidence suggests that green coffee extract has been primarily investigated for weight management and cardiometabolic outcomes, including glycaemic control, blood pressure, and lipid profile. Table 3 summarizes key randomized trials and meta analyses by study type, sample characteristics, dosing regimens, and principal outcomes, enabling cross-study comparison across populations with overweight or obesity, metabolic syndrome, nonalcoholic fatty liver disease, and type 2 diabetes.[44–49]

Table 3 Summary of evidence on GCE study design dose and key health outcomes[a]

Study type	Participants	Sample size	GCE dose and duration	Key outcomes	Reference
Systematic review, dose–response meta-analysis of RCTs	Overweight/obesity adults	13 Articles, 16 RCTs	• GCE dose: 25–10 mg per day • Durations: 4–12 weeks	BMI decreased (WMD −0.403 kg m^{-2}), no significant change in body weight or waist circumference overall, stronger effect when baseline BMI ≥ 25 kg m^{-2}, interventions <4 weeks showed no effect	44
Randomized, double-blind, placebo-controlled trial	People with metabolic syndrome, having BMI > 25 kg m^{-2}	50 Recruited, 43 completed	• GCE dose: 800 mg per day • Durations: 8 weeks	SBP reduction greater *vs.* placebo, FBS and HOMA-IR decreased *vs.* placebo, waist circumference decreased, weight and BMI reduction about 2× placebo but marginal significance, no difference in lipid profile	45
Randomized, double-blind, placebo-controlled trial	Patients with NAFLD, aged 20–60 years with BMI ranged 25–35 kg m^{-2}	48 Total, 24 per arm	• GCE dose: 400 mg per day • Durations: 8 weeks	BMI decreased, HDL increased, TC decreased within GCE group, TG reduced but became non-significant after adjustment, hepatic steatosis grade and liver enzymes did not change	46
Randomized, double-blind, placebo-controlled trial	44 Patients with T2D and overweight/obesity, having a history of diabetes between 1 and 10 years, having BMI of 25–35 kg m^{-2}	44 Total, 22 per arm	• GCE dose: 800 mg per day • Durations: 10 weeks	Body weight and BMI decreased, SBP decreased, TG decreased, HDL increased, hs-CRP decreased, FBG reduction marginal, no effect on insulin, HOMA-IR, LDL, total cholesterol, DBP	47
Systematic review and meta-analysis of RCTs	Individuals aged ≥18 years old	13 Publications, 17 RCTs	• GCE dose variations: 400–6000 mg per day • Durations: 4–8 weeks	TC decreased (WMD −4.51 mg dL^{-1}), LDL-C decreased (WMD −4.38 mg dL^{-1}), HDL-C increased (WMD +2.63 mg dL^{-1}), TG change non-significant	48
Systematic review and meta-analysis of RCTs	Adult population's ≥18 and ≤65 years with or without disease	27 Articles	• GCE dose variations: 46–6000 mg per day • Durations: 8–11 weeks	FBS decreased, insulin decreased, TG decreased, HDL increased, no significant change in HOMA-IR, LDL, CRP	49

[a] BMI = body mass index; WMD = weighted mean difference; SBP = systolic blood pressure; DBP = diastolic blood pressure; FBS = fasting blood sugar; FBG = fasting blood glucose; HOMA-IR = homeostatic model assessment of insulin resistance; HDL = high-density lipoprotein; HDL-C = high-density lipoprotein cholesterol; LDL = low-density lipoprotein; LDL-C = low-density lipoprotein cholesterol; TC = total cholesterol; TG = triglycerides; CRP = C-reactive protein; hs-CRP = high-sensitivity C-reactive protein.

Across weight related endpoints, the overall effects appears modest. The dose response meta analysis of randomized trials reported a statistically significant reduction in BMI of about 0.40 kg m^{-2}, whereas changes in body weight and waist circumference were not significant overall.[44] Subgroup analysis suggested larger effects among participants whose baseline BMI was at least 25 kg m^{-2} and little evidence of benefit in interventions shorter than four weeks.[44] This findings imply that any benefit may require sufficient duration and is more detectable in populations with higher baseline adiposity. Nonetheless, even when significant, the magnitude of change is modest and may not translate into clinically meaningful weight reduction on its own, particularly when compared with established lifestyle interventions. Evidence focused specifically on chlorogenic acid rich preparations also points to a limited dataset, where the pooled reduction in body weight was observed but based on only a few small trials, underscoring the need for longer and adequately powered studies before firm conclusions can be drawn.[5]

For cardiometabolic outcomes, trials in higher risk populations indicate potential benefits for systolic blood pressure and selected glycaemic markers, but results vary by endpoint. In individuals with metabolic syndrome, an 8 week intervention with decaffeinated GCE improved systolic blood pressure and fasting blood glucose-related measures compared with placebo, while lipid profile outcomes were largely unchanged.[45] In type 2 diabetes, a ten week trial of aqueous GCE reported improvements in systolic blood pressure, triglycerides, high density

lipoprotein, and inflammation markers, whereas effects on fasting glucose and insulin resistance indices were less consistent.[47] When pooled evidence is considered, meta analyses suggest reductions in fasting blood sugar, insulin, and triglycerides with increases in high density lipoprotein, but no consistent improvements in low-density lipoprotein, C-reactive protein, or HOMA IR.[49] Collectively, these results reflect heterogeneous findings across trials and populations.

A methodological limitation across these studies is the variability in extract composition and dosing comparability. GCE does not represent a uniform intervention, and products can vary in chlorogenic acid profile, caffeine content, and processing, including decaffeination or aqueous extraction. Analytical work by Vinson *et al.*[50] on commercial GCE preparations demonstrated discrepancies between labeled and measured chlorogenic acid content, along with wide variation in caffeine levels. This directly complicates interpretation of dose–response relationships and cross study comparison. Given that reported clinical effects are generally small, this becomes a major concern since modest differences in actual bioactive compounds exposure may influence statistical significance and contribute to inconsistent trends across trials.

Study quality constraints further limit confidence in several outcomes. Many individual randomized trials involved fewer than 50 participants per study with follow ups of eight to ten weeks, reducing statistical power to detect clinically meaningful changes and limits assessment of long-term sustainability and safety.[45–47] Outcome inconsistency is particularly evident for lipid and liver related endpoints. Although one lipid-focused meta analysis found statistically significant changes in total cholesterol and low density lipoprotein, the direction and clinical desirability of high density lipoprotein changes differed across syntheses, and triglyceride effects were often modest or non significant.[48,49] In nonalcoholic fatty liver disease (NAFLD), improvements were more apparent in BMI and parts of the lipid profile than in hepatic steatosis grade or liver enzymes, suggesting that liver specific benefits remain uncertain in short term human trials.[46]

As summarized in Table 3, the clinical studies reviewed here consistently report study design parameters, dosing regimens, and key health outcomes, yet none of the included studies provided pharmacokinetic (PK) data such as maximum plasma concentration (C_{max}), time to peak concentration (T_{max}), or area under the plasma concentration–time curve (AUC) for CGA or its primary metabolites. This represents a notable gap in the current evidence base, as the absence of such data makes it difficult to establish meaningful dose–response relationships or to determine whether the reported health outcomes are directly attributable to circulating CGA-derived compounds at physiologically relevant concentrations. The interpretation of clinical findings is further complicated by the fact that CGA undergoes extensive presystemic and colonic metabolism, resulting in a heterogeneous pool of circulating phenolic metabolites whose individual PK profiles remain incompletely characterized in the context of GCE supplementation. Future clinical investigations should therefore prioritize the integration of PK endpoints alongside efficacy outcomes, ideally with time-course plasma sampling and validated analytical methods capable of distinguishing intact CGA from its microbial and hepatic metabolites. Such data would substantially strengthen the mechanistic interpretation of dose-dependent effects and support the rational design of GCE-based nutraceutical or pharmaceutical formulations.

Overall, current findings warrant a cautious interpretation. GCE appears to deliver modest improvements in BMI and certain cardiometabolic markers in some groups, yet meaningful clinical inference is limited by variability in formulations, small sample sizes, and mixed results for lipid and liver outcomes. Future studies should focus on standardized GCE products, clear quantification and reporting of chlorogenic acids and caffeine, and longer follow up using clinically interpretable endpoints.

4. Production of GCE

4.1 Extraction and isolation

Extraction is a defining step in producing GCE because it largely determines the final CGA and caffeine profile, process efficiency, and the overall safety and sustainability of the product. Conventional solvent-based techniques remain widely used due to their simplicity and scalability, but they are often associated with long processing times, large solvent volumes, and higher environmental and occupational burdens, particularly when volatile or toxic solvents are involved.[51] These limitations have intensified interest in greener extraction strategies.

Recent work has emphasized on intensified and greener extraction routes, including microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), pressurized or subcritical water extraction (SWE), and aqueous-based systems such as aqueous extraction processing (AEP) and enzyme-assisted aqueous extraction processing (EAEP). Table 4 provides a comparison of major GCE extraction approaches by summarizing solvent choice, processing intensity including time, temperature, pressure or power input, reported CGA and caffeine yields, and qualitative environmental implications relevant to industrial implementation.

Among the evaluated approaches, aqueous extraction under mild conditions, particularly AEP and EAEP, appears the most immediately industry-ready pathway for food-grade GCE. Both methods were operated at 50 °C for 60 minutes, indicating that the energy requirement for AEP and EAEP is considerably lower than that of conventional extractions, which are conducted at 70 °C for up to 25 hours. Furthermore, AEP and EAEP are carried out under neutral conditions (pH 7.0) and rely exclusively on water as the primary solvent, which aligns well with safety and sustainability expectations for food applications, in contrast to conventional extractions that employ chloroform, a toxic solvent, as part of the extraction system. The main scale-up burden typically shifts downstream to clarification and water removal, but these operations are standard in the food industry and can be optimized with established filtration or membrane and concentration technologies. Importantly, available evidence specific to green coffee indicates that AEP and EAEP can deliver high nutritional functionality, with consistently

Table 4 Comparison of green coffee extraction methods and sustainability metrics

No.	Method of extraction	Yield of caffeine and CGA	Solvent use	Time/energy consumption	Environmental impact	Reference
1	Microwave assisted extraction (MAE)	• Caffeine: 40.06% of the extract • CGA: 46.41% of the exreact	Water	• Time: 5 min • Temperature: 50 °C • Energy: 800 W	Low toxicity, food-grade, minimal solvent hazard, electricity demand moderate	52
2	Microwave assisted extraction (MAE)	• Caffeine: 38.10% of the extract • CGA: 61.87% of the exreact	Methanol	• Time: 5 min • Temperature: 50 °C • Energy: 800 W	High toxicity and not food-grade, stricter handling and waste treatment required, higher environmental/ health burden	
3	Microwave assisted extraction (MAE)	• Caffeine: 34.08% of the extract • CGA: 55.31% of the exreact	Ethanol	• Time: 5 min • Temperature: 50 °C • Energy: 800 W	Ethanol is assigned a score of 3 for health and environmental impact and a score of 4 for safety, resulting in an overall classification as a recommended solvent according to the CHEM21 solvent selection guide and food grade	
4	NADES-ultrasonic assisted extraction (NADES-UAE)	• Caffeine: 7.89 mg g^{-1} of the extract • CGA: 28.62 mg g^{-1} of the extract	Mixture of water and natural deep eutectic solvents (NADES)	• Time: 30 min • Temperature: room temperature • Energy: not reported	Green solvent claim supported (low toxicity and biodegradable), however, NADES viscosity and added electricity may shift impacts to energy and downstream processing	53
5	Supercritical CO_2 extraction ($scCO_2$)	• Caffeine: 7 mg g^{-1} of the extract • CGA: 0.48 mg g^{-1} of the extract	CO_2 99% and mixture of CO_2 and ethanol 5% (wt/wt)	• Temperature: 50 °C • High pressure: 35.2 MPa	Low-toxicity solvent with minimal residues and recyclable CO_2, but high energy demand due to high-pressure operation; co-solvents may add solvent handling and recovery steps	54
6	Subcritical water extraction (SWE)	• Caffeine: 0.395 mg mL^{-1} extract • CGA: not reported	Water	• Time: 27.4 min • Temperature: 162.4 °C • Underhigh pressure	Uses water only (no organic solvents) and offers high scalability, the main trade-off is energy demand for heating/pressurization, with additional impacts from aqueous effluent handling and downstream concentration/drying	55
7	Subcritical water hydrolysis (SCWH)	• Caffeine: 2519.63 mg g^{-1} of extract • CGA: 7017.38 mg g^{-1} of extract	Water	• Time: 30 min • Temperature: 180 °C • Pressure: 3 MPa	Uses water as the only reagent (no organic solvents), but requires high temperature and pressure, leading to higher energy demand environmental performance depends on heat recovery and management of aqueous effluents	56
8	Subcritical water hydrolysis (SCWH)	• Caffeine: 2211.69 mg g^{-1} of extract • CGA: 5803.21 mg g^{-1} of extract	Water	• Time: 43 min • Temperature: 220 °C • Pressure: 6 MPa	Uses water as the only reagent (no organic solvents), but requires high temperature and pressure, leading to higher energy demand especially at 220 °C/60 bar; environmental performance depends on heat	

Table 4 (*Contd.*)

No.	Method of extraction	Yield of caffeine and CGA	Solvent use	Time/energy consumption	Environmental impact	Reference
					recovery and management of aqueous effluents	
9	Enzyme-assisted aqueous extraction process (EAEP)	• Caffeine: 1194.48 mg/100 g extract • CGA: 6194.13 mg/100 g extract	Mixture of water and enzyme	• Time: 60 min • Temperature: 50 °C • pH: 7.0	Water-based and solvent-free, but adds the environmental burden of enzyme production and use, impacts depend on enzyme dosage and additional separation/cleanup steps, alongside electricity demand for processing and aqueous effluent management	57
10	Aqueous extraction process (AEP)	• Caffeine: 1260.22 mg/100 g extract • CGA: 6335.32 mg/100 g extract	Water	• Time: 60 min • Temperature: 50 °C • pH: 7.0	Water-based and solvent-free, with relatively low chemical hazard, offers high scalability, impacts mainly come from water use, energy for mixing/heating (if applied), and energy-intensive separation/clarification of aqueous streams	
11	Conventional extractions	• Caffeine: 1.82% of extract • CGA: 36.24% of extract	Hexane, ethyl acetate, water, chloroform	• Time: 25 hours • Temperature: 70 °C	High solvent and energy demand due to long extraction time and heating, use of volatile/toxic solvents (especially chloroform and hexane) increases health and waste-treatment burdens, and solvent recovery is required to reduce emissions and environmental impact	58

high *in vitro* protein digestibility and compositional differences depending on whether enzymes are used, supporting the feasibility of these processes for industrial adoption.

For process intensification, MAE using food-grade solvents such as water or ethanol represents a promising option when short residence time and high throughput are needed, achieving caffeine yields of 34.08% to 40.06% and CGA yields of 46.41% to 61.87% within only 5 minutes, which is substantially shorter compared to other extraction methods that require anywhere from 27.4 minutes to 25 hours. Consistent with the broader assisted-extraction literature, MAE can substantially shorten extraction time and enhance mass transfer relative to conventional heating. However, industrial readiness depends on engineering controls to ensure uniform heating, manage hazards, and address scale-up constraints such as field distribution and penetration depth. These issues are well recognized in MAE scale-up and safety-focused discussions. In contrast, MAE using non-food-grade solvents is less attractive for food manufacturing despite favorable performance due to toxicity concerns and stricter waste handling requirement, undermining the sustainability argument for the MAE industry.

SWE and SCWH or related pressurized hot-water processing offers an attractive solvent alternative because it relies on water under elevated temperature and pressure to enhance solvation power and can reduce or eliminate organic solvents. Nevertheless, Table 4 highlights the trade-off of higher thermal and pressurization demand, as the method operates at temperatures ranging from 162.4 °C to 220 °C and pressures of 3 to 6 MPa, which would inevitably entail greater energy consumption and equipment investment. These methods become most promising at industrial scale when plants can implement heat integration and recovery, and when aqueous effluent and downstream concentration are designed efficiently so that the solvent advantage is not offset by energy penalties.

Supercritical carbon dioxide ($scCO_2$) extraction is industrially mature and well positioned for selective operations such as decaffeination and fractionation. However, it may be less competitive as a single-step route for CGA-rich extracts, given that it operates under extremely high pressure conditions of up to 35.2 MPa. Natural deep eutectic solvents (NADES) combined with UAE have demonstrated promising laboratory-scale performance, but still hinges on practical scale-up issues around viscosity and downstream solvent recovery before it can be considered a default industrial choice.

Overall, no single extraction technology is universally optimal. Water-based systems (AEP and EAEP) currently offer the most balanced profile for food-grade GCE when evaluated against safety, regulations, scalability, and environmental impact. Intensified and pressurized methods offer advantages regarding efficiency but require sustainability considerations to ensure that gains in extraction performance are not traded-off by increased energy demand or operational complexity. Therefore, future process considerations should integrate extraction yield, bioactive stability, solvent safety, energy intensity, and downstream processing efficiency within a unified sustainability framework.

4.2 Microencapsulation of GCE

4.2.1 Carriers used. Carriers are the primary determinants of encapsulate microstructure and thus govern retention, powder handling, reconstitution, and compatibility with different food matrices. In spray-dried systems, carbohydrate-based carriers such as maltodextrin are frequently used due to their solubility, low viscosity, and film-forming properties. In addition, maltodextrin is a high molecular weight material with a relatively high glass transition temperature, a characteristic that helps reduce powder stickiness during and after spray drying[59] thereby increasing the yield of powder.[60] Desai *et al.*[61] investigated the enrichment of decaffeinated green coffee extract derived from Robusta cherries, containing approximately 70 ± 5% CGA, followed by microencapsulation using maltodextrin. A higher proportion of maltodextrin was associated with reduced hygroscopicity, smoother surface morphology, improved solubility across a wide pH range, and lower moisture content, all of which contribute to enhanced storage stability and extended shelf life.[62] Encapsulation efficiency exceeded 70%, indicating that maltodextrin effectively protected CGA and other phenolic compounds from degradation during drying and storage.[61]

Beyond single-carrier systems, combining carbohydrate matrices with protein components can modulate functionality and performance. In a related formulation study, an optimized mixture of 8.5% maltodextrin and 2.32% skim milk yielded a microencapsulated product with higher total phenolic content (53.33 mg GAE per g) and stronger antioxidant activity (LC_{50} 71.10 ppm) compared with the non-encapsulated extract (46.32 mg GAE per g; LC_{50} 87.7).[63] This study claimed that the spray-dried product quality surpassed existing market diet supplements, emphasizing that carrier selection can translate into higher functional potency and product competitiveness.[63]

Carrier choice also extends to hydrocolloids and protein-based walls that target stability and sensory compatibility. do Carmo *et al.*[64] evaluated protective colloids (PD) and ionic polysaccharides (IN) as stabilizers, while Garcia-Solis *et al.*[65] used a combination of agave fructans and gum arabic (optimum formulation of 3% fructans + 2% gum arabic) to protect phenolics from green coffee waste extract (GCWE). This system achieved 94.36% encapsulation efficiency for chlorogenic acid, retained of 18.86 mg per g chlorogenic acid, and preserved antioxidant activity.[65]

Meanwhile, protein-based walls offer additional advantages. Husni *et al.*[66] employed whey protein concentrate (WPC) as a wall material, producing irregular microspheres with a mean diameter of 1.367 μm and retained bioactivity (CGA 7.19%; IC_{50} 374.53 μg mL^{-1}). They successfully encapsulated CGA and caffeine and improved sensory properties by masking undesirable flavor. Protein-based wall systems may therefore be particularly advantageous in applications where flavor is a critical consideration, as a higher proportion of WPC in the coating material enhances protective capacity and improves heat resistance.[67]

Finally, cyclodextrins provide a mechanistically distinct carrier strategy by molecular inclusion rather than matrix

Table 5 Summaries of methods and types of carriers in the GCE microencapsulation process[a]

No.	Encapsulation method	Wall material	Process conditions	Key outcomes	Reference
1	Spray drying	Maltodextrin (MD), skim milk (SM)	IT: 120 °C OT: 67 °C	Spray drying with 120 °C inlet temperature and 10% maltodextrin as the wall material yielded microparticles with 84% encapsulation efficiency that provided significantly superior protection to chlorogenic acid under simulated gastrointestinal digestion compared to non-encapsulated GCE	61
2	Spray drying	Maltodextrin (MD), skim milk (SM)	IT: 120 °C OT: 67 °C	The optimal spray drying process found using 8.61% maltodextrin and 3.22% skim milk. This condition produced a dietary supplement powder with higher total phenolic content (TPC) and better antioxidant activity than a comparable commercial product	71
3	Spray drying	Polydextrose (PD), inulin (IN)	IT: 150 °C OT: not reported	Using inulin as encapsulating agent at an 150 °C inlet temperature produced spherical microparticles and when incorporated into a dairy beverage, significantly increased its phenolic content and antioxidant activity	64
4	Freeze drying	Polydextrose (PD), inulin (IN)	Frozen temperature: −20 °C Frozen time: 48 hours Dried temperature: −50 °C Dried pressure: <200 μmHg Dried time: 5 days	Freeze drying GCE with inulin as encapsulating agent produced microparticles with excellent physical characteristics and, when added into a dairy beverage, achieved the highest sensory acceptability scores for overall impression	64
5	Spray drying	Agave fructans, Gum Arabic (GA)	IT: 120 °C OT: 70 °C	Spray drying at 120 °C inlet temperature with a wall material consisting of 3% fructans and 2% gum arabic resulted in microcapsules with high encapsulation efficiency of 94.36%, effectively preserving chlorogenic acid content	65
6	Spray drying	Whey protein concentrate (WPC)	IT: 180 °C OT: 70 °C	The process yielded 39.5% of microparticles with a mean size of 1.367 μm, which successfully encapsulated GCE with 75% and 80% caffeine and chlorogenic acid, respectively. This result significantly improved sensory properties of the product by masking unpleasant flavor and aroma	66
7	Nano spray drying	Maltodextrin	Feed flow rate: 300 mL h^{-1} Drying air flow rate: 60 m^3 h^{-1}	The process was optimized using Response Surface Methodology (RSM), yielding optimal nanoparticles at an inlet temperature of 125 °C and a wall-to-core ratio of 2 : 1, which resulted in 40% product yield, ∼70% encapsulation efficiency, a particle size of 82.34 nm, a zeta potential of −28.8 mV, and provided excellent controlled release in the intestine, with over 80% CGA availability and significantly improved storage stability	70
8	Inclusion complex formation	β-Cyclodextrin (β-CD)	Solvent used: water Temperature: 50 °C Time: 2 hours Precipitation: 24 hours at 0 °C Centrifugation: 20 min at 18 000×*g* and 4 °C	On molar ratio in final complex: β-CD : CGA = 1 : 1, complexation efficiency was maximized, effectively limiting interactions between CGAs and food proteins (whey, egg white, and soy protein isolates)	68

[a] IT: inlet temperature; OT: outlet temperature.

entrapment. Budryn *et al.*[68] demonstrated that β-cyclodextrin (β-CD) forms inclusion complexes with chlorogenic acids (CGAs), limiting their interaction with dietary proteins. Free CGAs bound to proteins (whey, egg white, soy) at 62.9–96.2%, whereas complexation reduced binding to 0.23–0.48%. This effect was attributed to shielding of the CGA aromatic ring within the hydrophobic β-CD cavity, supporting phenolic preservation and likely improved availability after digestion.[68]

Collectively, carbohydrate matrices (maltodextrin), hydrocolloid systems (gum arabic and fructan), protein walls (WPC), and β-CD complexation have been reported to address various challenges including powder stability and solubility,[61,63] high retention and preservation of antioxidants in by-products,[65] sensory masking with preserved biological activity,[66] and reduction of protein binding to maintain phenolic availability.[69] Therefore, the selection of carrier material should consider not only encapsulation efficiency, but also the intended food matrix, release profile, sensory properties, stability, and digestibility.

4.2.2 Encapsulation methods. Encapsulation performance is strongly influenced by the drying or structuring route, which determines particle architecture, moisture, water activity, and scalability. Among the reviewed studies, spray drying (SD) is the most frequently used technology for producing shelf-stable powders. Desai *et al.*[70] produced maltodextrin-based spray-dried microcapsules with favorable powder properties and EE > 70%, while[63] also used spray drying to generate a product with improved total phenols (53.33 mg GAE per g) and LC50 (71.10 ppm) *versus* the non-encapsulated extract. Spray drying has also been applied beyond conventional microcapsules to waste-derived extracts and protein-based systems under specific thermal profiles. Garcia-Solis *et al.*[65] used SD for GCWE encapsulation under 120 °C inlet and 70 °C outlet, achieving 94.36% EE for chlorogenic acid and high retention (18.86 mg g^{-1}).[65] Husni *et al.*[66] applied SD at 180 °C inlet/70 °C outlet using WPC (whey protein concentrate), obtaining a microparticle yield of 39.5% and improved sensory quality through masking of off-notes, alongside retained CGA bioactivity.[66] A comparative overview of GCE microencapsulation methods, including spray drying, freeze drying, nano spray drying, and complex formation, is presented in Table 5.

Freeze-drying (FD) is commonly positioned as a gentler alternative, particularly when thermal sensitivity is a concern. do Carmo *et al.*[64] compared SD and FD combined with PD or IN, reporting that IN-FD yielded superior physical characteristics (lower moisture content, water activity, hygroscopicity), highlighting the role of method selection in dictating powder robustness and storage behavior.[64]

Nanoencapsulation introduces an additional scale dimension, aiming to enhance dispersion and controlled delivery. Desai *et al.*[70] employed spray drying with maltodextrin and optimized the process *via* RSM, identifying 125 °C inlet temperature and 2 : 1 wall-to-core ratio (10% w/w maltodextrin) to produce nanoparticles (82.34 nm) with 70% EE for CGA and 40% product yield. In parallel, Budryn *et al.*[69] presented inclusion complex formation with β-CD as a non-drying, molecular encapsulation approach that targets interaction control rather than particle engineering.

Overall, spray drying remains the most widely used technique due to its ability to support continuous powder production, compatibility with a wide range of carrier materials, and its rapid, flexible, and straightforward operation, while also being a cost-effective process reported to be up to eight times more economical than freeze-drying.[72] Nevertheless, optimization of processing conditions is essential to minimize degradation or loss of bioactive compounds in green coffee extract during spray drying.[73] FD may provide superior physical stability depending on the protective agent, but is less attractive for large-scale production. On the other hand, nanoencapsulation and β-CD inclusion offer complementary routes for dispersion and interaction control. Therefore, selection of encapsulation method selection should align with the intended application, required product profile, cost considerations, and scale of processing.

4.2.3 Stability, release behavior, and bioavailability. The central value proposition of microencapsulation for green coffee bioactives is to preserve stability during processing and storage while maintaining effective release and availability after incorporation into foods and digestion. In maltodextrin-based systems, Desai *et al.*[70] reported low-moisture powders with improved pH-solubility and EE > 70%, supporting longer shelf life and greater usability in food applications, the authors attributed these improvements to phenolic protection within the carrier matrix. Perdani *et al.*[63] similarly demonstrated functional improvements after encapsulation, with higher total phenols (53.33 mg GAE per g) and improved LC50 (71.10 ppm) compared with the non-encapsulated extract (total phenols 46.32 mg GAE per g; LC50 87.7), and suggested that the microencapsulated product outperformed some commercial supplements.

Stability outcomes also translate into performance in real food matrices and during storage. do Carmo *et al.*[64] reported that microencapsulated GCE incorporated into unfermented dairy beverages increased phenolic content and antioxidant properties and enabled controlled release throughout storage. Importantly, despite differences in encapsulation route, the authors found similar bioaccessibility after gastrointestinal digestion across encapsulation techniques, suggesting that multiple technological routes can still support efficient release and potential absorption.

Encapsulation can also preserve high antioxidant activity in waste-derived extracts, supporting sustainable ingredient development. Garcia-Solis *et al.*[65] achieved strong CGA protection in GCWE microcapsules (EE 94.36%, CGA 18.86 mg g^{-1}) while maintaining antioxidant activity, indicating that spray drying with agave fructans and gum arabic can convert by-products into stable functional ingredients. Ali Husni *et al.*[66] reported that WPC-based spray-dried microparticles retained bioactivity (CGA 7.19%, IC_{50} 374.53 μg mL^{-1}) while improving sensory quality through masking, highlighting a practical link between stability and consumer-relevant attributes.

Controlled release and long-term stability become more explicit at the nanoscale. Desai *et al.*[70] showed that

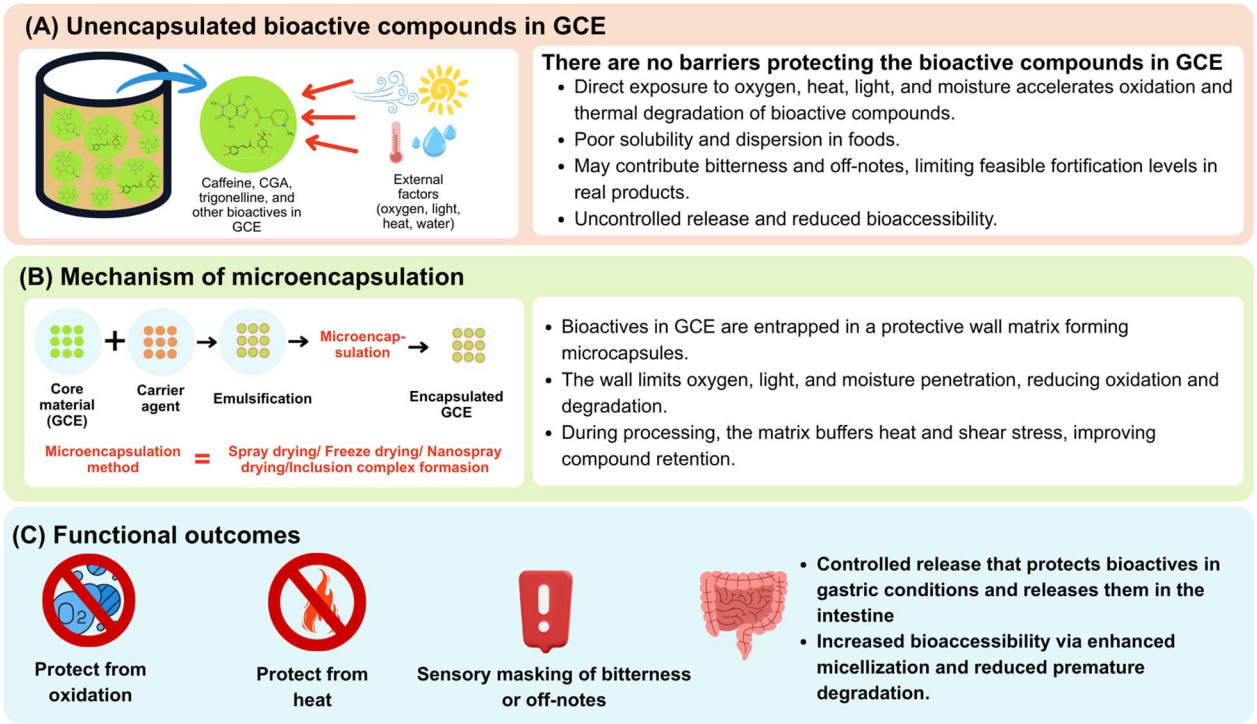

Fig. 5 Microencapsulation mechanism and functional benefits.

nanoencapsulation produced nanoparticles (82.34 nm) with 70% EE and 40% yield, with improved storage stability over 150 days and a digestion-relevant release profile in which 80% CGA was available in the intestine under simulated gastrointestinal conditions.

A key mechanism influencing functional bioavailability is the mitigation of undesired binding to food proteins. Budryn *et al.*[68] demonstrated that β-CD inclusion complexes reduced CHA–protein binding from 62.9–96.2% (free CGAs) to 0.23–0.48%, a dramatic shift that supports phenolic preservation during processing and suggests improved availability after gastrointestinal breakdown of the complexes. Overall, achieving antioxidant bioavailability after food incorporation remains a central goal, and economically feasible encapsulation routes are required for practical and sustainable implementation.[69]

While these findings highlight the technological potential of microencapsulation in enhancing controlled release and improving bioaccessibility, such outcomes should be interpreted within the broader context of the inherent pharmacokinetic limitations of CGA. Despite improvements in stability and gastrointestinal release, CGA exhibits relatively low oral bioavailability, as it is not efficiently absorbed in its intact form within the upper gastrointestinal tract. Only a small fraction is absorbed in the small intestine, whereas a substantial proportion progresses to the colon, where it undergoes extensive biotransformation by the gut microbiota into lower molecular weight phenolic metabolites, including caffeic acid, ferulic acid, and other related phenolic acids.[74,75] Consequently, the compounds detected in systemic circulation are predominantly these microbial-derived metabolites rather than the parent CGA molecule.

This metabolic transformation should be considered a major factor influencing both the bioavailability and biological activity of green coffee extract. Accordingly, the physiological effects associated with GCE are likely mediated, at least in part, by these secondary metabolites rather than by intact CGA itself. From this perspective, strategies aimed at improving CGA stability and controlled release, such as microencapsulation, may enhance its delivery through the gastrointestinal environment and potentially regulate the site and rate of metabolite formation. However, such approaches do not necessarily translate into increased systemic availability of the native compound. Therefore, improvements in technological stability should be interpreted alongside the intrinsically limited absorption of CGA and its extensive metabolism by the gut microbiome.

Across a range of carrier systems and processing approaches, the reported advantages consistently cluster into three main outcomes, namely enhanced storage stability through reduced moisture or water activity and better protection of phenolics, improved performance in food applications, including higher solubility, sensory masking, and compatibility with dairy matrices, and greater digestive availability *via* mechanisms such as controlled release or minimized protein interactions, as demonstrated for nanoencapsulation and β-cyclodextrin inclusion. Ultimately, however, cost-effectiveness remains a key determinant for successful scale-up and real-world adoption. To provide a clearer overview, Fig. 5 illustrates the microencapsulation mechanism, showing how the wall matrix protects GCE bioactives.

5. Application of green coffee extract in food

Several studies have reported the application of green coffee extract in food and beverages, as summarized in Table 6. To improve readability and interpretation, the applications can be grouped by food type, and discussed through three recurring lenses: the functional role of GCE, sensory considerations, and processing stability. Across matrices, GCE is mainly used as an antioxidant and, in some cases, as an antimicrobial or as a contributor to flavor modification. At the same time, its use is often limited by green coloration, bitterness, and reduced stability during high-temperature processing.

5.1 Bakery products

Bakery and cereal systems represent one of the most frequently studied applications because green coffee extract can increase antioxidant capacity and, in certain cases, reduce undesirable processing by-products. Budryn *et al.*[68] investigated the enrichment of various products using green coffee extract at 0.25 to 1 g per 100 g, including gnocchi, sponge cake, bread, donuts, mayonnaise, marshmallows, caramel candies, and jellies. The addition of green coffee extract significantly increased antioxidant activity across products, with the strongest increase observed in sponge cake. In donuts, green coffee extract increased dough hardness and stickiness and also increased the hardness of fried donuts, which was attributed to covalent reactions between phenolic compounds and wheat flour proteins. The same study reported that the addition of 0.1 and 1 g per 100 g green coffee extract reduced acrylamide content in fried donuts by 7 to 9% compared with the control, suggesting that antioxidant compounds in green coffee extract may suppress pathways involved in acrylamide formation during frying. Processing stability differed markedly between product types. In mayonnaise and jellies, phenolic compounds were relatively stable because these products are processed at low temperatures, while higher losses were found in bread, sponge cake, marshmallows, and caramel candies, which was linked to heat exposure and water evaporation during baking.

Similar outcomes were reported for bread fortification. Mukkundur Vasudevaiah *et al.*[58] found that adding 1.5% green coffee extract significantly increased total polyphenols, chlorogenic acid, radical scavenging activity, and antioxidant activity. Importantly, the authors noted that 1.5% was the highest level that enhanced bread functionality without a significant negative effect on taste. Sensory constraints become more apparent at higher incorporation levels of coffee-derived ingredients. Zain *et al.*[76] investigated bread fortified with ground coffee bean powder at 3%, 5%, and 7% and reported increased phenolic content and antioxidant properties, but odour and taste acceptability decreased at higher concentrations due to greenish crust development and off-flavour formation. The 3% level provided the best balance between functional enhancement and sensory quality. A sustainability-oriented approach was reported by Desai *et al.*,[77] who valorized green coffee spent to produce cookies enriched with prebiotic oligosaccharides. Roasted green coffee spent improved cookie acceptability at 10 to 12% compared with unroasted material, which produced more greenish color and a harder texture, reinforcing that color and texture are recurring limitations in baked systems.

Taken together, bakery and cereal matrices demonstrate both the benefits and trade-offs of green coffee extract. Phenolic compounds can enhance antioxidant activity and may reduce acrylamide, yet protein binding and thermal exposure can shift texture and accelerate phenolic losses, making dose optimization and processing considerations critical.

5.2 Dairy products and dairy-based beverages

Dairy matrices highlight the role of protein–polyphenol interactions in determining product stability and texture. Dönmez *et al.*[78] incorporated green coffee extract at 0 to 2% into yoghurt and reported reduced syneresis during storage. The enriched yoghurt showed higher pH values than the control between 14 and 21 days, and the reduced syneresis was attributed to changes in protein–polyphenol interactions and pH-dependent casein behavior. Pimpley *et al.*[79] investigated yoghurt fortified with spray-dried green coffee extract at 0.5 to 2% and observed a decrease in pH with increasing extract concentration, linked to increased phenolic acid content. The authors also reported changes in syneresis tendency and significant differences in hardness, adhesiveness, and springiness compared with the control. Despite these physicochemical changes, sensory evaluation indicated higher overall acceptance during storage for yoghurts containing spray-dried green coffee extract.

Microencapsulation provides an additional strategy in dairy beverages to improve both stability and acceptability. do Carmo *et al.*[64] compared microencapsulated green coffee extracts produced by spray drying and freeze drying using polydextrose and inulin as encapsulating agents in unfermented dairy beverages. The fortified beverages exhibited higher total phenolic compounds and antioxidant activities, and inulin-encapsulated green coffee extract achieved the highest acceptability score. These findings support the view that dairy systems can accommodate green coffee extract effectively, but the outcome depends on how phenolics shift protein network stability and pH behavior, while encapsulation can help mitigate direct sensory impact and protect bioactive compounds.

5.3 Beverages

Beverage applications emphasize bioaccessibility and consumer-facing sensory attributes. Sęczyk *et al.*[80] reported that green coffee extract fortification increased phenolic content and antioxidant activity in soymilk and that the beverage showed high *in vitro* bioaccessibility. Increasing the dose improved protein and starch digestibility, offering additional functional relevance beyond antioxidant enhancement. Sensory evaluation showed improved acceptance of aroma and texture but reduced acceptance of color, consistent with the limitation of green coloration in light-colored beverages. Encapsulation can improve beverage performance and acceptance, especially in dark, flavor-rich matrices. Indiarto *et al.*[81] incorporated encapsulated green coffee extract into cocoa drinks and reported

Table 6 Integrated overview of GCE applications across food systems

Food type	Food matrix	Dose of GCE	Functional roles	Key outcomes	Sensory considerations	Stability conciderations	Reference
Bakery	Gnocchi, sponge cake, bread, donuts, mayonnaise, marshmallows, caramel candies, jellies (multi-product study)	0.25–1 g/100 g food product	Antioxidant, process contaminant mitigation	Antioxidant activity increased (the highest increase was observed in sponge cake), donuts showed higher hardness and stickiness, fried donuts showed 7–9% lower acrylamide than control	Texture changes were noted in donuts, sensory was not consistently reported across all products	Low-temperature products such as mayonnaise and jellies showed relatively stable phenolics, baked products showed 20–40% phenolic loss, likely linked to heat exposure and water evaporation	69
Bakery	Bread	1.5%	Nutritional enhancement, antioxidant enrichment	Total polyphenols increased, chlorogenic acid increased, radical scavenging activity increased, antioxidant activity increased	Acceptable at 1.5% without significant taste impact	Heat processing may reduce phenolics, dose optimization is important	58
Bakery	Bread	3–7%	Antioxidant enrichment	Total phenolics increased, antioxidant properties increased, 3% gave the best balance between functionality and sensory quality	Higher concentrations reduced odour and taste acceptability, slightly green crust and off-flavour were reported at higher levels	Baking increases sensory risk at higher addition levels	76
Bakery	Cookies	10–12%	Prebiotic potential, fiber enrichment	Nutritional profile improved, ash increased, protein increased, fat increased, dietary fiber increased, oligosaccharide contribution supported prebiotic value	Unroasted GCS produced greener color and harder texture, roasted GCS improved acceptability	Ingredient pre-treatment influences final quality in baked systems	77
Dairy	Yoghurt	0–2%	Matrix stabilization, potential antioxidant enrichment	Syneresis decreased during storage, enriched yoghurt showed higher pH than control at later storage periods	Sensory was not the primary focus in this study	Effects were linked to protein–polyphenol interaction and pH-dependent casein behavior	78
Dairy	Yoghurt	0.5–2%	Antioxidant enrichment, texture modification	pH decreased with higher GCE concentration, syneresis tendency changed, hardness differed, adhesiveness differed, springiness differed, overall acceptance was higher than control during storage	Overall acceptance improved during storage	Phenolic acids can alter acid balance and casein stability, formulation-dependent response	79
Dairy beverage	Unfermented dairy beverages	10 g/200 mL beverage samples	Antioxidant enrichment, sensory optimization	Total phenolics increased, antioxidant activity increased, inulin-encapsulated GCE produced the highest acceptability score	Encapsulation improved acceptability, inulin performed best in sensory	Encapsulation helps protect bioactives during processing and storage, and reduces direct sensory impact	64

Table 6 (*Contd.*)

Food type	Food matrix	Dose of GCE	Functional roles	Key outcomes	Sensory considerations	Stability conciderations	Reference
Beverage	Soymilk	0.025–1 mg of phenolics per mL samples	Antioxidant enrichment, bioaccessibility improvement, digestive modulation	Phenolics increased, antioxidant activity increased, *in vitro* bioaccessibility was high, higher dose increased protein digestibility and starch digestibility	Aroma acceptance increased, texture acceptance increased, color acceptance decreased	Beverage systems make color and bitterness more noticeable, dispersion and sensory masking are critical	80
Beverage	Cocoa drink	Up to 10% acceptable	Antioxidant enrichment	Total polyphenols increased, flavonoid content increased, antioxidant activity increased, products remained acceptable up to 10%	Acceptable for all sensory attributes up to 10%	Encapsulation and cocoa matrix support stability and sensory masking	81
Meat, seafood	Mackerel mince, fish cake	1–1.5%	Lipid oxidation control, shelf-life support	Lipid oxidation indicators improved, TBARS increase was not significant during chill storage compared to control, final product acceptance was not negatively affected	No adverse consumer acceptance reported	Chill storage conditions highlight antioxidant protection effect	82
Meat products	Chevon nuggets	5%	Antioxidant, antimicrobial, shelf-life extension	Total plate count decreased, psychrophilic count decreased, yeast and mold decreased, improved microbial stability during 60 days at -18 ± 2 °C	Sensory was not the main emphasis	Frozen storage supports antimicrobial and antioxidant function	83
Lipid-rich emulsions	Mayonnaise	1.5%	Natural antioxidant replacement	Antioxidant activity increased, oxidation was delayed as indicated by peroxide value, pH and texture were unchanged	Sensory penalties were not highlighted as major issues	Effective in emulsion oxidation control, stability benefit is measurable	84
Lipid-rich spreads	Margarine	0.01%	Oxidative stability enhancement, sustained release	Peroxide values decreased, *p*-anisidine values decreased, DPPH retention was higher during 90 days, sensory scores were comparable to TBHQ-containing sample	Comparable acceptance to synthetic antioxidant	Encapsulation protected bioactives and supported sustained antioxidant activity during storage	85

concentration-dependent increases in total polyphenol content, flavonoid content, and antioxidant activity. The addition of up to 10% encapsulated green coffee extract remained acceptable to panelists across sensory attributes, indicating that encapsulation and matrix selection can support higher fortification levels without compromising sensory quality.

5.4 Meat and seafood products

In meat and seafood systems, green coffee extract is primarily utilized to slow lipid oxidation and improve microbial stability during storage. Parvathy *et al.*[82] incorporated green coffee extract at 1 to 1.5% into mackerel mince and reported reduced lipid oxidation and protein degradation during chill storage, with no negative impact on consumer acceptance of the final fish cake product. Meena *et al.*[83] evaluated chevon nuggets containing 5% green coffee extract during 60 days of frozen storage and observed lower total plate count, psychrophilic count, yeast count, and mold count compared with the control. This improved microbial quality was attributed to the natural antioxidant and antimicrobial compounds present in green coffee extract, particularly chlorogenic acid derivatives, supporting its potential as a natural.

5.5 Lipid-rich foods, emulsions, and spreads

Oil-based systems provide strong evidence for green coffee extract as a natural antioxidant alternative to synthetic additives. da Silva Polvarini *et al.*[84] investigated mayonnaise fortified with green coffee extract and reported that 1.5% increased antioxidant activity without altering pH and texture, while delaying oxidation as indicated by peroxide value. Microencapsulation further strengthens performance in lipid-rich foods by protecting actives and enabling sustained antioxidant action. Javadpour *et al.*[85] incorporated tragacanth–chitosan hydrogel microcapsules containing supercritical CO_2-extracted green coffee antioxidants into margarine and reported improved oxidative stability during 90 days of storage, supported by lower peroxide and *p*-anisidine values and higher DPPH retention. Sensory evaluation showed comparable scores to a sample containing TBHQ, indicating that microencapsulated green coffee antioxidants can provide oxidative protection without compromising product acceptance.

5.6 Flavor modification through phenolic–protein interactions

Beyond preservation and nutritional enhancement, interactions between GCE phenolics and proteins can contribute to aroma development. Budryn *et al.*[69] studied the possibility of phenolic–protein interactions in food products including bread, cookies, caramel cottage cheese, nutty filling, and stuffing products. The authors reported that adding GCE together with protein hydrolysates promoted the formation of volatile components, particularly furans and pyrazines, which positively affected aroma. They also noted that chlorogenic acid in encapsulated form may reduce degradation but can also reduce interaction with proteins, lowering the formation of aroma-related volatile substances. This finding highlights a practical formulation trade-off: stabilizing phenolics through encapsulation can be beneficial for retention, but it may reduce interaction-driven aroma formation in protein-containing foods where that interaction is desirable.

5.7 Integrated interpretation and limitations

Across food systems, limitations are consistently linked to green coloration, bitterness, and phenolic instability during high-temperature processing. These constraints are most apparent in lightly colored products and in baked or fried products where heat exposure and moisture loss accelerate phenolic degradation. The studies in Table 6 collectively indicate that successful incorporation of green coffee extract requires careful dose selection, appropriate matrix choice, and the use of microencapsulation when stability and sensory masking are critical. At the same time, when flavor development relies on phenolic–protein interactions, excessive protection through encapsulation may reduce aroma formation, requiring product-specific balancing of stability and interaction effects.

Overall, the integration of GCE into food systems demands an approach or framework that considers extract composition, processing intensity, carrier selection, matrix interactions, sensory impact, and economic viability simultaneously. Instead of a singular solution, successful implementation depends on specific strategies that optimize based on stability, functionality, sensory quality, and sustainability within the intended product characteristic.

6. Conclusion and future recommendations

This review highlights GCE as a rich source of chlorogenic acids and related phenolics with consistent antioxidant capacity and growing evidence for metabolic benefits. Across preclinical and clinical studies, the most reproducible signals are improvements in oxidative stress markers and modest effects on body weight and glycemic control, while findings for lipid profile and liver related outcomes remain mixed. The wide variability in extract composition, dosing regimens, and study duration is a major reason why results are not always comparable and why clinical relevance is sometimes difficult to interpret.

Encapsulation and other delivery approaches emerged as practical strategies to protect sensitive compounds, improve aqueous dispersibility, and support targeted release during digestion, which can enhance functional performance in food and nutraceutical applications. However, these technological advances will only translate into reliable products if they are paired with standardized extract characterization and fit for purpose stability testing in realistic matrices. In particular, chromatographic profiling using high performance liquid chromatography with appropriate reference standards should be applied to quantify total and individual chlorogenic acid isomers, commonly referred to as HPLC-DAD-MS or HPLC-ESI-MS/MS. This approach allows for the unambiguous identification and quantification of individual CGA isomers, including 5-caffeoylquinic acid, 3-caffeoylquinic acid, 4-caffeoylquinic acid,

and their dicaffeoylquinic acid counterparts, which differ in their stability profiles, bioavailability, and biological activity.[86,87] Quantification should be performed against authenticated reference standards, such as those available from Sigma-Aldrich or PhytoLab, and results expressed relative to dry weight of extract to allow cross-study comparison. The use of external calibration curves with at least five concentration points and a documented limit of detection and limit of quantification is considered minimum practice for analytical rigor.

Beyond identity and quantity, characterization protocols should also account for the oxidation state of phenolic compounds, since CGA is susceptible to enzymatic and non-enzymatic oxidation during processing and storage, which generates quinone derivatives that are analytically distinct and may exhibit different functional properties (Cheynier, 2012).[88] Incorporating antioxidant capacity assays such as DPPH, ABTS, and FRAP alongside chromatographic profiling provides a more complete picture of extract functionality and batch to batch consistency. Standardization efforts aligned with recognized frameworks, such as those proposed by the Association of Official Analytical Chemists or ISO guidelines for food grade botanical extracts, would further strengthen the comparability of findings across laboratories and support regulatory acceptance of GCE based nutraceutical products.

Key take home findings from this review are summarized below:

- Green coffee extract is consistently rich in phenolic compounds, especially CGA, which underpin strong antioxidant activity.
- Human studies suggest modest benefits for body weight and glycemic outcomes, but effects on lipids and liver markers are inconsistent across trials.
- Differences in extraction, roasting status, and formulation lead to large variation in chemical profiles, making comparisons across studies difficult.
- Encapsulation can improve stability and handling, and may support bioaccessibility through controlled release, but performance depends on wall materials and processing conditions.
- Safety assessment is generally reassuring at commonly used doses, yet long term data and standardized reporting of adverse events are still limited.

Taken together, these findings support the potential of green coffee extract, yet significant gaps remain that limit comparability, clinical evidence, and product stability and safety. Future work should prioritize standardization, clinical validation, sustainability assessment, and product relevant performance testing to move the field from promising evidence to actionable, evidence-based guidance.

First, extract composition should be standardized and transparently reported. At minimum, studies should quantify major chlorogenic acid isomers, caffeine content, and key markers of degradation, and link these data to biological outcomes to allow meaningful dose response comparisons.

Second, well powered randomized controlled trials are needed in populations with clearly defined cardiometabolic risk, using standardized dosing and adequate duration. Trials should include clinically meaningful endpoints, robust dietary control, and consistent reporting of adverse events to strengthen conclusions about efficacy and safety.

Third, sustainability must be assessed at scale rather than inferred from laboratory practice. Life cycle and techno economic analyses comparing solvent intensive methods with greener alternatives are essential, alongside strategies for solvent recovery, energy efficiency, and valorization of processing by products. Fourth, stability and efficacy should be demonstrated in real food systems. Research should test green coffee extract and encapsulated forms in diverse matrices such as beverages, dairy or plant based products, bakery items, and lipid rich foods, under realistic processing and storage conditions. Outcomes should include retention of key bioactives, sensory impact, and bioaccessibility after digestion.

Finally, safety research should expand beyond short interventions. Long term intake studies, evaluation of higher dose ranges, and interactions with medications commonly used for diabetes and cardiovascular disease are needed to define clear consumption guidelines. Addressing these priorities will strengthen methodology, enhance reproducibility, and enable more reliable transition of green coffee extract into safe, effective, and sustainable functional food ingredient.

Conflicts of interest

The authors report there are no competing interests to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Acknowledgements

This research is funded by the Indonesian Endowment Fund for Education (LPDP) on behalf of the Indonesian Ministry of Higher Education, Science and Technology and managed under the EQUITY Program (Contract No. 4298/B3/DT.03.08/2025).

References

1 E. M. Ijanu, M. A. Kamaruddin and F. A. Norashiddin, Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative, *Appl. Water Sci.*, 2020, **10**(1), 11.
2 B. Kamalapreetha, R. Anbarasan, R. Jagan Mohan and R. Mahendran, Evaluation of plasma bubbling assisted high-pressure processed green coffee bean extract: Yield, quality characterization and e-nose aroma profiling, *Food Human.*, 2025, **4**, 100570.
3 S. A. Moreira, E. M. C. Alexandre, M. Pintado and J. A. Saraiva, Effect of emergent non-thermal extraction technologies on bioactive individual compounds profile from different plant materials, *Food Res. Int.*, 2019, **115**, 177–190.

4 O. Gligor, S. Clichici, R. Moldovan, D. Muntean, A. M. Vlase, G. C. Nadăş, *et al.*, The Effect of Extraction Methods on Phytochemicals and Biological Activities of Green Coffee Beans Extracts, *Plants*, 2023, **12**(4), 712.
5 S. Kanchanasurakit, S. Saokaew, P. Phisalprapa and A. Duangjai, Chlorogenic acid in green bean coffee on body weight: a systematic review and meta-analysis of randomized controlled trials, *Syst. Rev.*, 2023, **12**(1), 163.
6 E. Bojórquez-Quintal, D. Xotlanihua-Flores, L. Bacchetta, G. Diretto, O. Maccioni, S. Frusciante, *et al.*, Bioactive Compounds and Valorization of Coffee By-Products from the Origin: A Circular Economy Model from Local Practices in Zongolica, Mexico, *Plants*, 2024, **13**(19), 2741.
7 A. Valdés, G. Álvarez-Rivera, B. Socas-Rodríguez, M. Herrero, E. Ibáñez and A. Cifuentes, Foodomics: Analytical Opportunities and Challenges, *Anal. Chem.*, 2022, **94**(1), 366–381.
8 C. Bao, P. Jiang, J. Chai, Y. Jiang, D. Li, W. Bao, *et al.*, The delivery of sensitive food bioactive ingredients: Absorption mechanisms, influencing factors, encapsulation techniques and evaluation models, *Food Res. Int.*, 2019, **120**, 130–140.
9 C. L. Ky, J. Louarn, S. Dussert, B. Guyot, S. Hamon and M. Noirot, Caffeine, trigonelline, chlorogenic acids and sucrose diversity in wild Coffea arabica L. and C. canephora P. accessions, *Food Chem.*, 2001, **75**(2), 223–230.
10 A. Sualeh, K. Tolessa and A. Mohammed, Biochemical composition of green and roasted coffee beans and their association with coffee quality from different districts of southwest Ethiopia, *Heliyon*, 2020, **6**(12), e05812.
11 A. Farah, M. C. Monteiro, V. Calado, A. S. Franca and L. C. Trugo, Correlation between cup quality and chemical attributes of Brazilian coffee, *Food Chem.*, 2006, **98**(2), 373–380.
12 C. A. B. De Maria, L. C. Trugo, R. F. A. Moreira and M. Petracco, Simultaneous determination of total chlorogenic acid, trigonelline and caffeine in green coffee samples by high performance gel filtration chromatography, *Food Chem.*, 1995, **52**(4), 447–449.
13 M. Atlabachew, A. Abebe, T. Alemneh Wubieneh and Y. Tefera Habtemariam, Rapid and simultaneous determination of trigonelline, caffeine, and chlorogenic acid in green coffee bean extract, *Food Sci. Nutr.*, 2021, **9**(9), 5028–5035.
14 P. Mazzafera and A. Carvalho, Breeding for low seed caffeine content of coffee (Coffea L.) by interspecific hybridization, *Euphytica*, 1991, **59**(1), 55–60.
15 A. A. Abu-Hashem, O. Hakami, M. El-Shazly, H. A. S. El-Nashar and M. N. M. Yousif, Caffeine and Purine Derivatives: A Comprehensive Review on the Chemistry, Biosynthetic Pathways, Synthesis-Related Reactions, Biomedical Prospectives and Clinical Applications, *Chem. Biodivers.*, 2024, **21**(7), e202400050.
16 D. Shofinita, D. Lestari, S. Ayu Ambarwati, K. C. Gunawan and A. B. Achmadi, Optimization of Defective Coffee Beans Decaffeination Using Palm Oil, *ASEAN J. Chem. Eng.*, 2023, **23**(2), 142–2.
17 D. Shofinita, D. Lestari, F. Fiorine, A. Rochili, A. Raksajati and A. Achmadi, Life Cycle Assessment of Decaffeinated Coffee Beans Production, *J. Eng. Technol. Sci.*, 2025, **57**(3), 315–326.
18 J. Huang, M. Xie, L. He, X. Song and T. Cao, Chlorogenic acid: a review on its mechanisms of anti-inflammation, disease treatment, and related delivery systems, *Front. Pharmacol.*, 2023, **14**, 1–10.
19 D. Shofinita, L. Dianika, R. Purwadi, G. A. Sumampouw, K. C. Gunawan, S. A. Ambarwati, A. B. Achmadi and J. T. Tjahjadi, Effects of different decaffeination methods on caffeine contents, physicochemical, and sensory properties of coffee, *Int. J. Food Eng.*, 2024, **20**(8), 561–581.
20 W. W. Perdana, Y. Bindar and D. Shofinita, Selective green extraction of caffeine and chlorogenic acid from robusta coffee beans for the development of functional ingredients, *Discover Food*, 2025, **6**(55), 1–14.
21 J. Zhou, L. Chan and S. Zhou, Trigonelline: A Plant Alkaloid with Therapeutic Potential for Diabetes and Central Nervous System Disease, *Curr. Med. Chem.*, 2012, **19**(21), 3523–3531.
22 N. Konstantinidis, H. Franke, S. Schwarz and D. W. Lachenmeier, Risk Assessment of Trigonelline in Coffee and Coffee By-Products, *Molecules*, 2023, **28**(8), 3460.
23 V. Nguyen, E. G. Taine, D. Meng, T. Cui and W. Tan, Pharmacological Activities, Therapeutic Effects, and Mechanistic Actions of Trigonelline, *Int. J. Mol. Sci.*, 2024, **25**(6), 3385.
24 A. Santato, D. Bertoldi, M. Perini, F. Camin and R. Larcher, Using elemental profiles and stable isotopes to trace the origin of green coffee beans on the global market, *J. Mass Spectrom.*, 2012, **47**(9), 1132–1140.
25 A. Bobková, A. Demianová, K. Poláková, M. Capcarová, J. Lidiková, J. Árvay, *et al.*, Variability of caffeine content in green and roasted *Coffea arabica* regarding the origin, post-harvest processing, and altitude, and overview of recommended daily allowance, *J. Environ. Sci. Health, Part B*, 2022, **57**(12), 989–998.
26 F. Kulapichitr, C. Borompichaichartkul, I. Suppavorasatit and K. R. Cadwallader, Impact of drying process on chemical composition and key aroma components of Arabica coffee, *Food Chem.*, 2019, **291**, 49–58.
27 S. H. Sinaga and E. Julianti, Physical characteristics of Gayo arabica coffee with semi-washed processing, *IOP Conf. Ser. Earth Environ. Sci.*, 2021, **782**(3), 032093.
28 A. A. Tassew, G. B. Yadessa, A. D. Bote and T. K. Obso, Influence of location, elevation gradients, processing methods, and soil quality on the physical and cup quality of coffee in the Kafa Biosphere Reserve of SW Ethiopia, *Heliyon*, 2021, **7**(8), e07790.
29 N. K. Donovan, K. A. Foster and A. P. Salinas, Quality Management And The Economics Of Green Coffee Hermetic Storage, *International Journal of Food and Agricultural Economics*, 2020, **8**(1), 1–20.
30 E. B. Tarigan, E. Wardiana, Y. S. Hilmi and N. A. Komarudin, The changes in chemical properties of coffee during roasting: A review, *IOP Conf. Ser. Earth Environ. Sci.*, 2022, **974**(1), 012115.

31 A. Duangjai, S. Saokaew, B. H. Goh and P. Phisalprapa, Shifting of Physicochemical and Biological Characteristics of Coffee Roasting Under Ultrasound-Assisted Extraction, *Front. Nutr.*, 2021, **8**, 724591.
32 M. Zhu, Y. Long, Y. Ma, Y. Chen, Q. Yu, J. Xie, *et al.*, Comparison of chemical and fatty acid composition of green coffee bean (Coffea arabica L.) from different geographical origins, *LWT-Food Sci. Technol.*, 2021, **140**, 110802.
33 A. Hameed, S. A. Hussain, M. U. Ijaz, S. Ullah, I. Pasha and H. A. R. Suleria, Farm to Consumer: Factors Affecting the Organoleptic Characteristics of Coffee. II: Postharvest Processing Factors, *Compr. Rev. Food Sci. Food Saf.*, 2018, **17**(5), 1184–1237.
34 A. Bobková, M. Hudáček, S. Jakabová, Ľ. Belej, M. Capcarová, J. Čurlej, *et al.*, The effect of roasting on the total polyphenols and antioxidant activity of coffee, *J. Environ. Sci. Health, Part B*, 2020, **55**(5), 495–500.
35 V. Strezov and T. J. Evans, Thermal Analysis of the Reactions and Kinetics of Green Coffee During Roasting, *Int. J. Food Prop.*, 2005, **8**(1), 101–111.
36 Y. C. Liao, T. Kim, J. L. Silva, W. Y. Hu and B. Y. Chen, Effects of roasting degrees on phenolic compounds and antioxidant activity in coffee beans from different geographic origins, *LWT-Food Sci. Technol.*, 2022, **168**, 113965.
37 H. Wu, P. Lu, Z. Liu, J. Sharifi-Rad and H. A. R. Suleria, Impact of roasting on the phenolic and volatile compounds in coffee beans, *Food Sci. Nutr.*, 2022, **10**(7), 2408–2425.
38 M. G. S. Palmieri, L. T. Cruz, F. S. Bertges, H. M. Húngaro, L. R. Batista, S. S. da Silva, *et al.*, Enhancement of antioxidant properties from green coffee as promising ingredient for food and cosmetic industries, *Biocatal. Agric. Biotechnol.*, 2018, **16**, 43–48.
39 L. Alnsour, R. Issa, S. Awwad, D. Albals and I. Al-Momani, Quantification of Total Phenols and Antioxidants in Coffee Samples of Different Origins and Evaluation of the Effect of Degree of Roasting on Their Levels, *Molecules*, 2022, **27**(5), 1591.
40 A. R. Cho, K. W. Park, K. M. Kim, S. Y. Kim and J. Han, Influence of Roasting Conditions on the Antioxidant Characteristics of Colombian Coffee (*Coffea arabica* L.) Beans, *J. Food Biochem.*, 2014, **38**(3), 271–280.
41 N. Chindapan, N. Chaninkun and S. Devahastin, Comparative evaluation of phenolics and antioxidant activities of hot air and superheated steam roasted coffee beans (*Coffea canephora*), *Int. J. Food Sci. Technol.*, 2022, **57**(1), 342–350.
42 S. Awwad, R. Issa, L. Alnsour, D. Albals and I. Al-Momani, Quantification of Caffeine and Chlorogenic Acid in Green and Roasted Coffee Samples Using HPLC-DAD and Evaluation of the Effect of Degree of Roasting on Their Levels, *Molecules*, 2021, **26**(24), 7502.
43 C. F. Tsai and I. P. J. Jioe, The Analysis of Chlorogenic Acid and Caffeine Content and Its Correlation with Coffee Bean Color under Different Roasting Degree and Sources of Coffee (Coffea arabica Typica), *Processes*, 2021, **9**(11), 2040.
44 Z. Gorji, H. K. Varkaneh, S. talaei, A. Nazary-Vannani, C. C. T. Clark, S. Fatahi, *et al.*, The effect of green-coffee extract supplementation on obesity: A systematic review and dose-response meta-analysis of randomized controlled trials, *Phytomedicine*, 2019, **63**, 153018.
45 H. Roshan, O. Nikpayam, M. Sedaghat and G. Sohrab, Effects of green coffee extract supplementation on anthropometric indices, glycaemic control, blood pressure, lipid profile, insulin resistance and appetite in patients with the metabolic syndrome: a randomised clinical trial, *Br. J. Nutr.*, 2018, **119**(3), 250–258.
46 S. Hosseinabadi, M. Rafraf, S. Asghari, M. Asghari-Jafarabadi and S. Vojouhi, Effect of green coffee extract supplementation on serum adiponectin concentration and lipid profile in patients with non-alcoholic fatty liver disease: A randomized, controlled trial, *Complement. Med. Ther.*, 2020, **49**, 102290.
47 S. Khalili-Moghadam, M. Hedayati, M. Golzarand and P. Mirmiran, Effects of green coffee aqueous extract supplementation on glycemic indices, lipid profile, CRP, and malondialdehyde in patients with type 2 diabetes: a randomized, double-blind, placebo-controlled trial, *Front. Nutr.*, 2023, **10**, 1241844.
48 F. Ding, B. Ma, A. Nazary-Vannani, H. Kord-Varkaneh, S. Fatahi, M. Papageorgiou, *et al.*, The effects of green coffee bean extract supplementation on lipid profile in humans: A systematic review and meta-analysis of randomized controlled trials, *Nutr. Metabol. Cardiovasc. Dis.*, 2020, **30**(1), 1–10.
49 M. Morvaridi, E. Rayyani, M. Jaafari, A. Khiabani and M. Rahimlou, The effect of green coffee extract supplementation on cardio metabolic risk factors: a systematic review and meta-analysis of randomized controlled trials, *J. Diabetes Metab. Disord.*, 2020, **19**(1), 645–660.
50 J. A. Vinson, X. Chen and D. D. Garver, Determination of Total Chlorogenic Acids in Commercial Green Coffee Extracts, *J. Med. Food*, 2019, **22**(3), 314–320.
51 Q. W. Zhang, L. G. Lin and W. C. Ye, Techniques for extraction and isolation of natural products: a comprehensive review, *Chin. Med.*, 2018, **13**(1), 20.
52 R. Upadhyay, K. Ramalakshmi and L. Jagan Mohan Rao, Microwave-assisted extraction of chlorogenic acids from green coffee beans, *Food Chem.*, 2012, **130**(1), 184–188.
53 A. M. Syakfanaya, F. C. Saputri and A. Munim, Simultaneously Extraction of Caffeine and Chlorogenic Acid from Coffea canephora Bean using Natural Deep Eutectic Solvent-Based Ultrasonic Assisted Extraction, *Pharmacogn. J.*, 2019, **11**(2), 267–271.
54 A. B. A. d. Azevedo, P. Mazzafera, R. S. Mohamed, S. A. B. V. d. Melo and T. G. Kieckbusch, Extraction of caffeine, chlorogenic acids and lipids from green coffee beans using supercritical carbon dioxide and co-solvents, *Brazilian Journal of Chemical Engineering*, 2008, **25**(3), 543–552.
55 S. Sutrisno, M. E. Yulianto, D. Ariwibowo, V. Paramita, F. D. Utari, B. Azhara, *et al.*, Optimization of Coffee Bean

Extraction Using Subcritical Water: A Response Surface Methodology Approach for Maximizing Caffeine and Antioxidant Yield, *Indones. Food Sci. Technol. J.*, 2025, **9**(1), 19–27.

56 A. T. Getachew and B. S. Chun, Influence of hydrothermal process on bioactive compounds extraction from green coffee bean, *Innov. Food Sci. Emerg. Technol.*, 2016, **38**, 24–31.

57 F. S. Almeida, F. F. G. Dias, M. W. Ford, S. Bogusz Junior, A. C. K. Sato and J. M. L. N. de Moura Bell, Exploring the nutritional and biological properties of green coffee extracts: A comparative study of aqueous and enzymatic extraction processes, *Curr. Res. Food Sci.*, 2024, **9**, 100890.

58 A. Mukkundur Vasudevaiah, A. Chaturvedi, R. Kulathooran and I. Dasappa, Effect of green coffee extract on rheological, physico-sensory and antioxidant properties of bread, *J. Food Sci. Technol.*, 2017, **54**(7), 1827–1836.

59 D. Shofinita, Y. Bindar, T. Walmiki Samadhi, N. Shufia Choliq and A. A. Jaelawijaya, Increasing the Yield of Powder and Bioactive Materials during Extraction and Spray Drying of Dragon Fruit Skin Extracts, *J. Eng. Technol. Sci.*, 2021, **53**(6), 210612–2.

60 D. Shofinita, Y. Bindar, T. W. Samadhi, A. Jaelawijaya, D. Theodric and A. B. Achmadi, Effect of Extraction and Spray Drying Temperatures on The Bioactive Materials Content in Red Dragon Fruit Skin, *Int. J. Technol. Manag.*, 2024, **15**(5), 1282–2.

61 N. M. Desai, D. J. Haware, K. Basavaraj and P. S. Murthy, Microencapsulation of antioxidant phenolic compounds from green coffee, *Prep. Biochem. Biotechnol.*, 2019, **49**(4), 400–406.

62 D. Shofinita, Y. Bindar, T. Walmiki Samadhi, A. Aprillia Jaelawijaya and M. Fawwaz, Reducing the stickiness of dragon fruit skin extract powder as food colorant by addition of maltodextrin during freeze drying, *AIP Conf. Proc.*, 2020, **2219**(1), 070011.

63 C. G. Perdani, T. A. Prihardhini and D. Pranowo, Optimization of Microencapsulation Process of Green Coffee Extract With Spray Drying Method as a Dietary Supplement, *Pelita Perkebunan.*, 2020, **36**(1), 56–67.

64 L. B. do Carmo, D. B. Benincá, M. Grancieri, L. V. Pereira, T. Lima Filho, S. H. Saraiva, *et al.*, Green Coffee Extract Microencapsulated: Physicochemical Characteristics, Stability, Bioaccessibility, and Sensory Acceptability through Dairy Beverage Consumption, *Int. J. Environ. Res. Publ. Health*, 2022, **19**(20), 13221.

65 S. E. Garcia-Solis, V. Perez-Perez, D. Tapia-Maruri, F. Villalobos-Castillejos, M. L. Arenas-Ocampo, B. H. Camacho-Diaz and L. Alamilla-Beltran, Microencapsulation of the green coffee waste extract with high antioxidant activity by spray-drying, *J. Food Process. Preserv.*, 2022, **46**(10), e16864.

66 M. A. Husni, A. K. Nugroho, N. Fakhrudin and T. N. S. Sulaiman, Microencapsulation of Ethyl Acetate Extract from Green Coffee Beans (Coffea Canephora) by Spray Drying Method, *Indones. J. Pharm.*, 2021, **28**, 221–231.

67 D. Shofinita, A. Harimawan, N. Almaishya, A. M. Dewi, J. Thamleonard and A. B. Achmadi, Enhancing Viability of Probiotic by Microencapsulation: A Case Study in Ice Cream, *Int. J. Technol.*, 2025, **16**(4), 1337.

68 G. Budryn, B. Pałecz, D. Rachwał-Rosiak, J. Oracz, D. Zaczyńska, S. Belica, *et al.*, Effect of inclusion of hydroxycinnamic and chlorogenic acids from green coffee bean in β-cyclodextrin on their interactions with whey, egg white and soy protein isolates, *Food Chem.*, 2015, **168**, 276–287.

69 G. Budryn, D. Zaczyńska and J. Oracz, Effect of addition of green coffee extract and nanoencapsulated chlorogenic acids on aroma of different food products, *LWT-Food Sci. Technol.*, 2016, **73**, 197–204.

70 N. M. Desai, J. Gilbert Stanley and P. S. Murthy, Green coffee nanoparticles: optimisation, *in vitro* bioactivity and bio-release property, *J. Microencapsul.*, 2020, **37**(1), 52–64.

71 D. Pranowo, C. Gadizza Perdani, T. Ayu Prihardhini Susinggih Wijana, Q. M. R. A. Syihab Fahmi and A. D. Marza, Optimization Of Microencapsulation Process Of Green Coffee Extract With Spray Drying Method As A Dietary Supplement, *Sys. Rev. Pharm.*, 2020, **11**(10), 715–721.

72 D. Shofinita, D. Lestari, L. Aliwarga, G. Arneldi Sumampouw, S. Ambarwati, K. Christine Gunawan and A. B. Achmadi, Drying Methods of Coffee Extracts and Their Effects on Physicochemical Properties: A Review, *Food Bioprocess Technol.*, 2023, **17**(1), 1–26.

73 D. Shofinita and T. A. G. Langrish, The redox (pro-oxidant/antioxidant) balance in the spray drying of orange peel extracts, *Drying Technol.*, 2016, **34**(14), 1719–1725.

74 A. Farah, M. Monteiro, C. M. Donangelo and S. Lafay, Chlorogenic Acids from Green Coffee Extract are Highly Bioavailable in Humans, *J. Nutr.*, 2008, **138**(12), 2309–2315.

75 A. Stalmach, W. Mullen, D. Barron, K. Uchida, T. Yokota, C. Cavin, *et al.*, Metabolite Profiling of Hydroxycinnamate Derivatives in Plasma and Urine after the Ingestion of Coffee by Humans: Identification of Biomarkers of Coffee Consumption, *Drug Metabol. Dispos.*, 2009, **37**(8), 1749–1758.

76 M. Z. M. Zain, A. S. Baba and A. B. Shori, Effect of polyphenols enriched from green coffee bean on antioxidant activity and sensory evaluation of bread, *J. King Saud Univ. Sci.*, 2018, **30**(2), 278–282.

77 N. M. Desai, B. Mallik, S. D. Sakhare and P. S. Murthy, Prebiotic oligosaccharide enriched green coffee spent cookies and their nutritional, physicochemical and sensory properties, *LWT-Food Sci. Technol.*, 2020, **134**, 109924.

78 Ö. Dönmez, B. A. Mogol and V. Gökmen, Syneresis and rheological behaviors of set yogurt containing green tea and green coffee powders, *J. Dairy Sci.*, 2017, **100**(2), 901–907.

79 V. A. Pimpley, S. Maity and P. S. Murthy, Green coffee polyphenols in formulations of functional yoghurt and their quality attributes, *Int. J. Dairy Technol.*, 2022, **75**(1), 159–170.

80 Ł. Sęczyk, M. Świeca and U. Gawlik-Dziki, Soymilk enriched with green coffee phenolics – Antioxidant and nutritional properties in the light of phenolics-food matrix interactions, *Food Chem.*, 2017, **223**, 1–7.

81 R. Indiarto, S. Rahimah, E. Subroto, N. A. G. Putri and A. D. Pangawikan, Antioxidant activity and characteristics

of a cocoa drink formulated with encapsulated green coffee extract, *Int. J. Food Prop.*, 2022, **25**(1), 2477–2494.

82 U. Parvathy, G. K. Sivaraman, L. N. Murthy, S. Visnuvinayagam, A. Jeyakumari and C. N. Ravishankar, Green coffee extract as a natural antioxidant in chill stored Indian mackerel (Rastrelliger kanagurta) mince, *Indian J. Fish.*, 2018, **65**(1), 86–95.

83 P. Meena, A. Pandey, A. Singh Gurjar, R. Raman, S. Kumar Meel, R. Meena, *et al.*, Effect of green coffee extract on microbial characteristics of chevon nuggets at frozen storage, *Pharm. Innov. J.*, 2022, **6**, 2991–2993.

84 G. da Silva Polvarini, C. T. Sant' Ana, P. E. M. Toshimitu, E. C. Silva, P. I. Silva, S. H. Saraiva, J. P. O. Villanova and A. G. V. Costa, Green Coffee Extract (*Coffea canephora*) as an Antioxidant in Mayonnaise in Replacement of Synthetic Agents, *Eur. J. Lipid Sci. Technol.*, 2025, **127**(4), e70007.

85 M. Javadpour, E. Hosseini, L. Nateghi and S. Bazrafshan, Enhancing margarine oxidative stability, antioxidant retention, and sensory quality via tragacanth-chitosan hydrogel microencapsulation of supercritical CO_2-extracted green coffee, *Food Chem.: X*, 2025, **28**, 102580.

86 A. Farah and C. M. Donangelo, Phenolic compounds in coffee, *Braz. J. Plant Physiol.*, 2006, **18**(1), 23–36.

87 N. Clifford Michael, I. B. Jaganath, I. A. Ludwig and A. Crozier, Chlorogenic acids and the acyl-quinic acids: discovery, biosynthesis, bioavailability and bioactivity, *Nat. Prod. Rep.*, 2017, **34**(12), 1391–1421.

88 V. Cheynier, Phenolic compounds: from plants to foods, *Phytochem. Rev.*, 2012, **11**, 153–177.