VALORIZATION OF SPENT COFFEE GROUNDS: BIOACTIVE RECOVERY, HEALTH BENEFITS, AND SUSTAINABLE APPLICATIONS

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ABSTRACT

Spent coffee grounds (SCGs), a major by-product of the coffee industry, are increasingly recognized for their rich profile of bioactive compounds and diverse functional properties. This review synthesizes current research on the chemical composition of SCGs, highlighting key constituents such as phenolic acids, flavonoids, dietary fiber, and melanoidins. Advanced extraction techniques, including supercritical CO_2 and ultrasound-assisted methods, have demonstrated effectiveness in maximizing the recovery of these bioactives. The health benefits of SCGs are evident in their strong antioxidant and anti-inflammatory activities, melanin inhibition relevant to cosmetic applications, and notable prebiotic potential that supports gut microbiota and short-chain fatty acid production. Beyond health, SCGs exhibit utility in industrial sectors, including food formulation, cosmeceuticals, pharmaceuticals, wastewater treatment, and environmental remediation. Emerging applications, such as enzyme immobilization and adsorbent material development for heavy metal removal, signal promising directions for future research. However, challenges such as regulatory approval, standardization, and consumer acceptance remain significant barriers to commercialization. This review concludes that valorizing SCGs represents a sustainable and economically viable strategy for circular bioeconomy models, and calls for further *in vivo* and clinical studies to validate their functional efficacy in human health and industrial settings.

Keywords: *spent coffee grounds, bioactive compounds, antioxidant, prebiotics, cosmetics, environmental application, functional food, circular economy*

1. INTRODUCTION

Coffee is among the most widely consumed beverages globally, standing second only to water and tea in popularity and commercial significance. Consequently, significant quantities of coffee processing by-products are generated annually, including coffee husks, pulp, silver skins, and notably SCGs (Janissen & Huynh, 2018). The global coffee sector is estimated to produce approximately 6 million tonnes of SCGs annually, posing both a food-waste burden and environmental challenge when managed through conventional disposal routes (Ramón-Gonçalves et al., 2019; Kourmentza et al., 2018; C. Andrade et al., 2022). In parallel with circular-economy goals, SCGs are increasingly recognized as a renewable feedstock for value-added products.

Chemically, SCGs are enriched in bioactive constituents - notably chlorogenic acids, caffeic and ferulic acids, flavonoids, caffeine, melanoidins, and mannans - that underpin antioxidant, anti-inflammatory, and antimicrobial activities (Ramón-Gonçalves et al., 2019; Campos-Vega et al., 2015). For example, chlorogenic and p-coumaric acids have been identified as major contributors to SCG antioxidant capacity (Ramón-Gonçalves et al., 2019). Recent work also explores how extraction conditions modulate the recovery and bioactivity profile of these compounds, reinforcing the need for optimized, green methodologies (Andrade et al., 2012; Karprakhon et al., 2025).

Beyond health-related functions, the composition and porosity of SCGs open pathways across multiple domains. In environmental remediation, SCG-derived materials act as efficient adsorbents for heavy metals and organic pollutants in wastewater (Janissen & Huynh, 2018; Fujii & Kondo, 2018; Campbell et al., 2024). In bioenergy, SCGs support bioethanol and biogas production within biorefinery schemes (Karmee, 2017; Zabaniotou & Kamaterou, 2019; Mahmoud et al., 2022). Within foods, SCG ingredients have been incorporated into bakery matrices to deliver dietary fiber, antioxidants, and distinctive flavor notes; their extracts also show promise for improving food safety and shelf life via antimicrobial effects attributed to polyphenols and melanoidins (Campos-Vega et al., 2015; Jiménez-Zamora et al., 2015). In health-oriented applications, bioactives from coffee by-products - including SCGs - exhibit cytoprotective,

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anti-aging, and metabolic benefits, as exemplified by protective effects reported for coffee silverskin extracts with compositional parallels to SCG extracts (Iriondo-DeHond et al., 2016; Campos-Vega et al., 2015).

Despite this breadth, several bottlenecks still constrain full-scale valorization: variability in SCG composition across origins and processing routes; the need to standardize and green extraction/conversion technologies; gaps in mechanistic understanding of bioactivity; techno-economic and scale-up hurdles; and regulatory constraints for food, cosmetic, and pharmaceutical uses (Karmee, 2017; Iriondo-DeHond et al., 2019; Zabaniotou & Kamaterou, 2019). Addressing these challenges is essential to unlock SCG's economic and environmental value within a circular bioeconomy. Accordingly, this review synthesizes recent advances on SCG valorization, emphasizing bioactive profiles, health-promoting properties, and cross-sector applications, while critically outlining current limitations and research gaps to guide future development.

2. CONTENTS

2.1. Research content and methodology

This review employed a structured scoping methodology incorporating systematic elements in line with PRISMA-ScR guidelines. Relevant literature published from 2000 to 2025 was retrieved from PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar using a targeted search strategy. Keywords combined terms for spent coffee grounds (SCGs) or coffee by-products with: (1) composition and bioactive profiling; (2) green/advanced extraction techniques (e.g., SFE, SWE, UAE, MAE, EAE, fermentation/biotransformation); (3) health-related bioactivities (e.g., antioxidant, anti-inflammatory, prebiotic, antimelanogenic); and (4) industrial applications (e.g., food, cosmetics, environmental remediation, materials, energy).

Compared with previous reviews, this study emphasizes the integration of emerging sustainable extraction technologies and expanding biomedical/environmental applications of SCGs. A qualitative synthesis was performed across five thematic axes: (1) bioactive composition; (2) green extraction methods; (3) functional health benefits; (4) industrial applicability; and (5) research gaps and commercialization challenges. This framework highlights both the versatility of SCGs and unresolved issues related to safety, standardization, and upscaling.

Figure 1 provides a schematic overview of the valorization concept and mechanisms for SCGs within a circular bioeconomy. From SCGs, advanced extraction techniques - supercritical CO_2, ultrasound, microwave, subcritical solvents, and solid-phase extraction - are employed to recover key bioactives (phenolic acids, flavonoids, melanoidins, and dietary fiber). These constituents underpin reported health benefits (antioxidant, anti-inflammatory, prebiotic support of gut microbiota, and melanin inhibition for cosmetic use) and translate into sustainable applications, including functional foods, pharmaceuticals/cosmeceuticals, wastewater treatment with heavy-metal adsorbents, and bioenergy (biogas). The diagram highlights the upgrade of SCGs from a by-product to a functional, commercially promising feedstock; the following sections elaborate each component in detail.

Figure 1. Valorization of spent coffee grounds: extraction of bioactive compounds, health benefits, and sustainable applications

2.2 Chemical composition and bioactive compounds from SCGs

SCGs, the main by-product of the coffee brewing process, retain a significant proportion of the original bean's macronutrients and bioactive compounds. Their complex chemical matrix includes carbohydrates, proteins, lipids, dietary fiber, and various phytochemicals such as caffeine, chlorogenic acids, and melanoidins. These constituents confer multiple functional properties - antioxidant, anti-inflammatory, antimicrobial, and prebiotic - that support SCGs' potential applications across the food, cosmetic, pharmaceutical, and environmental sectors. Table 1 summarizes the major components and key bioactive compounds identified in SCGs, along with their typical concentration ranges and associated health-promoting or functional roles.

2.2.1. General chemical composition

SCGs are generated as the main solid waste product from coffee brewing processes, constituting approximately 50% of the original coffee beans (Janissen & Huynh, 2018). The chemical composition of SCGs reflects a complex matrix of macronutrients and bioactive compounds, including polysaccharides, lignin, lipids, proteins, minerals, and phytochemicals such as caffeine and polyphenols. According to comprehensive compositional analyses, SCGs generally contain 45–55% carbohydrates (mainly cellulose and hemicellulose), 11–20% lipids, 13–17% proteins, and 1–2% caffeine, along with significant amounts of chlorogenic acids, melanoidins, and other antioxidant compounds (Campos-Vega et al., 2015; Iriondo-DeHond et al., 2019).

2.2.2. Phenolics, flavonoids, dietary fiber, and antioxidants

Phenolic compounds and flavonoids: Phenolic compounds represent one of the major classes of bioactive phytochemicals found in SCGs, known for their antioxidant, anti-inflammatory, and antimicrobial properties (Ballesteros et al., 2017; Ramón-Gonçalves et al., 2019). Major phenolic compounds identified include chlorogenic acid and its derivatives (such as caffeic, ferulic, and p-coumaric acids), which contribute significantly to the antioxidant activity and health-promoting potential of SCGs (Panusa et al., 2013; Hikichi et al., 2017). Flavonoids, a subgroup of phenolics, have also been detected in lower concentrations, enhancing the overall bioactivity profile of SCGs (Martinez-Saez & del Castillo, 2019; Vázquez-Sánchez et al., 2018; Fernandes et al., 2017).

Dietary fiber: SCGs are recognized as an excellent source of dietary fiber, primarily composed of insoluble fibers such as cellulose, hemicellulose, and lignin, as well as smaller amounts of soluble fibers including pectins (Ballesteros et al., 2017; Panzella et al., 2017). Dietary fibers from SCGs exhibit significant prebiotic activity, enhancing gut microbiota composition, and subsequently contributing to gut health and immunological improvements (Jiménez-Zamora et al., 2015). Furthermore, these dietary fibers also possess antioxidative properties, potentially reducing the risk of chronic diseases by mitigating oxidative stress and inflammation (López-Barrera et al., 2016).

Antioxidant compounds: The antioxidant properties of SCGs are attributed largely to their phenolic content, particularly chlorogenic acids, caffeic acid, ferulic acid, and melanoidins, which are formed during coffee roasting and brewing processes (Hikichi et al., 2017). SCGs-derived antioxidants have demonstrated the ability to scavenge free radicals and reduce oxidative stress, which could mitigate the development of chronic diseases such as cancer, cardiovascular diseases, and neurodegenerative disorders (Ballesteros et al., 2017; Martinez-Saez et al., 2017). Recent research further emphasized the role of SCGs antioxidants in food preservation, enhancing shelf-life and safety (Ballesteros et al., 2017).

Table 1. The major composition and bioactive compounds from SCGs

Component/Bioactive Compound	Range (%) / Amount	Health Functionality	References
Carbohydrates (mainly cellulose, hemicellulose)	45–55%	Prebiotic effect, dietary fiber, gut health	Campos-Vega et al., 2015; Janissen & Huynh, 2018
Lipids	11–20%	Energy source, contains beneficial fatty acids	K. S. Andrade et al., 2012; Ramón-Gonçalves et al., 2019
Proteins	13–17%	Nutritional value, bioactive peptides	Campos-Vega et al., 2015
Caffeine	1–2%	Stimulant, antioxidant	Campos-Vega et al., 2015; Iriondo-DeHond et al., 2019
Chlorogenic acids	2–8 mg/g	Antioxidant, anti-inflammatory	Panusa et al., 2013; Hikichi et al., 2017

Component/Bioactive Compound	Range (%) / Amount	Health Functionality	References
Caffeic acid	0.5–2 mg/g	Antioxidant, anti-inflammatory	Ballesteros et al., 2017
Ferulic acid	0.1–0.5 mg/g	Antioxidant, skin health	Rodrigues et al., 2023
Melanoidins	Variable	Antioxidant, gut modulation	Tores de la Cruz et al., 2019
Flavonoids	Trace – 1 mg/g	Antioxidant, anti-inflammatory	Martinez-Saez & del Castillo, 2019
Dietary fiber (total)	50–60%	Gut microbiota modulation, metabolic health	Jiménez-Zamora et al., 2015; López-Barrera et al., 2016
Short-chain fatty acids (from fermentation)	N/A (fermentation product)	Colon health, anti-inflammatory	Panzella et al., 2017; López--Barrera et al., 2016
Polyphenols (total)	20–50 mg GAE/g	Antioxidant, anti-inflammatory	Ramón-Gonçalves et al., 2019; Ballesteros et al., 2017

2.3. Sustainable extraction and fermentation-based approaches for bioactive compounds recovery from SCGs

The extraction methods play a critical role in obtaining bioactive compounds efficiently and sustainably from SCGs. Recent studies have focused on optimizing extraction conditions to maximize yields and bioactivity, emphasizing green and sustainable methodologies (Bhadange et al., 2024). Table 2 provides a comparative summary of these extraction techniques, highlighting their principles, target compounds, advantages, and current limitations.

2.3.1. Supercritical fluid extraction with CO_2

Supercritical fluid extraction (SFE) using carbon dioxide (CO_2) has been widely recognized as an efficient, selective, and environmentally friendly technique to recover high-value lipophilic bioactives from SCGs. Operating at moderate temperatures and high pressures, SFE preserves thermolabile compounds while yielding solvent-free extracts, making it particularly attractive for applications in food, cosmetics, and pharmaceuticals (Couto et al., 2009; K. S. Andrade et al., 2012). SFE of SCGs typically recovers lipids rich in fatty acids such as palmitic (C16:0) and linoleic acid (C18:2), which constitute up to 70% of the extracted oil (Couto et al., 2009). Studies have shown that SCGs extracted with supercritical CO_2 under optimized conditions (e.g., 25 MPa and 323 K) can yield up to 15.4% oil content (Couto et al., 2009), with high antioxidant activity attributable to co-extracted chlorogenic acids and caffeine (K. S. Andrade et al., 2012). The addition of co-solvents like ethanol further enhances the extraction efficiency and selectivity, enabling recovery of more polar compounds and improving antioxidant profiles (K. S. Andrade et al., 2012; Ramón-Gonçalves et al., 2019). Kinetic modeling of extraction data has supported mass transfer-controlled behavior and facilitated scale-up strategies for industrial implementation (Couto et al., 2009). Altogether, SFE represents a green valorization pathway for SCGs within the circular bioeconomy.

2.3.2. Solvent extraction methods

Traditional solvent extraction methods, including water, ethanol, methanol, and acetone extractions, remain prevalent due to their simplicity and economic feasibility. Among these solvents, aqueous and ethanolic extractions have demonstrated effectiveness in obtaining phenolics, chlorogenic acids, and caffeine from SCGs (Panusa et al., 2013; Hikichi et al., 2017). However, concerns regarding solvent residues, toxicity, and environmental impact prompt research toward more sustainable alternatives like ethanol-water mixtures and deep eutectic solvents (Ballesteros et al., 2017; Hikichi et al., 2017).

2.3.3. Solid-state fermentation

Solid-state fermentation (SSF) has recently gained attention as a promising biotechnological approach to enhance the nutritional and functional properties of SCGs. SSF involves the cultivation of microorganisms - typically fungi or bacteria - on moist solid substrates without free-flowing water. This technique has been shown to significantly increase the bioavailability of phenolic compounds and boost antioxidant capacity in agro-industrial by-products.

Although research specifically applying SSF to SCGs is still emerging, studies have demonstrated that fermentation of coffee by-products can lead to the generation of additional bioactive metabolites, including organic acids and short-chain fatty acids with prebiotic effects. For example, Panzella et al. (2017) reported that enzymatic hydrolysis followed by microbial fermentation enhanced the antioxidant and prebiotic potential of hydrolyzed SCGs in a simulated colon model (Panzella et al., 2017). Similarly, López-Barrera et al. (2016) observed that SCGs supported microbial metabolism capable of producing beneficial compounds during fermentation (López-Barrera et al., 2016).

These findings support the application of SSF as a cost-effective and eco-friendly strategy to valorize SCGs for use in functional food and nutraceutical formulations, aligning with circular bioeconomy principles.

2.3.4. Emerging green techniques

Novel sustainable approaches, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzyme-assisted extraction (EAE), have recently been explored to optimize the recovery of bioactive compounds from SCGs. UAE and MAE methods effectively reduce extraction time and solvent consumption while increasing extraction yields of phenolics, caffeine, and antioxidants (Ballesteros et al., 2017; Janissen & Huynh, 2018). EAE specifically targets polysaccharide breakdown and enhances the release of bound phenolics and bioactive fibers, showing promise as a sustainable extraction method (Panusa et al., 2013; Solomakou et al., 2022).

Table 2. Sustainable extraction and fermentation-based approaches for bioactive compounds recovery from SCGs

Extraction method	Description	Key compounds extracted	Advantages	References
Supercritical fluid extraction (SFE) with CO_2	Uses CO_2 at high pressure and moderate temperature to extract lipophilic bioactives.	Lipids (palmitic acid, linoleic acid), caffeine, chlorogenic acids	Solvent-free, preserves thermolabile compounds, high selectivity and antioxidant yield	Couto et al., 2009; K. S. Andrade et al., 2012; Ramón-Gonçalves et al., 2019
Solvent extraction	Utilizes solvents like ethanol, methanol, acetone, or water to extract polar compounds.	Phenolics, caffeine, chlorogenic acids	Simple, cost-effective, widely used in research	Panusa et al., 2013; Hikichi et al., 2017; Ballesteros et al., 2017
Solid-state fermentation (SSF)	Employs microbes on moist SCGs to enhance bioactivity and produce new metabolites.	Phenolics, SCFAs, antioxidants	Increases bioavailability and antioxidant potential, low-cost and sustainable	Panzella et al., 2017; López--Barrera et al., 2016
Emerging green techniques (UAE, MAE, EAE)	Includes ultrasound, microwave, and enzyme-assisted extraction to improve yield and sustainability.	Phenolics, caffeine, antioxidants, fibers	Eco-friendly, time-efficient, enhances extraction of bound compounds	Ballesteros et al., 2017; Janissen & Huynh, 2018; Solomakou et al., 2022

In conclusion, extraction and bioprocessing routes exhibit distinct performance profiles. Supercritical CO_2 affords high selectivity for lipophilic constituents (oils, diterpenes, caffeine) with negligible solvent residues, but requires substantial capital investment and is sensitive to feedstock moisture. UAE shortens processing time and energy demand while enhancing phenolic yields, yet risks co-extraction of impurities and necessitates careful solvent and scale-up optimization. Solid-state fermentation can biosynthesize or transform metabolites and elevate total phenolics/antioxidant capacity; however, outcomes depend on microbial strain, water activity, and downstream purification. Broadly, SFE is optimal for lipophiles, UAE for phenolic recovery, and SSF for augmenting bioactivity. Reported discrepancies often reflect heterogeneity in moisture content, particle size, pretreatments, and operating parameters across studies.

2.4. Bioactive properties and health benefits of SCGs

2.4.1. Antioxidant activity

SCGs, a major by-product of coffee brewing, are increasingly recognized as a rich source of bioactive compounds with notable antioxidant potential. Among these, phenolic acids such as chlorogenic acid, caffeic acid, and ferulic acid, as well as flavonoids, are the predominant contributors to the free radical scavenging activity of SCG extracts (del Castillo et al., 2018; Martinez-Saez et al., 2017; Martinez-Saez & del Castillo, 2019; Vázquez-Sánchez et al., 2018; Rodrigues et al., 2023). These compounds are known to mitigate oxidative stress by neutralizing reactive oxygen species (ROS), thereby reducing the risk of oxidative damage that contributes to chronic diseases, including cardiovascular disorders, neurodegeneration, and certain cancers.

Recent studies have highlighted innovative approaches to enhance the antioxidant properties of SCGs. Solid-state fermentation (SSF) using probiotic strains such as *Bacillus clausii* has been shown to significantly increase the total phenolic and flavonoid contents in SCGs. Janissen & Huynh, (2018) reported that SSF led to a 36% enhancement in total phenolic content and a 13% increase in total flavonoids, resulting in a 15% improvement in antioxidant activity as assessed by DPPH radical scavenging assays. These findings demonstrate the effectiveness of microbial biotransformation in amplifying the functional properties of SCG-derived bioactives.

Moreover, recent advancements in extraction technologies have further optimized the recovery of antioxidant compounds from SCGs. Subcritical water extraction (SWE), particularly when integrated with carbon dioxide as a co-solvent, has shown promise for achieving high extraction efficiency under environmentally benign conditions. For instance, a recent study reported that SWE at 198 °C with a solid-to-water ratio of 0.027 g/mL and an extraction duration of 60 min yielded 217.26 mg gallic acid equivalents (GAE) per gram dry weight and a DPPH scavenging activity of 23.28 μmol Trolox equivalents per gram dry weight (karprakhon et al., 2025). This method surpasses conventional solvent extraction both in terms of yield and eco-efficiency, positioning it as a sustainable approach for the valorization of SCGs.

Collectively, these results underscore the potential of SCGs as a low-cost, sustainable source of natural antioxidants. Their integration into functional foods, dietary supplements, and cosmeceutical formulations could provide a dual benefit: reducing industrial coffee waste while contributing to human health through the mitigation of oxidative stress.

2.4.2. Anti-inflammatory activity

Chronic inflammation plays a central role in the pathogenesis of numerous metabolic and degenerative diseases, including type 2 diabetes, cardiovascular disorders, and obesity-related complications. Recent research has revealed that SCGs, once regarded merely as waste, harbor phenolic compounds with significant anti-inflammatory properties. These bioactive compounds, primarily chlorogenic acid, caffeic acid, and their derivatives, exert modulatory effects on key cellular signaling pathways associated with inflammation, such as the nuclear factor-kappa B (NF-κB) and mitogen-activated protein kinase (MAPK) cascades (Choi et al., 2012; Iriondo-DeHond et al., 2019)

In vitro and in vivo studies have consistently demonstrated the potential of SCG-derived polyphenols to attenuate inflammatory responses. For instance, several recent research found that aqueous SCG extracts markedly reduced the expression of pro-inflammatory cytokines - including tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β) - in lipopolysaccharide (LPS)-stimulated RAW 264.7 macrophages (Angeloni et al., 2021; Ho et al., 2020). This suppression was attributed to the inhibition of NF-κB nuclear translocation and the downregulation of cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS) expression, two pivotal enzymes in the inflammatory response.

In a complementary study, Vázquez-Sánchez et al. (2018) demonstrated that polyphenol-rich SCG extracts alleviated inflammation-induced insulin resistance in 3T3-L1 adipocytes. The extract reduced TNF-α levels and restored insulin signaling by modulating the phosphorylation states of IRS-1 and Akt. This anti-inflammatory and insulin-sensitizing dual action highlights the potential of SCG bioactives in mitigating the metabolic dysregulation characteristic of obesity and type 2 diabetes.

Furthermore, the integration of SCG-derived anti-inflammatory agents into functional food matrices offers an attractive approach to developing dietary interventions for chronic disease prevention. As Iriondo-DeHond et al. (2016); Tores de la Cruz et al. (2019); Iriondo-DeHond et al. (2019) suggested, the stability and bioaccessibility of these compounds under simulated gastrointestinal conditions further support their applicability in food systems designed for health promotion.

Collectively, these findings underscore the value of SCGs as a bioactive resource for inflammation control. The anti-inflammatory efficacy, coupled with the abundance and availability of SCGs from global coffee consumption, presents a compelling case for their upcycling into nutraceuticals and functional food products targeting inflammation-related disorders.

2.4.3. Melanin inhibition and cosmetic applications

Hyperpigmentation disorders such as melasma, age spots, and post-inflammatory hyperpigmentation result from the overproduction and accumulation of melanin in the skin, often induced by ultraviolet (UV) exposure, hormonal imbalance, or oxidative stress. The global cosmetics industry has shown growing interest in identifying safer, natural alternatives to synthetic depigmenting agents, many of which (e.g., hydroquinone) pose long-term safety concerns. In this context, SCGs have emerged as a novel source of bioactives with potent antimelanogenic and photoprotective properties, making them promising candidates for incorporation into dermatological and cosmetic formulations (Rodrigues et al., 2023).

Recent studies demonstrate that extracts obtained from SCGs can significantly inhibit melanogenesis in vitro. Notably, supercritical CO_2 extracts of SCGs were shown to reduce melanin synthesis in B16F10 murine melanoma cells by downregulating melanogenic signaling cascades, including the cAMP/PKA (Huang et al., 2016). These pathways regulate the expression and activity of microphthalmia-associated transcription factor (MITF), a master controller of tyrosinase, tyrosinase-related protein-1 (TRP-1), and TRP-2—enzymes responsible for melanin biosynthesis. Treatment with SCG extracts led to decreased expression of these enzymes, confirming the antimelanogenic efficacy of SCG-derived polyphenols and diterpenes.

Additionally, SCG oil-based nanoemulsions have shown demonstrated that a nanoemulsion composed of coffee oil and algae oil significantly attenuated UVA-induced skin damage in murine models (Varol et al., 2016). The formulation reduced markers of oxidative stress, inflammation, and lipid peroxidation, while enhancing the expression of skin barrier proteins and collagen synthesis. These results suggest that SCG derivatives not only inhibit melanin production but also confer broader protective benefits against photoaging.

The cosmetic utility of SCG extracts is further supported by studies investigating their antioxidant capacity, which plays a vital role in preventing melanogenesis triggered by ROS. Chlorogenic acids, caffeic acid, and ferulic acid present in SCGs have been shown to scavenge ROS, suppress UV-induced oxidative damage, and inhibit lipid peroxidation in keratinocytes and fibroblasts (Iriondo-DeHond et al., 2019; Ballesteros et al., 2017). These actions indirectly contribute to the prevention of UV-stimulated melanin overproduction and skin inflammation.

Furthermore, SCG-derived bioactives are compatible with modern delivery systems; encapsulation in nano- and microcarriers enhances dermal penetration and enables controlled release, thereby improving efficacy and stability (Marto et al., 2016; Blackburn et al., 2008). The use of green solvents and eco-friendly extraction technologies, such as supercritical CO_2 and microwave-assisted extraction, aligns with consumer preferences for sustainable, natural ingredients (Janissen & Huynh, 2018; Martinez-Saez & del Castillo, 2019).

In summary, SCGs constitute a sustainable and multifunctional source of bioactive compounds for the cosmetic industry. Their inhibitory effects on melanogenesis, combined with antioxidant and anti-photoaging properties, provide a scientific basis for their application in skin-whitening and photoprotective products. Continued research on safety, formulation compatibility, and *in vivo* efficacy will facilitate their integration into the next generation of functional cosmetics.

2.4.4. Prebiotic potential and digestive health

The human gastrointestinal microbiota plays a fundamental role in sustaining health by regulating immune responses, enhancing nutrient absorption, producing bioactive metabolites, and preserving gut barrier integrity. Recent research has spotlighted SCGs as a promising source of dietary fibers with prebiotic effects. SCGs are particularly rich in insoluble fibers such as cellulose and hemicellulose, along with bioactive components like polyphenols that may contribute to microbiota modulation (Janissen & Huynh, 2018; Iriondo-DeHond et al., 2019).

In vitro simulations of gastrointestinal digestion followed by colonic fermentation have consistently shown that SCG-derived fiber fractions enhance the growth of beneficial gut microbial populations, especially Lactobacillus spp. and Bifidobacterium spp., which are widely recognized for their health-promoting functions (Campos-Vega et al., 2015; López-Barrera et al., 2016). Moreover, SCG fermentation leads to the production of key short-chain fatty acids (SCFAs), notably acetate, propionate, and butyrate, which support colonocyte energy metabolism, strengthen intestinal barrier function, and exert anti-inflammatory and systemic metabolic effects (Iriondo-DeHond et al., 2019; Tores de la Cruz et al., 2019).

Interestingly, dietary supplementation with SCG extracts has been associated with reductions in intestinal inflammation and oxidative stress markers in experimental animal models, providing further evidence for their role as functional ingredients supporting gut health. López-Barrera et al., (2016) demonstrated that SCG-derived compounds inhibited the production of inflammatory mediators *in vitro*, while Panzella et al. (2017) reported increased short-chain fatty acid (SCFA) production in a simulated colon fermentation model, indicating a prebiotic effect. These findings support the incorporation of SCG-derived dietary fiber into functional food and nutraceutical formulations designed to promote gut homeostasis and reduce the risk of metabolic disorders and inflammatory bowel diseases.

Although SCGs exhibit strong antioxidant, anti-inflammatory, cosmetic, and prebiotic potential, significant limitations remain. Many findings are restricted to in vitro or small-scale animal models, with scarce clinical validation. Bioactive yields vary widely depending on extraction method, coffee variety, and roasting conditions, complicating standardization. Long-term safety, bioavailability, and dose–response relationships are poorly characterized. Furthermore, most applications remain at laboratory scale, with limited evidence of industrial translation or regulatory approval. Future research should focus on harmonizing extraction protocols, conducting clinical trials, assessing techno-economic feasibility, and developing scalable delivery systems to bridge the gap between experimental promise and commercial application.

2.5. Emerging industrial applications of SCGs

2.5.1. Applications in food industry

The integration of SCGs into food systems has gained considerable interest due to their high content of dietary fibers, phenolic compounds, and essential nutrients. SCGs have been successfully incorporated into bakery products, including bread, cookies, and muffins, serving as functional additives that enhance nutritional profiles, particularly fiber content and antioxidant activity (Martinez-Saez et al., 2017; Martinez-Saez & del Castillo, 2019); Beyond their role in dietary fiber enrichment, extracts from SCGs have shown considerable promise as natural preservatives, owing to their inherent antimicrobial and radical-scavenging properties. These characteristics can enhance the shelf life of food products while supporting clean-label formulation strategies. Campos-Vega et al. (2015) emphasized the antioxidant capacity of SCGs, which is largely attributed to their high content of chlorogenic acids and melanoidins, compounds known for their ability to inhibit lipid oxidation and microbial growth. In addition to preservation, SCGs have been investigated as fermentation substrates for the production of bioactive compounds. For instance, Panzella et al. (2017) demonstrated that hydrolyzed SCGs promoted the generation of short-chain fatty acids (SCFAs) during in vitro fermentation, indicating their potential prebiotic function. This supports the use of SCGs in the formulation of functional foods and nutraceuticals aimed at modulating gut health. Furthermore, Campos-Vega et al. (2015) and Karmee, (2017) noted the potential of SCGs as carriers for probiotic delivery or as sources of bioactive peptides and organic acids, reinforcing their role in the development of next-generation food products with added physiological benefits.

2.5.2. Applications in cosmetics

The cosmetic industry has increasingly incorporated SCGs into product formulations due to their rich composition of bioactive compounds with dermatological benefits. SCG extracts are particularly abundant in chlorogenic acids, caffeine, and other phenolic constituents that exhibit anti-aging, skin-brightening, and antioxidant properties.

Key mechanisms underlying their efficacy involve the inhibition of enzymes such as tyrosinase, elastase, and collagenase - critical mediators in melanin production and dermal extracellular matrix degradation. Huang et al. (2016) demonstrated that supercritical fluid extracts from SCGs suppressed melanogenesis via downregulation of the PKA, PI3K/Akt, and MAPK signaling pathways, indicating potential for application in skin-whitening and anti-photoaging products. Similarly, Rodrigues et al. (2023) reviewed the dermatological potential of chlorogenic acids and caffeine from coffee by-products, highlighting their antioxidant and photoprotective roles in topical formulations.

In addition, SCG-derived ingredients have been explored for use in sunscreens and cosmetic emulsions due to their capacity to neutralize free radicals and reduce UV-induced skin damage. Marto et al. (2016) formulated green sunscreen prototypes incorporating coffee by-products, demonstrating effective UV protection and skin compatibility. These findings underscore the potential of SCGs as multifunctional and sustainable ingredients in natural cosmetics and dermaceuticals, contributing to both consumer health and circular bioeconomy goals.

2.5.3. Pharmaceutical and healthcare applications

Bioactive compounds in SCGs, including caffeine, diterpenes, and phenolic acids, have demonstrated therapeutic potential across a spectrum of health conditions. Research has shown their anti-inflammatory, antidiabetic, antimicrobial, and neuroprotective properties, supporting the development of SCG-derived ingredients in dietary supplements, anti-obesity formulations, and even as adjuvants in chronic disease management (Rebollo-Hernanz et al., 2019; Tores de la Cruz et al., 2019; Iriondo-DeHond et al., 2019). Furthermore, SCGs can serve as bioactive carriers for controlled drug delivery systems due to their porous structure and biocompatibility, aligning with the growing demand for green pharmaceutical excipients (Janissen & Huynh, 2018).

2.5.4. Environmental and wastewater treatment applications

SCGs and SCG-derived carbons are effective sorbents for water and wastewater remediation. The Figure 2 synthesizes how SCG-derived biochar attenuates metal(loid)s through four coupled pathways. (1) Nonspecific adsorption arises from electrostatic attraction and cation exchange on charged surfaces. (2) Specific adsorption occurs via donor–acceptor interactions and surface complexation at oxygenated functional groups (–OH, –COOH, phenolics) and π-electron sites. (3) Precipitation/co-crystallization is promoted by ash minerals (PO_4^{3-}, CO_3^{2-}) and pH/CEC increases, especially in Ca/Mg-rich chars. (4) Redox reactions proceed as quinone/graphitic domains and Fe-oxide phases shuttle electrons, enabling reductions such as Cr(VI)→Cr(III). Macro-, micro- and nanopores govern mass transfer and accessibility, linking processing-controlled structure to remediation performance.

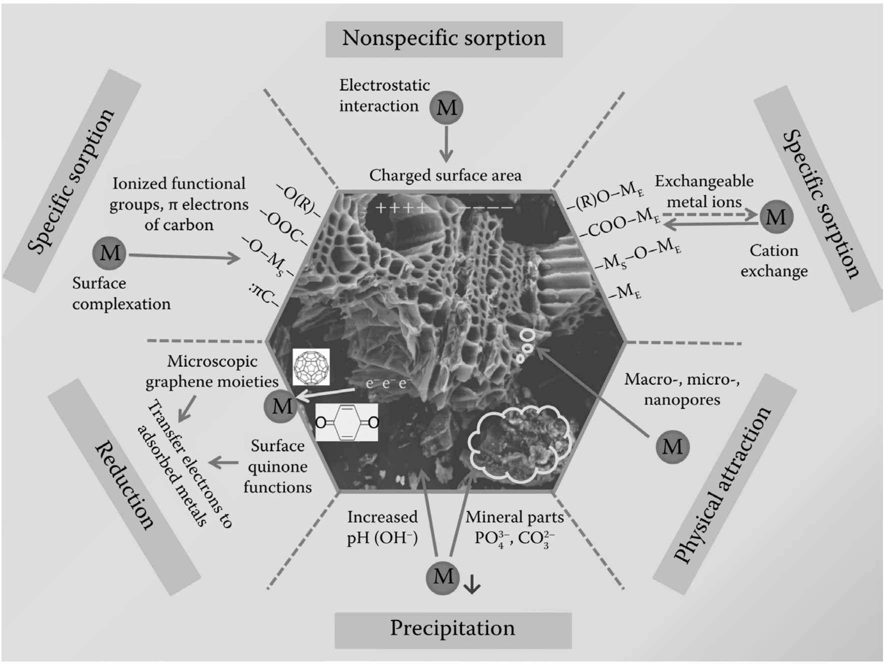

Figure 2. Mechanistic map of metal(loid) attenuation on SCG-derived biochar. *(Adapted from Thangarajan, R. et al., "Biochar for Inorganic Contaminant Management in Soil," in Ok, Y.-S. et al. (eds.), Biochar: Production, Characterization, and Applications, CRC Press/Taylor & Francis, 2016, Chapter 5).*

Spent coffee grounds are dried (≤10% moisture) and slow-pyrolyzed (400–800°C, 30–60 min, inert) to produce biochar, syngas, and bio-oil. Subsequent physical (steam/CO_2, 750–900°C) or chemical (KOH/H_3PO_4, 750–850°C) activation, followed by washing/neutralization, yields micro–mesoporous carbons with S (BET): Total surface area per gram of a solid determined by the Brunauer–Emmett–Teller ≈ 800–1500 $m^2 g^{-1}$ and acidic sites. The lignocellulosic origin endows surfaces with –OH/–COOH/phenolic groups that, together with the porous network, drive the four remediation pathways illustrated in Figure 3: (i) nonspecific adsorption (electrostatics/cation exchange), (ii) specific adsorption via donor–acceptor interactions and surface complexation at oxygenated groups (and $–NH_2$ after amination), (iii) precipitation/co-crystallization with Ca/Mg-rich mineral phases, and (iv) microbial/enzyme immobilization on high-area surfaces.

These mechanisms underpin the fast uptake and high capacities observed for dyes and trace metals; notably, SCG-based activated carbon effectively removed Cr(VI) from synthetic wastewater, supporting scale-up and integration into treatment trains (Campbell et al., 2024). Performance is tunable through post-functionalization (acid/alkali oxidation, amination) or embedding in composite matrices to improve mechanical stability, pressure-drop control, and recyclability (Kourmentza et al., 2018; Zabaniotou & Kamaterou, 2019). Typical quality control includes BET surface area, pH/pH_{pzc}, FTIR/XPS, SEM, and adsorption isotherm/kinetic tests. Beyond aqueous treatment, SCG valorization extends to bioplastic/biocomposite fillers, bioenergy carriers, and carbon-rich sorbents for gas capture or odor control (Karmee, 2017; Vítězová et al., 2019).

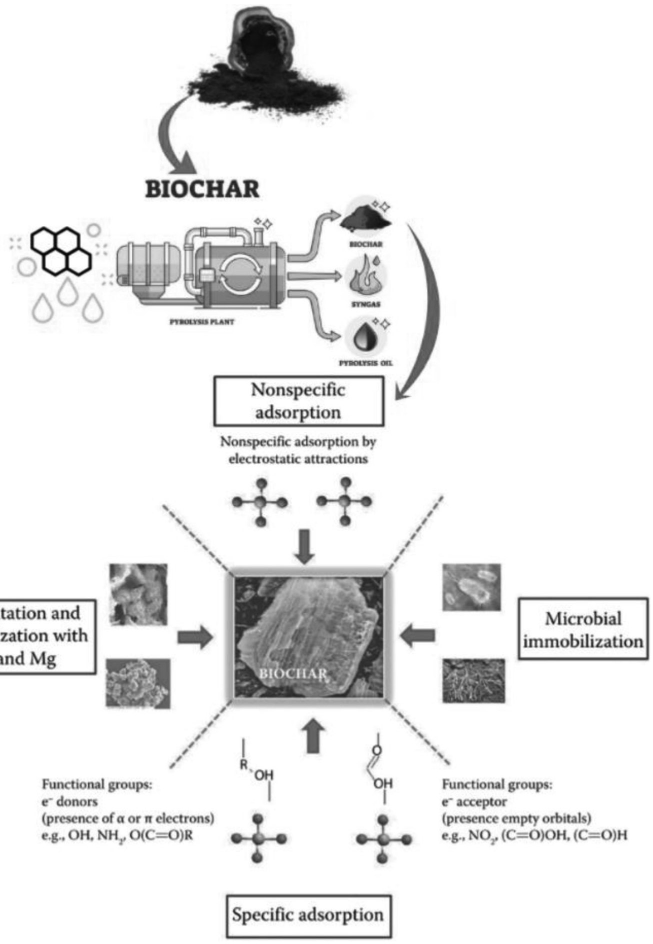

Figure 3. Mechanisms relevant to SCG-derived biochar as a functional material. *(Adapted and modified from Thangarajan, R. et al., "Biochar for Inorganic Contaminant Management in Soil," in Ok, Y.-S. et al. (eds.), Biochar: Production, Characterization, and Applications, CRC Press/Taylor & Francis, 2016, Chapter 5).*

2.6. Future perspectives

In recent years, the valorization of SCGs has moved beyond conventional uses, with a growing body of research exploring their advanced applications in industrial biotechnology, environmental remediation, and biomedical science. Owing to their unique physicochemical properties - such as a porous lignocellulosic structure and rich composition of bioactive compounds - SCGs have demonstrated significant potential as functional materials for enzyme immobilization, biosorption of heavy metals, and the development of health-promoting agents. Moreover, preliminary *in vivo* and *ex vivo* studies have highlighted their therapeutic prospects in mitigating oxidative stress, metabolic dysfunction, and gut dysbiosis. However, the translation of these findings into clinical or commercial products remains constrained by challenges in standardization, bioavailability, and regulatory validation. Table 3 summarizes the emerging applications of SCGs and outlines future research directions necessary to unlock their full potential within a circular bioeconomy framework.

2.6.1. Enzyme immobilization for industrial applications

SCGs have attracted growing interest as cost-effective and environmentally sustainable supports for enzyme immobilization in industrial processes. Their fibrous lignocellulosic matrix offers high surface area, porous architecture, and a diversity of functional groups (e.g., hydroxyl, carboxyl, phenolic), which provide suitable sites for covalent or non-covalent enzyme attachment (Campos-Vega et al., 2015; Janissen & Huynh, 2018).

Recent valorization strategies propose the use of SCGs as carriers for hydrolases, including cellulases and proteases, to enhance enzyme stability, reusability, and catalytic efficiency under industrial operating conditions (Kourmentza et al., 2018). Such biocatalyst systems have shown applicability in sectors ranging from biofuel production to food processing and textile treatment. The porous and modifiable surface of SCGs also facilitates mass transfer, making them advantageous over synthetic supports in continuous-flow reactors (Zabaniotou & Kamaterou, 2019).

Moreover, SCGs exhibit physicochemical properties similar to other plant-based residues successfully used in enzyme support systems. As emphasized by del Castillo et al. (2018) and Karmee, (2017), the integration of SCGs into biotechnological platforms not only enhances processing efficiency but also contributes to resource recovery, waste minimization, and circular bioeconomy goals. These applications exemplify the transition from waste biomass to functional biocatalytic materials, adding economic and environmental value to the coffee supply chain.

2.6.2. Biosorbents for heavy metal removal

SCGs have demonstrated high potential as eco-friendly biosorbents for removing heavy metals such as chromium, copper, cadmium, and lead from wastewater. Their lignocellulosic matrix, rich in hydroxyl, carboxyl, and phenolic groups, enables effective metal ion binding. Thermochemical modifications - especially conversion to activated carbon - significantly enhance adsorption efficiency. As shown by Campbell et al. (2024), SCG-derived activated carbon effectively removes hexavalent chromium from synthetic wastewater (Campbell et al., 2024). Moreover, Kourmentza et al. (2018); Zabaniotou & Kamaterou (2019) emphasize SCGs' role in circular bioeconomy strategies through wastewater remediation and resource recovery. Additionally, SCGs can enhance microbial respiration in biological treatment systems (Vítězová et al., 2019). These findings highlight SCGs as a low-cost, sustainable material for industrial effluent treatment and environmental protection within an integrated valorization framework.

2.6.3. In vivo and clinical applications

Although numerous *in vitro* and *ex vivo* investigations have confirmed the antioxidant, anti-inflammatory, and metabolic-modulating effects of SCGs, studies validating these outcomes *in vivo* or in clinical settings remain limited. Preliminary animal models have shown that SCG-derived bioactives hold promising therapeutic properties. For example, Iriondo-DeHond et al. (2019) reported that SCG extracts alleviated oxidative stress, improved glucose metabolism, and reduced hepatic inflammation in murine models, supporting their potential role in managing metabolic syndrome.

Similarly, Rebollo-Hernanz et al. (2019) demonstrated that phenolic compounds from coffee by-products modulated mitochondrial dysfunction, insulin resistance, and inflammation in adipocytes through PI3K/AKT signaling, reinforcing their utility in obesity-related pathologies. In the context of intestinal health, Panzella et al. (2017) showed that hydrolyzed SCGs enhanced short-chain fatty acid (SCFA) production in a simulated digestion–fermentation model, suggesting prebiotic effects that warrant *in vivo* exploration.

Despite these promising findings, substantial challenges must be addressed before SCG-derived compounds can be applied clinically. These include the lack of standardized, food-grade extraction protocols; the poor oral bioavailability of many polyphenols and melanoidins; and the absence of toxicological data and pharmacokinetic studies in humans. Furthermore, no randomized controlled trials to date have evaluated the efficacy or safety of SCG-based nutraceuticals or therapeutic interventions in clinical populations.

Future research should prioritize rigorous *in vivo* and human clinical studies, including dose–response assessments, long-term safety evaluations, and efficacy trials in specific disease contexts. Interdisciplinary collaboration will be essential to establish the pharmacological profiles and formulation strategies necessary for the development of functional foods, dietary supplements, and pharmaceutical applications derived from SCGs.

Table 3. Future perspectives of SCGs

Applications	Description	Benefits	References
Enzyme immobilization	SCGs serve as cost-effective, sustainable supports for enzyme immobilization due to their fibrous lignocellulosic matrix, offering high surface area and diverse functional groups suitable for enzyme attachment.	Enhances enzyme stability, reusability, and catalytic efficiency; applicable in biofuel production, food processing, and textile treatment.	Campos-Vega et al., 2015; Janissen & Huynh, 2018; Kourmentza et al., 2018; Zabaniotou & Kamaterou, 2019; Pongsiriyakul et al., 2024; Ahmed et al., 2024
Biosorbents for heavy metal removal	SCGs, rich in functional groups like hydroxyl, carboxyl, and phenolic, effectively bind heavy metals. Thermochemical modifications, especially conversion to activated carbon, enhance adsorption efficiency for metals like chromium, copper, cadmium, and lead.	Provides a low-cost, sustainable material for wastewater treatment; contributes to environmental protection and aligns with circular bioeconomy strategies.	Campbell et al., 2024; Kourmentza et al., 2018; Zabaniotou & Kamaterou, 2019; Vítězová et al., 2019
***In vivo* and clinical applications**	Preliminary animal studies indicate SCG-derived bioactives possess antioxidant, anti-inflammatory, and metabolic-modulating effects, suggesting potential therapeutic properties. However, clinical validations are limited.	Potential development of SCG-based nutraceuticals and therapeutic interventions for managing metabolic syndrome and related conditions.	Iriondo-DeHond et al., 2019; Rebollo-Hernanz et al., 2019; Panzella et al., 2017

2.7. Challenges and strategic solutions

Despite the promising potential of spent coffee grounds (SCGs) in food, pharmaceutical, cosmetic, and environmental applications, several critical barriers limit their industrial-scale utilization. One major constraint is the compositional variability of SCGs, which arises from differences in coffee species (Arabica vs. Robusta), geographic origin, roasting degree, brewing methods, and post-processing conditions, leading to inconsistencies in bioactive compound content and hindering process standardization (Campos-Vega et al., 2015; Mussatto et al., 2011). Additionally, the lack of harmonized protocols for extraction, purification, and formulation - particularly in regulated sectors such as food and pharmaceuticals—poses challenges for safety assessments and market approval. SCG-derived ingredients are often categorized as novel foods or unconventional additives, requiring extensive regulatory clearance, while toxicological risks associated with contaminants such as acrylamide, mycotoxins, or heavy metals necessitate further scrutiny (Pongsiriyakul et al., 2024; Iriondo-DeHond et al., 2019; Socas-Rodríguez et al., 2021; Serna-Jiménez et al., 2022). Logistical limitations also persist, as SCGs are generated in decentralized locations, with high moisture content (~50–60%) that promotes microbial spoilage and requires energy-intensive stabilization, thereby complicating cost-effective collection and transport (Mussatto et al., 2011; Ballesteros et al., 2017; Zabaniotou & Kamaterou, 2019). From a technological perspective, although processes such as enzymatic hydrolysis, fermentation, and supercritical extraction offer potential, they are hampered by high costs, enzyme instability, and the absence of integrated bioreactor systems, leading to limited process efficiency and low product yields (Serna-Jiménez et al., 2022). To address these barriers, strategic measures should include the development of standardized SCG classification systems based on composition and microbial safety; implementation of decentralized preprocessing infrastructure to reduce transport and storage burdens; harmonization of cross-sector regulatory frameworks to accelerate product approvals; investment in pilot-scale validation studies and techno-economic assessments; and the promotion of collaborative partnerships among academia, industry, and policymakers to support circular economy adoption and scalable SCG valorization.

3. CONCLUSIONS

The valorization of SCGs presents a promising pathway toward environmental sustainability and the generation of high-value products for the food, cosmetic, pharmaceutical, and environmental sectors. Owing to their rich content of bioactive compounds, dietary fibers, lipids, and functional polymers, SCGs represent a versatile and renewable biomass suitable for circular bioeconomy applications. Leveraging advanced biotechnological tools and green extraction technologies can unlock innovative solutions for resource recovery and waste minimization.

To fully realize the potential of SCG valorization, the following strategic actions are recommended:

1) Foster interdisciplinary research integrating materials science, microbiology, food chemistry, and process engineering to optimize the extraction, transformation, and application of SCG-derived compounds.

2) Invest in pilot- and industrial-scale demonstration projects to bridge the gap between laboratory research and commercial implementation.

3) Develop supportive policy frameworks that incentivize circular economy practices and promote the integration of agro-industrial by-products into sustainable production systems.

4) In summary, SCGs offer a unique opportunity to convert organic waste into sustainable solutions, supporting both environmental protection and economic innovation.

GIÁ TRỊ HÓA BÃ THẢI CÀ PHÊ: THU HỒI HỢP CHẤT SINH HỌC, LỢI ÍCH SỨC KHỎE VÀ ỨNG DỤNG BỀN VỮNG

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Ngày nhận bài: 01/06/2025; Ngày phản biện thông qua: 16/10/2025; Ngày duyệt đăng: 15/12/2025

TÓM TẮT

Bã cà phê (spent coffee grounds - SCGs), một phụ phẩm chính của ngành công nghiệp cà phê, ngày càng được quan tâm nhờ hàm lượng cao các hợp chất sinh học và đặc tính chức năng đa dạng. Bài tổng quan này tổng hợp các nghiên cứu hiện tại về thành phần hóa học của SCGs, làm nổi bật các hợp chất chính như acid phenolic, flavonoid, chất xơ thực phẩm và melanoidin. Các kỹ thuật chiết xuất tiên tiến, bao gồm chiết siêu tới hạn CO_2 và hỗ trợ bằng sóng siêu âm, đã chứng minh hiệu quả cao trong việc thu hồi các hoạt chất sinh học này. Các lợi ích sức khỏe của SCGs thể hiện rõ qua khả năng chống oxy hóa, chống viêm mạnh mẽ, khả năng ức chế quá trình hình thành melanin có giá trị trong lĩnh vực mỹ phẩm, và tiềm năng tiền sinh học giúp cải thiện hệ vi sinh đường ruột và quá trình tạo acid béo chuỗi ngắn. Ngoài lĩnh vực sức khỏe, SCGs còn có nhiều ứng dụng trong công nghiệp như chế biến thực phẩm, mỹ phẩm, dược phẩm, xử lý nước thải và bảo vệ môi trường. Các ứng dụng mới nổi như cố định enzyme và sản xuất vật liệu hấp phụ kim loại nặng cho thấy tiềm năng nghiên cứu đáng kể trong tương lai. Tuy nhiên, các thách thức như quy định pháp lý, tiêu chuẩn hóa và sự chấp nhận của người tiêu dùng vẫn là rào cản đối với thương mại hóa. Bài viết kết luận rằng việc tái sử dụng SCGs là một chiến lược bền vững và có giá trị kinh tế cao trong mô hình kinh tế tuần hoàn, đồng thời kêu gọi cần có thêm các nghiên cứu *in vivo* và lâm sàng để xác thực hiệu quả của SCGs trong thực tiễn.

Từ khóa: *bã cà phê, hợp chất sinh học, chất chống oxy hóa, tiền sinh học, mỹ phẩm, ứng dụng môi trường, thực phẩm chức năng, kinh tế tuần hoàn.*

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