

# Sustainable Food Technology

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## Sustainability Spotlight

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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 supporting 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).



# Green Coffee Extracts: Advances in Green Extraction, Bioactivity, and Food Applications with Emphasis on Sustainable Processing

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## Abstract

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  $543.23 \pm 8.92$  mg/L in green coffee compared with  $90.53 \pm 12.97$  to  $270.93 \pm 10.76$  mg/L 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/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.

Keywords: green coffee extract, extraction, antioxidant, microencapsulation



## 1 1. Background

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

8 Scientific interest in green coffee processing as a novel food ingredient has substantially  
9 spiked over the past two decades (see **Figure 1**). These works have mostly addressed several  
10 select aspects of green coffee extracts (GCE), including processing techniques, phytochemical  
11 profiles, and biological activities (4). However, comparative evaluation of extraction techniques  
12 from a processing sustainability perspective remains limited, making it difficult to identify  
13 environmentally preferable and scalable routes for producing GCE. Therefore, an updated review  
14 is needed to consolidate evidence and guide the development of greener and more sustainable  
15 GCE extraction strategies.

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



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

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

22



## 1 2. Chemical Composition of Green Coffee: Bioactives, Variability, and Processing Effects

### 2 2.1 Major Bioactive Compounds in Green Coffee

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

14 Variations in the levels of these three compounds in green coffee are primarily driven by  
15 genetic factors, most notably differences between species and, to a lesser extent, between  
16 varieties (14). Caffeine (1,3,7 trimethylxanthine) (**Figure 2**) is an alkaloid belonging to the  
17 methylxanthine family and is present in foods, beverages, and pharmaceuticals, with major  
18 natural sources including coffee, tea, and other plants (15). It is readily soluble in organic solvents  
19 (87). In brewed coffee, caffeine is a principal contributor to bitterness (11). Beyond its sensory  
20 role, caffeine is functionally significant as a central nervous system stimulant. Its primary  
21 mechanism involves antagonism of adenosine receptors, thereby counteracting sleep-promoting  
22 signaling and enhancing alertness. This effect may also be accompanied by increased release of



1 hormones such as cortisol and adrenaline, contributing to improved focus and perceived energy.  
2 However, higher caffeine intake may induce adverse effects in some individuals, including  
3 arrhythmias, although such risks can be mitigated through the use of decaffeination processes  
4 (88).

5 CGA ( $C_{16}H_{18}O_9$ ) (**Figure 3**) represents the predominant polyphenolic group in green coffee  
6 and is well known for its strong antioxidant and antimicrobial properties, with reported anti  
7 inflammatory and cardiometabolic benefits (16). Structurally, CGA comprises a group of related  
8 esters commonly referred to as its isomeric forms, including caffeoylquinic acids (CQA),  
9 dicaffeoylquinic acids (diCQA), and feruloylquinic acids (FQA) (85). In addition, CGA contributes  
10 to the acidity, flavor, aroma, and characteristic green color of coffee beans, making it a functional  
11 component that can be utilized to enhance sensory attributes, particularly color and aroma, in  
12 food and beverage applications (17).

13 Trigonelline ( $C_7H_7NO_2$ ) (**Figure 4**) is a pyridine alkaloid and a niacin related compound  
14 naturally present in green coffee beans. It has a bitter taste and has been used as a food additive  
15 to enhance coffee like aroma and flavor in food products (18). Owing to its hydrophilic and polar  
16 nature, trigonelline is readily formulated in aqueous systems for food and pharmaceutical  
17 applications. Commercially, trigonelline is largely obtained from plant sources and can contribute  
18 nutritional value because it may degrade to niacin during baking or thermal processing(19). In  
19 addition, trigonelline has been reported to exhibit diverse biological activities, including  
20 antimigraine, anticancer, antidiabetic, neuroprotective, and hypocholesterolemic effects (20).

## 21 **2.2 Variability in chemical composition**



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

6 In a recent study by Bojórquez-Quintal et al. (6), the content of individual mineral  
7 elements in green coffee was determined using energy-dispersive X-ray spectroscopy (EDS), with  
8 the highest mineral level reported being potassium ( $3.37 \pm 0.03\%$ ) and calcium ( $0.45 \pm 0.04\%$ ),  
9 which are minerals that play multiple roles in biological function (21). The mineral composition  
10 can vary among green coffee types and is influenced by several factors, including the  
11 geographical region where coffee is cultivated, agronomic practices, and postharvest bean  
12 processing (6).

### 13 **2.3 Effect of processing**

14 Moisture content is a key quality attribute of green coffee and reflects both origin and  
15 postharvest handling. Arabica green coffee beans have been reported not to exceed 12.5%  
16 moisture regardless of geographical origin (22), although some samples, particularly from Africa,  
17 exhibited low moisture contents below 7%. Moisture contents between 8.0% and 12.5% are  
18 generally considered optimal to maintain bean quality (22). Wet processing typically results in  
19 moisture contents of 9.83–11.75% (23–25), and beans with higher moisture can be redried using  
20 solar or mechanical methods (26).

21 After postharvest handling, processing steps such as steaming and roasting determine  
22 subsequent physicochemical changes. Steaming of green coffee beans has been reported to have



1 a minimal impact on caffeine content, with only a slight decrease of 0.4%. Roasting, in contrast,  
2 induces substantial transformations and is commonly described as two consecutive stages:  
3 dehydration and roasting.

4 During dehydration, the moisture content decreases from 10–12% in green beans to  
5 approximately 2.5% in roasted beans (27). Moisture loss will facilitate heat transfer and prepares  
6 the matrix for subsequent reactions during roasting. In the roasting stage, beans are heated in  
7 air, and roasting degree is typically monitored by bean color, namely light, medium, and dark  
8 (28). These visual changes coincide with marked physical modifications, including an almost  
9 twofold increase in volume, a weight loss of 15–25%, and continuous color development (29). At  
10 higher temperatures (up to 300°C), oil migration may occur; breakage of oleosomes allows lipids  
11 to leak out and contribute to desirable aromas (30). However, overroasting may result in  
12 structural cracking, swelling, and undesirable sensory properties.

13 Notably, while beans are roasted in air, the internal conditions are effectively pyrolytic  
14 because substantial carbon dioxide is released. This CO<sub>2</sub>, produced through decarboxylation of  
15 organic acids, helps protect volatile flavors formed during roasting by limiting oxidative  
16 degradation, thereby supporting flavor preservation. The final flavor profile is therefore  
17 determined not only by roasting degree but also by CO<sub>2</sub> dynamics within the bean matrix.

18 Roasting also drives major compositional shifts, particularly within the phenolic fraction.  
19 Polyphenols, including chlorogenic acids (CGA), are closely linked to the antioxidant properties  
20 of coffee, and the ability to inhibit oxidation as a commonly cited health-related attribute has  
21 been attributed to CGA and other polyphenolic compounds such as ferulic acid, caffeic acid, and  
22 *n*-coumaric acid. Longer roasting times have been associated with a significant decline in



1 polyphenol levels, reported to range from 7.3% to 32.1% across roasting stages (31). CGA can  
2 initially decompose into caffeic and chianaic acids, which may further generate phenolic  
3 compounds such as phenol, dihydroxybenzenes, guaiacol, 4-vinylguaiacol, and 4-ethylguaiacol.

4 The CGA content in green coffee has been reported to vary between 6% and 10% on a dry  
5 matter basis (32), and yet appreciable amounts of CGA can still be detected in coffee brews and  
6 commercial coffee powders after conventional roasting. As roasting progresses, CGA and quinic  
7 acid generally decrease, while several phenolic compounds, including caffeic acid, gallic acid,  
8 pyrogallol, and purpurogallin, increase (33). In line with this trend, light-roasted coffee is often  
9 associated with high total phenolic content, with TPC decreasing from green coffee toward the  
10 dark roast stage, whereas dark-roasted coffee has been reported to show higher flavonoid  
11 content and condensed tannins (34).

12 Beyond roasting, fermentation can further modulate phenolic composition. Fermentation  
13 of green coffee using *Aspergillus oryzae* for 24 h has been reported to increase phenolic content  
14 by up to 68% (35). Accordingly, the relationship between roasting degree and antioxidant  
15 capacity is not fully uniform across studies. Alnsour et al. (36) reported that antioxidant levels in  
16 arabica ground coffee correlated with roasting degree and were highest in green coffee beans,  
17 whereas Cho et al. (37) observed the highest antioxidant levels in light-roasted coffee followed  
18 by a pronounced loss (40–80%) with further roasting, which they attributed to Maillard reaction  
19 products responsible for brown pigment formation. Other findings indicate that antioxidant  
20 activity does not always decline in parallel with CGA depletion, Chindapan et al. (38) reported  
21 that despite a significant decrease in CGA with increasing roasting degree, antioxidant properties  
22 did not significantly decrease, potentially due to the formation of melanoidins or low-molecular-



1 weight compounds with antioxidant activity. From a nutritional standpoint, light- to medium-  
2 roasted coffee is often considered preferable because these conditions may retain the highest  
3 overall antioxidant properties.

4 Caffeine exhibits its own roasting-dependent behavior. While steaming causes only a  
5 minor decrease, caffeine content has been reported to increase with roasting degree up to light  
6 and medium roasting, likely due to mass loss and concentration effects, before declining in dark  
7 roasting where thermal degradation is likely to occur (39). This pattern is consistent with Tsai and  
8 Jioe (40), who similarly reported an increase in caffeine content after roasting.

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

### 16 3. Effects of GCE on Human Health

17 Human clinical evidence suggests that green coffee extract has been primarily  
18 investigated for weight management and cardiometabolic outcomes, including glycaemic  
19 control, blood pressure, and lipid profile. **Table 3** summarizes key randomized trials and meta  
20 analyses by study type, sample characteristics, dosing regimens, and principal outcomes,  
21 enabling cross-study comparison across populations with overweight or obesity, metabolic  
22 syndrome, nonalcoholic fatty liver disease, and type 2 diabetes (41–46).



1 Across weight related endpoints, the overall effects appears modest. The dose response  
2 meta analysis of randomized trials reported a statistically significant reduction in BMI of about  
3 0.40kg/m<sup>2</sup>, whereas changes in body weight and waist circumference were not significant overall  
4 (41). Subgroup analysis suggested larger effects among participants whose baseline BMI was at  
5 least 25 kg/m<sup>2</sup> and little evidence of benefit in interventions shorter than four weeks (41). This  
6 findings imply that any benefit may require sufficient duration and is more detectable in  
7 populations with higher baseline adiposity. Nonetheless, even when significant, the magnitude  
8 of change is modest and may not translate into clinically meaningful weight reduction on its own,  
9 particularly when compared with established lifestyle interventions. Evidence focused  
10 specifically on chlorogenic acid rich preparations also points to a limited dataset, where the  
11 pooled reduction in body weight was observed but based on only a few small trials, underscoring  
12 the need for longer and adequately powered studies before firm conclusions can be drawn (5).

13 For cardiometabolic outcomes, trials in higher risk populations indicate potential benefits  
14 for systolic blood pressure and selected glycaemic markers, but results vary by endpoint. In  
15 individuals with metabolic syndrome, an 8 week intervention with decaffeinated GCE improved  
16 systolic blood pressure and fasting blood glucose-related measures compared with placebo,  
17 while lipid profile outcomes were largely unchanged (42). In type 2 diabetes, a ten week trial of  
18 aqueous GCE reported improvements in systolic blood pressure, triglycerides, high density  
19 lipoprotein, and inflammation markers, whereas effects on fasting glucose and insulin resistance  
20 indices were less consistent (44). When pooled evidence is considered, meta analyses suggest  
21 reductions in fasting blood sugar, insulin, and triglycerides with increases in high density  
22 lipoprotein, but no consistent improvements in low-density lipoprotein, C-reactive protein, or



1 HOMA IR (46). Collectively, these results reflect heterogeneous findings across trials and  
2 populations.

3 A methodological limitation across these studies is the variability in extract composition  
4 and dosing comparability. GCE does not represent a uniform intervention, and products can vary  
5 in chlorogenic acid profile, caffeine content, and processing, including decaffeination or aqueous  
6 extraction. Analytical work by Vinson et al. (47) on commercial GCE preparations demonstrated  
7 discrepancies between labeled and measured chlorogenic acid content, along with wide variation  
8 in caffeine levels. This directly complicates interpretation of dose response relationships and  
9 cross study comparison. Given that reported clinical effects are generally small, this becomes a  
10 major concern since modest differences in actual bioactive compounds exposure may influence  
11 statistical significance and contribute to inconsistent trends across trials.

12 Study quality constraints further limit confidence in several outcomes. Many individual  
13 randomized trials involved fewer than 50 participants per study with follow ups of eight to ten  
14 weeks, reducing statistical power to detect clinically meaningful changes and limits assessment  
15 of long-term sustainability and safety (42–44). Outcome inconsistency is particularly evident for  
16 lipid and liver related endpoints. Although one lipid-focused meta analysis found statistically  
17 significant changes in total cholesterol and low density lipoprotein, the direction and clinical  
18 desirability of high density lipoprotein changes differed across syntheses, and triglyceride effects  
19 were often modest or non significant (45,46). In nonalcoholic fatty liver disease (NAFLD),  
20 improvements were more apparent in BMI and parts of the lipid profile than in hepatic steatosis  
21 grade or liver enzymes, suggesting that liver specific benefits remain uncertain in short term  
22 human trials (43).



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

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



## 1 4. Production of GCE

### 2 4.1. Extraction and Isolation

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

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

16 Among the evaluated approaches, aqueous extraction under mild conditions, particularly  
17 AEP and EAEP, appears the most immediately industry-ready pathway for food-grade GCE. Both  
18 methods were operated at 50°C for 60 minutes, indicating that the energy requirement for AEP  
19 and EAEP is considerably lower than that of conventional extractions, which are conducted at  
20 70°C for up to 25 hours. Furthermore, AEP and EAEP are carried out under neutral conditions (pH  
21 7.0) and rely exclusively on water as the primary solvent, which aligns well with safety and  
22 sustainability expectations for food applications, in contrast to conventional extractions that



1 employ chloroform, a toxic solvent, as part of the extraction system. The main scale-up burden  
2 typically shifts downstream to clarification and water removal, but these operations are standard  
3 in the food industry and can be optimized with established filtration or membrane and  
4 concentration technologies. Importantly, available evidence specific to green coffee indicates  
5 that AEP and EAEP can deliver high nutritional functionality, with consistently high in vitro protein  
6 digestibility and compositional differences depending on whether enzymes are used, supporting  
7 the feasibility of these processes for industrial adoption.

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

20 SWE and SCWH or related pressurized hot-water processing offers an attractive solvent  
21 alternative because it relies on water under elevated temperature and pressure to enhance  
22 solvation power and can reduce or eliminate organic solvents. Nevertheless, **Table 4** highlights



1 the trade-off of higher thermal and pressurization demand, as the method operates at  
2 temperatures ranging from 162.4°C to 220°C and pressures of 3 to 6 MPa, which would inevitably  
3 entail greater energy consumption and equipment investment. These methods become most  
4 promising at industrial scale when plants can implement heat integration and recovery, and when  
5 aqueous effluent and downstream concentration are designed efficiently so that the solvent  
6 advantage is not offset by energy penalties.

7       Supercritical carbon dioxide (scCO<sub>2</sub>) extraction is industrially mature and well positioned  
8 for selective operations such as decaffeination and fractionation. However, it may be less  
9 competitive as a single-step route for CGA-rich extracts, given that it operates under extremely  
10 high pressure conditions of up to 35.2 MPa. Natural deep eutectic solvents (NADES) combined  
11 with UAE have demonstrated promising laboratory-scale performance, but still hinges on  
12 practical scale-up issues around viscosity and downstream solvent recovery before it can be  
13 considered a default industrial choice.

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

#### 22 **4.2. Microencapsulation of GCE**



#### 1 **4.2.1 Carriers used**

2 Carriers are the primary determinants of encapsulate microstructure and thus govern  
3 retention, powder handling, reconstitution, and compatibility with different food matrices. In  
4 spray-dried systems, carbohydrate-based carriers such as maltodextrin are frequently used due  
5 to their solubility, low viscosity, and film-forming properties. In addition, maltodextrin is a high  
6 molecular weight material with a relatively high glass transition temperature, a characteristic  
7 that helps reduce powder stickiness during and after spray drying (89) thereby increasing the  
8 yield of powder (90). Desai et al. (49) investigated the enrichment of decaffeinated green coffee  
9 extract derived from Robusta cherries, containing approximately  $70 \pm 5\%$  CGA, followed by  
10 microencapsulation using maltodextrin. A higher proportion of maltodextrin was associated with  
11 reduced hygroscopicity, smoother surface morphology, improved solubility across a wide pH  
12 range, and lower moisture content, all of which contribute to enhanced storage stability and  
13 extended shelf life (91). Encapsulation efficiency exceeded 70%, indicating that maltodextrin  
14 effectively protected CGA and other phenolic compounds from degradation during drying and  
15 storage (49).

16 Beyond single-carrier systems, combining carbohydrate matrices with protein  
17 components can modulate functionality and performance. In a related formulation study, an  
18 optimized mixture of 8.5% maltodextrin and 2.32% skim milk yielded a microencapsulated  
19 product with higher total phenolic content (53.33 mg GAE/g) and stronger antioxidant activity  
20 ( $LC_{50}$  71.10 ppm) compared with the non-encapsulated extract (46.32 mg GAE/g;  $LC_{50}$  87.7) (50).  
21 This study claimed that the spray-dried product quality surpassed existing market diet



1 supplements, emphasizing that carrier selection can translate into higher functional potency and  
2 product competitiveness (50).

3 Carrier choice also extends to hydrocolloids and protein-based walls that target stability  
4 and sensory compatibility. de Carmo et al. (51) evaluated protective colloids (PD) and ionic  
5 polysaccharides (IN) as stabilizers, while Garcia-Solis et al. (52) used a combination of agave  
6 fructans and gum arabic (optimum formulation of 3% fructans + 2% gum arabic) to protect  
7 phenolics from green coffee waste extract (GCWE). This system achieved 94.36% encapsulation  
8 efficiency for chlorogenic acid, retained of 18.86 mg/g chlorogenic acid, and preserved  
9 antioxidant activity (52).

10 Meanwhile, protein-based walls offer additional advantages. Husni et al. (53) employed  
11 whey protein concentrate (WPC) as a wall material, producing irregular microspheres with a  
12 mean diameter of 1.367  $\mu\text{m}$  and retained bioactivity (CGA 7.19%;  $\text{IC}_{50}$  374.53  $\mu\text{g}/\text{mL}$ ). They  
13 successfully encapsulated CGA and caffeine and improved sensory properties by masking  
14 undesirable flavor. Protein-based wall systems may therefore be particularly advantageous in  
15 applications where flavor is a critical consideration, as a higher proportion of WPC in the coating  
16 material enhances protective capacity and improves heat resistance (93).

17 Finally, cyclodextrins provide a mechanistically distinct carrier strategy by molecular  
18 inclusion rather than matrix entrapment. Budryn et al. (54) demonstrated that  $\beta$ -cyclodextrin ( $\beta$ -  
19 CD) forms inclusion complexes with chlorogenic acids (CGAs), limiting their interaction with  
20 dietary proteins. Free CGAs bound to proteins (whey, egg white, soy) at 62.9–96.2%, whereas  
21 complexation reduced binding to 0.23–0.48%. This effect was attributed to shielding of the CGA



1 aromatic ring within the hydrophobic  $\beta$ -CD cavity, supporting phenolic preservation and likely  
2 improved availability after digestion (54).

3 Collectively, carbohydrate matrices (maltodextrin), hydrocolloid systems (gum arabic and  
4 fructan), protein walls (WPC), and  $\beta$ -CD complexation have been reported to address various  
5 challenges including powder stability and solubility (49,50), high retention and preservation of  
6 antioxidants in by-products (52), sensory masking with preserved biological activity (53), and  
7 reduction of protein binding to maintain phenolic availability (55). Therefore, the selection of  
8 carrier material should consider not only encapsulation efficiency, but also the intended food  
9 matrix, release profile, sensory properties, stability, and digestibility.

#### 10 **4.2.2 Encapsulation methods**

11 Encapsulation performance is strongly influenced by the drying or structuring route,  
12 which determines particle architecture, moisture, water activity, and scalability. Among the  
13 reviewed studies, spray drying (SD) is the most frequently used technology for producing shelf-  
14 stable powders. Desai et al. (56) produced maltodextrin-based spray-dried microcapsules with  
15 favorable powder properties and EE > 70%, while (50) also used spray drying to generate a  
16 product with improved total phenols (53.33 mg GAE/g) and LC50 (71.10 ppm) versus the non-  
17 encapsulated extract. Spray drying has also been applied beyond conventional microcapsules to  
18 waste-derived extracts and protein-based systems under specific thermal profiles. Garcia-Solis et  
19 al. (52) used SD for GCWE encapsulation under 120°C inlet and 70°C outlet, achieving 94.36% EE  
20 for chlorogenic acid and high retention (18.86 mg/g) (52). Husni et al. (53) applied SD at 180°C  
21 inlet / 70°C outlet using WPC (whey protein concentrate), obtaining a microparticle yield of 39.5%  
22 and improved sensory quality through masking of off-notes, alongside retained CGA bioactivity



1 (53). A comparative overview of GCE microencapsulation methods, including spray drying, freeze  
2 drying, nano spray drying, and complex formation, is presented in **Table 5**.

3 Freeze-drying (FD) is commonly positioned as a gentler alternative, particularly when  
4 thermal sensitivity is a concern. de Carmo et al. (51) compared SD and FD combined with PD or  
5 IN, reporting that IN-FD yielded superior physical characteristics (lower moisture content, water  
6 activity, hygroscopicity), highlighting the role of method selection in dictating powder robustness  
7 and storage behavior (51).

8 Nanoencapsulation introduces an additional scale dimension, aiming to enhance  
9 dispersion and controlled delivery. Desai et al. (56) employed spray drying with maltodextrin and  
10 optimized the process via RSM, identifying 125°C inlet temperature and 2:1 wall-to-core ratio  
11 (10% w/w maltodextrin) to produce nanoparticles (82.34 nm) with 70% EE for CGA and 40%  
12 product yield. In parallel, Budryn et al. (55) presented inclusion complex formation with  $\beta$ -CD as  
13 a non-drying, molecular encapsulation approach that targets interaction control rather than  
14 particle engineering.

15 Overall, spray drying remains the most widely used technique due to its ability to support  
16 continuous powder production, compatibility with a wide range of carrier materials, and its rapid,  
17 flexible, and straightforward operation, while also being a cost-effective process reported to be  
18 up to eight times more economical than freeze-drying (86). Nevertheless, optimization of  
19 processing conditions is essential to minimize degradation or loss of bioactive compounds in  
20 green coffee extract during spray drying (92). FD may provide superior physical stability  
21 depending on the protective agent, but is less attractive for large-scale production. On the other  
22 hand, nanoencapsulation and  $\beta$ -CD inclusion offer complementary routes for dispersion and



1 interaction control. Therefore, selection of encapsulation method selection should align with the  
2 intended application, required product profile, cost considerations, and scale of processing.

### 3 **4.2.3 Stability, release behavior, and bioavailability**

4 The central value proposition of microencapsulation for green coffee bioactives is to  
5 preserve stability during processing and storage while maintaining effective release and  
6 availability after incorporation into foods and digestion. In maltodextrin-based systems, Desai et  
7 al. (56) reported low-moisture powders with improved pH-solubility and EE > 70%, supporting  
8 longer shelf life and greater usability in food applications, the authors attributed these  
9 improvements to phenolic protection within the carrier matrix. Perdani et al. (50) similarly  
10 demonstrated functional improvements after encapsulation, with higher total phenols (53.33 mg  
11 GAE/g) and improved LC50 (71.10 ppm) compared with the non-encapsulated extract (total  
12 phenols 46.32 mg GAE/g; LC50 87.7), and suggested that the microencapsulated product  
13 outperformed some commercial supplements.

14 Stability outcomes also translate into performance in real food matrices and during  
15 storage. de Carmo et al. (51) reported that microencapsulated GCE incorporated into  
16 unfermented dairy beverages increased phenolic content and antioxidant properties and  
17 enabled controlled release throughout storage. Importantly, despite differences in encapsulation  
18 route, the authors found similar bioaccessibility after gastrointestinal digestion across  
19 encapsulation techniques, suggesting that multiple technological routes can still support efficient  
20 release and potential absorption.

21 Encapsulation can also preserve high antioxidant activity in waste-derived extracts,  
22 supporting sustainable ingredient development. Garcia-Solis et al. (52) achieved strong CGA



1 protection in GCWE microcapsules (EE 94.36%, CGA 18.86 mg/g) while maintaining antioxidant  
2 activity, indicating that spray drying with agave fructans and gum arabic can convert by-products  
3 into stable functional ingredients. Ali Husni et al. (53) reported that WPC-based spray-dried  
4 microparticles retained bioactivity (CGA 7.19%, IC<sub>50</sub> 374.53 µg/mL) while improving sensory  
5 quality through masking, highlighting a practical link between stability and consumer-relevant  
6 attributes.

7         Controlled release and long-term stability become more explicit at the nanoscale. Desai  
8 et al. (56) showed that nanoencapsulation produced nanoparticles (82.34 nm) with 70% EE and  
9 40% yield, with improved storage stability over 150 days and a digestion-relevant release profile  
10 in which 80% CGA was available in the intestine under simulated gastrointestinal conditions.

11         A key mechanism influencing functional bioavailability is the mitigation of undesired  
12 binding to food proteins. Budryn et al. (54) demonstrated that β-CD inclusion complexes reduced  
13 CHA–protein binding from 62.9–96.2% (free CGAs) to 0.23–0.48%, a dramatic shift that supports  
14 phenolic preservation during processing and suggests improved availability after gastrointestinal  
15 breakdown of the complexes. Overall, achieving antioxidant bioavailability after food  
16 incorporation remains a central goal, and economically feasible encapsulation routes are  
17 required for practical and sustainable implementation (55).

18         While these findings highlight the technological potential of microencapsulation in  
19 enhancing controlled release and improving bioaccessibility, such outcomes should be  
20 interpreted within the broader context of the inherent pharmacokinetic limitations of CGA.  
21 Despite improvements in stability and gastrointestinal release, CGA exhibits relatively low oral  
22 bioavailability, as it is not efficiently absorbed in its intact form within the upper gastrointestinal



1 tract. Only a small fraction is absorbed in the small intestine, whereas a substantial proportion  
2 progresses to the colon, where it undergoes extensive biotransformation by the gut microbiota  
3 into lower molecular weight phenolic metabolites, including caffeic acid, ferulic acid, and other  
4 related phenolic acids (81,82). Consequently, the compounds detected in systemic circulation are  
5 predominantly these microbial-derived metabolites rather than the parent CGA molecule.

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

16 Across a range of carrier systems and processing approaches, the reported advantages  
17 consistently cluster into three main outcomes, namely enhanced storage stability through  
18 reduced moisture or water activity and better protection of phenolics, improved performance in  
19 food applications, including higher solubility, sensory masking, and compatibility with dairy  
20 matrices, and greater digestive availability via mechanisms such as controlled release or  
21 minimized protein interactions, as demonstrated for nanoencapsulation and  $\beta$ -cyclodextrin  
22 inclusion. Ultimately, however, cost-effectiveness remains a key determinant for successful



1 scale-up and real-world adoption. To provide a clearer overview, **Figure 5** illustrates the  
2 microencapsulation mechanism, showing how the wall matrix protects GCE bioactives.

3

#### 4 **5. Application of green coffee extract in food**

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

#### 12 **5.1 Bakery products**

13 Bakery and cereal systems represent one of the most frequently studied applications  
14 because green coffee extract can increase antioxidant capacity and, in certain cases, reduce  
15 undesirable processing by-products. Budryn et al. (54) investigated the enrichment of various  
16 products using green coffee extract at 0.25 to 1 g per 100 g, including gnocchi, sponge cake,  
17 bread, donuts, mayonnaise, marshmallows, caramel candies, and jellies. The addition of green  
18 coffee extract significantly increased antioxidant activity across products, with the strongest  
19 increase observed in sponge cake. In donuts, green coffee extract increased dough hardness and  
20 stickiness and also increased the hardness of fried donuts, which was attributed to covalent  
21 reactions between phenolic compounds and wheat flour proteins. The same study reported that  
22 the addition of 0.1 and 1 g per 100 g green coffee extract reduced acrylamide content in fried



1 donuts by 7 to 9% compared with the control, suggesting that antioxidant compounds in green  
2 coffee extract may suppress pathways involved in acrylamide formation during frying. Processing  
3 stability differed markedly between product types. In mayonnaise and jellies, phenolic  
4 compounds were relatively stable because these products are processed at low temperatures,  
5 while higher losses were found in bread, sponge cake, marshmallows, and caramel candies, which  
6 was linked to heat exposure and water evaporation during baking.

7         Similar outcomes were reported for bread fortification. Mukkundur Vasudevaiah et al.  
8 (57) found that adding 1.5% green coffee extract significantly increased total polyphenols,  
9 chlorogenic acid, radical scavenging activity, and antioxidant activity. Importantly, the authors  
10 noted that 1.5% was the highest level that enhanced bread functionality without a significant  
11 negative effect on taste. Sensory constraints become more apparent at higher incorporation  
12 levels of coffee-derived ingredients. Zain et al. (58) investigated bread fortified with ground  
13 coffee bean powder at 3%, 5%, and 7% and reported increased phenolic content and antioxidant  
14 properties, but odour and taste acceptability decreased at higher concentrations due to greenish  
15 crust development and off-flavour formation. The 3% level provided the best balance between  
16 functional enhancement and sensory quality. A sustainability-oriented approach was reported by  
17 Desai et al. (59), who valorized green coffee spent to produce cookies enriched with prebiotic  
18 oligosaccharides. Roasted green coffee spent improved cookie acceptability at 10 to 12%  
19 compared with unroasted material, which produced more greenish color and a harder texture,  
20 reinforcing that color and texture are recurring limitations in baked systems.

21         Taken together, bakery and cereal matrices demonstrate both the benefits and trade-offs  
22 of green coffee extract. Phenolic compounds can enhance antioxidant activity and may reduce



1 acrylamide, yet protein binding and thermal exposure can shift texture and accelerate phenolic  
2 losses, making dose optimization and processing considerations critical.

### 3 **5.2 Dairy products and dairy-based beverages**

4 Dairy matrices highlight the role of protein–polyphenol interactions in determining  
5 product stability and texture. Dönmez et al. (60) incorporated green coffee extract at 0 to 2% into  
6 yoghurt and reported reduced syneresis during storage. The enriched yoghurt showed higher pH  
7 values than the control between 14 and 21 days, and the reduced syneresis was attributed to  
8 changes in protein–polyphenol interactions and pH-dependent casein behavior. Pimpley et al.  
9 (61) investigated yoghurt fortified with spray-dried green coffee extract at 0.5 to 2% and  
10 observed a decrease in pH with increasing extract concentration, linked to increased phenolic  
11 acid content. The authors also reported changes in syneresis tendency and significant differences  
12 in hardness, adhesiveness, and springiness compared with the control. Despite these  
13 physicochemical changes, sensory evaluation indicated higher overall acceptance during storage  
14 for yoghurts containing spray-dried green coffee extract.

15 Microencapsulation provides an additional strategy in dairy beverages to improve both  
16 stability and acceptability. doCarmo et al. (51) compared microencapsulated green coffee  
17 extracts produced by spray drying and freeze drying using polydextrose and inulin as  
18 encapsulating agents in unfermented dairy beverages. The fortified beverages exhibited higher  
19 total phenolic compounds and antioxidant activities, and inulin-encapsulated green coffee  
20 extract achieved the highest acceptability score. These findings support the view that dairy  
21 systems can accommodate green coffee extract effectively, but the outcome depends on how



1 phenolics shift protein network stability and pH behavior, while encapsulation can help mitigate  
2 direct sensory impact and protect bioactive compounds.

### 3 **5.3 Beverages**

4 Beverage applications emphasize bioaccessibility and consumer-facing sensory  
5 attributes. Sęczyk et al. (62) reported that green coffee extract fortification increased phenolic  
6 content and antioxidant activity in soymilk and that the beverage showed high in vitro  
7 bioaccessibility. Increasing the dose improved protein and starch digestibility, offering additional  
8 functional relevance beyond antioxidant enhancement. Sensory evaluation showed improved  
9 acceptance of aroma and texture but reduced acceptance of color, consistent with the limitation  
10 of green coloration in light-colored beverages. Encapsulation can improve beverage performance  
11 and acceptance, especially in dark, flavor-rich matrices. Indiarito et al. (63) incorporated  
12 encapsulated green coffee extract into cocoa drinks and reported concentration-dependent  
13 increases in total polyphenol content, flavonoid content, and antioxidant activity. The addition  
14 of up to 10% encapsulated green coffee extract remained acceptable to panelists across sensory  
15 attributes, indicating that encapsulation and matrix selection can support higher fortification  
16 levels without compromising sensory quality.

### 17 **5.4 Meat and seafood products**

18 In meat and seafood systems, green coffee extract is primarily utilized to slow lipid  
19 oxidation and improve microbial stability during storage. Parvathy et al. (64) incorporated green  
20 coffee extract at 1 to 1.5% into mackerel mince and reported reduced lipid oxidation and protein  
21 degradation during chill storage, with no negative impact on consumer acceptance of the final  
22 fish cake product. Meena et al. (65) evaluated chevon nuggets containing 5% green coffee extract



1 during 60 days of frozen storage and observed lower total plate count, psychrophilic count, yeast  
2 count, and mold count compared with the control. This improved microbial quality was  
3 attributed to the natural antioxidant and antimicrobial compounds present in green coffee  
4 extract, particularly chlorogenic acid derivatives, supporting its potential as a natural

### 5 **5.5 Lipid-rich foods, emulsions, and spreads**

6 Oil-based systems provide strong evidence for green coffee extract as a natural  
7 antioxidant alternative to synthetic additives. da Silva Polvarini et al. (66) investigated  
8 mayonnaise fortified with green coffee extract and reported that 1.5% increased antioxidant  
9 activity without altering pH and texture, while delaying oxidation as indicated by peroxide value.  
10 Microencapsulation further strengthens performance in lipid-rich foods by protecting actives and  
11 enabling sustained antioxidant action. Javadpour et al. (67) incorporated tragacanth–chitosan  
12 hydrogel microcapsules containing supercritical CO<sub>2</sub>-extracted green coffee antioxidants into  
13 margarine and reported improved oxidative stability during 90 days of storage, supported by  
14 lower peroxide and p-anisidine values and higher DPPH retention. Sensory evaluation showed  
15 comparable scores to a sample containing TBHQ, indicating that microencapsulated green coffee  
16 antioxidants can provide oxidative protection without compromising product acceptance.

### 17 **5.6 Flavor modification through phenolic–protein interactions**

18 Beyond preservation and nutritional enhancement, interactions between GCE phenolics  
19 and proteins can contribute to aroma development. Budryn et al. (55) studied the possibility of  
20 phenolic–protein interactions in food products including bread, cookies, caramel cottage cheese,  
21 nutty filling, and stuffing products. The authors reported that adding GCE together with protein  
22 hydrolysates promoted the formation of volatile components, particularly furans and pyrazines,



1 which positively affected aroma. They also noted that chlorogenic acid in encapsulated form may  
2 reduce degradation but can also reduce interaction with proteins, lowering the formation of  
3 aroma-related volatile substances. This finding highlights a practical formulation trade-off:  
4 stabilizing phenolics through encapsulation can be beneficial for retention, but it may reduce  
5 interaction-driven aroma formation in protein-containing foods where that interaction is  
6 desirable.

### 7 **5.7 Integrated interpretation and limitations**

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

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

22



## 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 (83,84). 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



1 with at least five concentration points and a documented limit of detection and limit of  
2 quantification is considered minimum practice for analytical rigor.

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

13 Key take home findings from this review are summarized below:

- 14 ● Green coffee extract is consistently rich in phenolic compounds, especially CGA, which  
15 underpin strong antioxidant activity.
- 16 ● Human studies suggest modest benefits for body weight and glycemic outcomes, but  
17 effects on lipids and liver markers are inconsistent across trials.
- 18 ● Differences in extraction, roasting status, and formulation lead to large variation in  
19 chemical profiles, making comparisons across studies difficult.
- 20 ● Encapsulation can improve stability and handling, and may support bioaccessibility  
21 through controlled release, but performance depends on wall materials and processing  
22 conditions.



- 1       • Safety assessment is generally reassuring at commonly used doses, yet long term data  
2           and standardized reporting of adverse events are still limited.

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

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

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

16      Third, sustainability must be assessed at scale rather than inferred from laboratory practice.  
17      Life cycle and techno economic analyses comparing solvent intensive methods with greener  
18      alternatives are essential, alongside strategies for solvent recovery, energy efficiency, and  
19      valorization of processing by products. Fourth, stability and efficacy should be demonstrated in  
20      real food systems. Research should test green coffee extract and encapsulated forms in diverse  
21      matrices such as beverages, dairy or plant based products, bakery items, and lipid rich foods,



1 under realistic processing and storage conditions. Outcomes should include retention of key  
2 bioactives, sensory impact, and bioaccessibility after digestion.

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

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## 12 **Disclosure Statement**

13 The authors report there are no competing interests to declare.

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1 **Table 1 Summary of bioactive compound ranges in green coffee extract**

Sample of coffee	Caffeine (%w/w)	CGA (% w/w)	CGA (mg/L)	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	

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

Roasting Degree	Roasting Temperature (°C)	Caffeine (mg/L)	CGA (mg/L)	Reference
Green coffee	-	166.72 ± 5.08	543.23 ± 8.92	(39)
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	

4





1 **Table 3** Summary of evidence on GCE study design dose and key health outcomes

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	<ul style="list-style-type: none"> <li>● GCE dose : 25 – 10 mg/day</li> <li>● Durations : 4 - 12 weeks</li> </ul>	BMI decreased (WMD –0.403 kg/m <sup>2</sup> ), no significant change in body weight or waist circumference overall, stronger effect when baseline BMI ≥25 kg/m <sup>2</sup> , interventions <4 weeks showed no effect	(41)
Randomized, double-blind, placebo-controlled trial	People with metabolic syndrome, having BMI >25 kg/m <sup>2</sup>	50 recruited, 43 completed	<ul style="list-style-type: none"> <li>● GCE dose : 800 mg/day</li> <li>● Durations : 8 weeks</li> </ul>	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	(42)
Randomized, double-blind, placebo-controlled trial	Patients with NAFLD, aged 20-60 years with BMI ranged 25–35 kg/m <sup>2</sup>	48 total, 24 per arm	<ul style="list-style-type: none"> <li>● GCE dose : 400 mg/day</li> <li>● Durations : 8 weeks</li> </ul>	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	(43)
Randomized, double-blind, placebo-controlled trial	44 patients with T2D and overweight/obesity, having a history of diabetes between 1 and 10	44 total, 22 per arm	<ul style="list-style-type: none"> <li>● GCE dose : 800 mg/day</li> <li>● Durations : 10 weeks</li> </ul>	Body weight and BMI decreased, SBP decreased, TG decreased, HDL increased, hs-CRP decreased, FBG reduction marginal, no	(44)

	years, having BMI of 25–35 kg/m <sup>2</sup>			effect on insulin, HOMA-IR, LDL, total cholesterol, DBP	
Systematic review and meta-analysis of RCTs	Individuals aged ≥ 18 years old	13 publications, 17 RCTs	<ul style="list-style-type: none"> <li>● GCE dose variations : 400 – 6000 mg/day</li> <li>● Durations : 4 – 8 weeks</li> </ul>	TC decreased (WMD –4.51 mg/dL), LDL-C decreased (WMD –4.38 mg/dL), HDL-C increased (WMD +2.63 mg/dL), TG change non-significant	(45)
Systematic review and meta-analysis of RCTs	Adult population's ≥ 18 and ≤65 y with or without disease	27 articles	<ul style="list-style-type: none"> <li>● GCE dose variations : 46 – 6000 mg/day</li> <li>● Durations : 8 – 11 weeks</li> </ul>	FBS decreased, insulin decreased, TG decreased, HDL increased, no significant change in HOMA-IR, LDL, CRP	(46)

- 1
- 2 \*) BMI = *Body Mass Index*; WMD = *Weighted Mean Difference*; SBP = *Systolic Blood Pressure*; DBP = *Diastolic Blood Pressure*; FBS =
- 3 *Fasting Blood Sugar*; FBG = *Fasting Blood Glucose*; HOMA-IR = *Homeostatic Model Assessment of Insulin Resistance*; HDL = *High-*
- 4 *Density Lipoprotein*; HDL-C = *High-Density Lipoprotein Cholesterol*; LDL = *Low-Density Lipoprotein*; LDL-C = *Low-Density Lipoprotein*
- 5 *Cholesterol*; TC = *Total Cholesterol*; TG = *Triglycerides*; CRP = *C-Reactive Protein*; hs-CRP = *High-Sensitivity C-Reactive Protein*.





1 **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)	<ul style="list-style-type: none"> <li>● Caffeine : 40.06% of the extract</li> <li>● CGA : 46.41 % of the exreact</li> </ul>	Water	<ul style="list-style-type: none"> <li>● Time : 5 min</li> <li>● Temperature : 50°C</li> <li>● Energy : 800 W</li> </ul>	Low toxicity, food-grade, minimal solvent hazard, electricity demand moderate.	(68)
2	Microwave assisted extraction (MAE)	<ul style="list-style-type: none"> <li>● Caffeine : 38.10% of the extract</li> <li>● CGA : 61.87 % of the exreact</li> </ul>	Methanol	<ul style="list-style-type: none"> <li>● Time : 5 min</li> <li>● Temperature : 50°C</li> <li>● Energy : 800 W</li> </ul>	High toxicity and not food-grade, stricter handling and waste treatment required, higher environmental/health burden.	
3	Microwave assisted extraction (MAE)	<ul style="list-style-type: none"> <li>● Caffeine : 34.08% of the extract</li> <li>● CGA : 55.31 % of the exreact</li> </ul>	Ethanol	<ul style="list-style-type: none"> <li>● Time : 5 min</li> <li>● Temperature : 50°C</li> <li>● Energy : 800 W</li> </ul>	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)	<ul style="list-style-type: none"> <li>● Caffeine : 7.89 mg/g of the extract</li> <li>● CGA : 28.62 mg/g of the extract</li> </ul>	Mixture of water and Natural Deep Eutectic Solvents (NADES)	<ul style="list-style-type: none"> <li>● Time : 30 min</li> <li>● Temperature : room temperature</li> <li>● Energy : not reported</li> </ul>	Green solvent claim supported (low toxicity and biodegradable), however, NADES viscosity and added electricity may shift impacts to energy and downstream processing.	(69)

5	Supercritical CO <sub>2</sub> extraction (scCO <sub>2</sub> )	<ul style="list-style-type: none"> <li>● Caffeine : 7 mg/g of the extract</li> <li>● CGA : 0.48 mg/g of the extract</li> </ul>	CO <sub>2</sub> 99% and mixture of CO <sub>2</sub> and ethanol 5% (wt/wt)	<ul style="list-style-type: none"> <li>● Temperature : 50°C</li> <li>● High pressure : 35.2 MPa</li> </ul>	Low-toxicity solvent with minimal residues and recyclable CO <sub>2</sub> , but high energy demand due to high-pressure operation; co-solvents may add solvent handling and recovery steps.	(70)
6	Subcritical Water Extraction (SWE)	<ul style="list-style-type: none"> <li>● Caffeine : 0.395 mg/mL extract</li> <li>● CGA : not reported</li> </ul>	Water	<ul style="list-style-type: none"> <li>● Time : 27.4 min</li> <li>● Temperature : 162.4°C</li> <li>● Underhigh pressure</li> </ul>	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	(71)
7	Subcritical water hydrolysis (SCWH)	<ul style="list-style-type: none"> <li>● Caffeine : 2519.63 mg/g of extract</li> <li>● CGA : 7017.38 mg/g of extract</li> </ul>	Water	<ul style="list-style-type: none"> <li>● Time : 30 min</li> <li>● Temperature : 180°C</li> <li>● Pressure : 3 MPa</li> </ul>	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.	(72)
8	Subcritical water hydrolysis (SCWH)	<ul style="list-style-type: none"> <li>● Caffeine : 2211.69 mg/g of extract</li> <li>● CGA : 5803.21 mg/g of extract</li> </ul>	Water	<ul style="list-style-type: none"> <li>● Time : 43 min</li> <li>● Temperature : 220°C</li> <li>● Pressure : 6 MPa</li> </ul>	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 recovery and management of aqueous effluents.	
9	Enzyme-Assisted Aqueous Extraction Process (EAEP)	<ul style="list-style-type: none"> <li>● Caffeine : 1194.48 mg/100 g extract</li> <li>● CGA : 6194.13 mg/100 g extract</li> </ul>	Mixture of water and enzyme	<ul style="list-style-type: none"> <li>● Time : 60 min</li> <li>● Temperature : 50°C</li> <li>● pH : 7.0</li> </ul>	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.	(73)
10	Aqueous Extraction Process (AEP)	<ul style="list-style-type: none"> <li>● Caffeine : 1260.22 mg/100 g extract</li> <li>● CGA : 6335.32 mg/100 g extract</li> </ul>	Water	<ul style="list-style-type: none"> <li>● Time : 60 min</li> <li>● Temperature : 50°C</li> <li>● pH : 7.0</li> </ul>	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	<ul style="list-style-type: none"> <li>● Caffeine : 1.82 % of extract</li> <li>● CGA : 36.24% of extract</li> </ul>	Hexane, ethyl acetat, water, chloroform	<ul style="list-style-type: none"> <li>● Time : 25 hours</li> <li>● Temperature : 70°C</li> </ul>	High solvent and energy demand due to long extraction time and heating, use of volatile/toxic solvents (especially chloroform and	(57)



					hexane) increases health and waste-treatment burdens, and solvent recovery is required to reduce emissions and environmental impact.	
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**Table 5** summaries of methods and types of carriers in the GCE microencapsulation process

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.	(49)
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.	(74)
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.	(51)
4	Freeze drying	Polydextrose (PD), inulin (IN)	Frozen temperature: -20°C Frozen time: 48 hours Dried temperature: -50°C	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.	(51)

			Dried pressure : <200 $\mu$ mHg Dried time: 5 days		
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.	(52)
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 $\mu$ m, 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.	(53)
7	Nano spray drying	Maltodextrin	Feed flow rate: 300 mL/h Drying air flow rate: 60 m <sup>3</sup> /h	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.	(56)
8	Inclusion complex formation	$\beta$ -Cyclodextrin ( $\beta$ -CD)	Solvent used: Water Temperature: 50°C Time: 2 hours	On molar ratio in final complex: $\beta$ -CD:CGA = 1:1, complexation efficiency was maximized, effectively limiting interactions between CGAs and food proteins (whey, egg white, and soy protein isolates)	(54)





			Precipitation: 24 hours at 0°C Centrifugation: 20 min at 18,000xg and 4°C	
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1 \*)IT: inlet temperature; OT: outlet temperature

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**Table 6** Integrated overview of GCE applications across food systems

Food Type	Food Matrix	Dose of GCE	Functional Roles	Key Outcomes	Sensory Considerations	Stability Considerations	Reference
Bakery	Gnocchi, sponge cake, bread, donuts, mayonnaise, marshmallows, caramel candies, jellies (multi-product study)	0.25g – 1g/100g 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	(55)
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	(57)
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	(58)

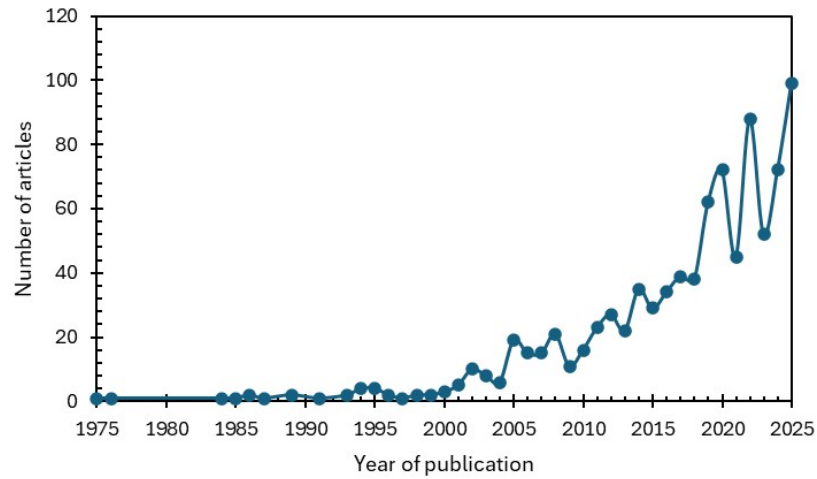
Bakery	Cookies	10 – 12%	Prebiotic potential, fiber enrichment	Nutritional profile improved, ash increased, protein increased, fat increased, dietary fiber increased, oligosaccharide contribution supported prebiotic value	Unroasted GCS produced greener color and harder texture, roasted GCS improved acceptability	Ingredient pre-treatment influences final quality in baked systems	(59)
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	(60)
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	(61)
Dairy beverage	Unfermented dairy beverages	10g/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	(51)
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	(62)



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	(63)
Meat, seafood	Makarel 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	(64)
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 $-18 \pm 2^{\circ}\text{C}$	Sensory was not the main emphasis	Frozen storage supports antimicrobial and antioxidant function	(65)
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	(66)
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	(67)

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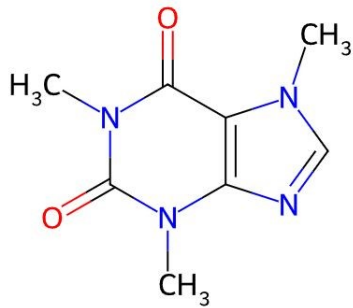


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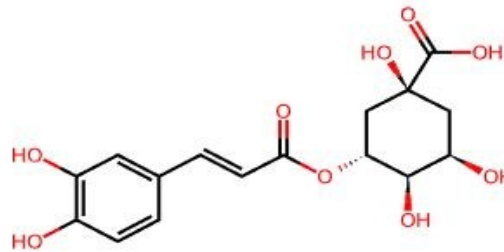
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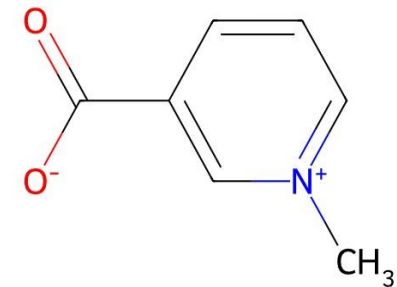
**Figure 1** Number of scientific publications on green coffee processing in Scopus under the subarea of agricultural science and process engineering.



**Figure 2** Chemical structure of caffeine



**Figure 3** Chemical structure of CGA



**Figure 4** Chemical structure of trigonelline





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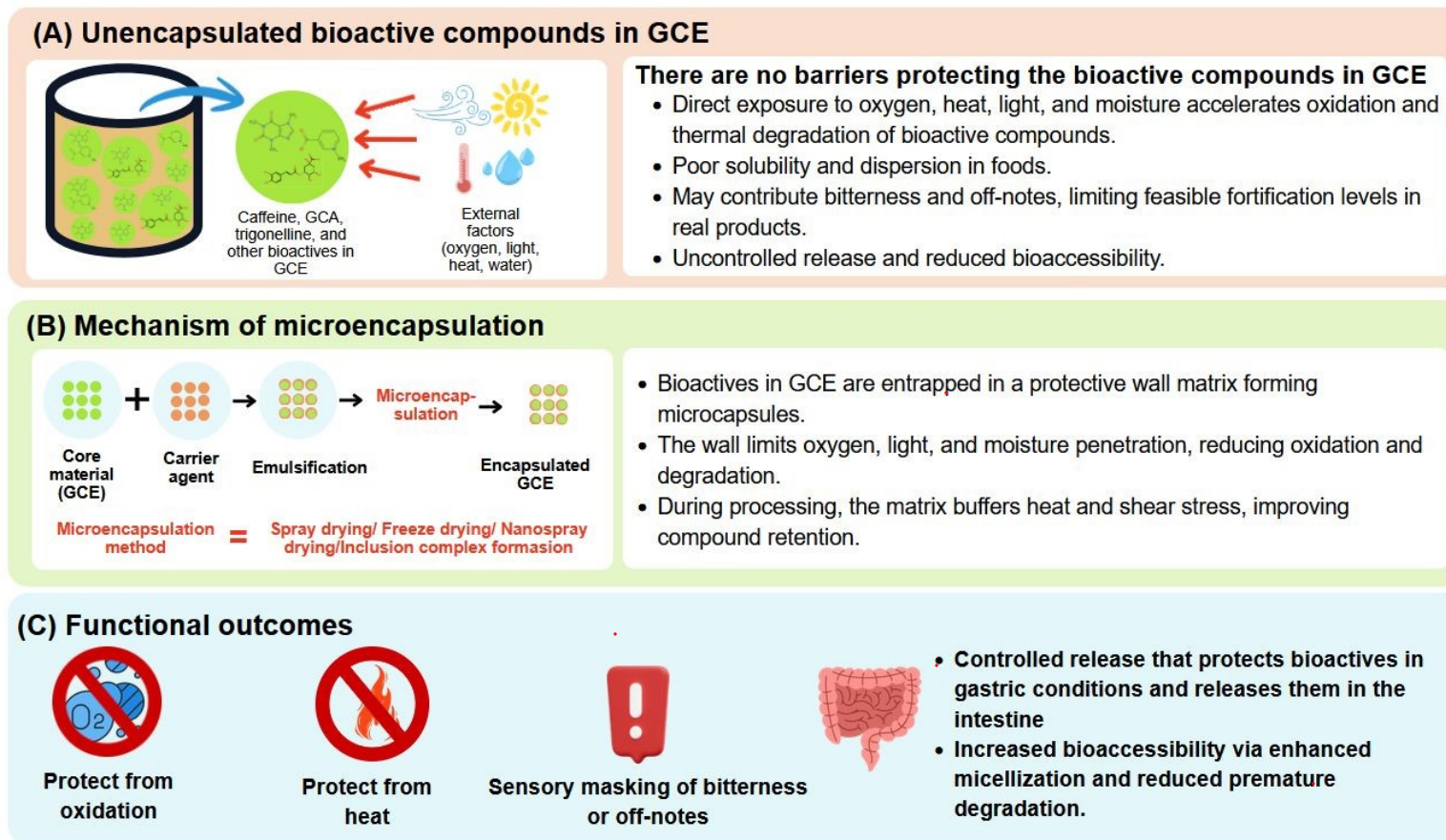


Figure 5 Microencapsulation Mechanism and Functional Benefits

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## Data Availability Statements

[View Article Online](#)  
DOI: 10.1039/D5FB00768B

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

