

Coffee by-products as functional food ingredients: bioactive compounds and health effects

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ABSTRACT

Various by-products such as pulp, mucilage, parchment, husk, and silver skin are generated in large quantities during the coffee production process, and these are mostly discarded despite their abundant nutritional and functional potential. This review comprehensively considers recent research to use these coffee by-products as functional food raw materials. In particular, the effects of processing methods such as fermentation, drying, roasting, and storage on major physiologically active ingredients such as chlorogenic acid, caffeine, dietary fiber, and phenolic antioxidants were analyzed. In addition, changes in ingredients and functional characteristics of coffee by-products were identified by examining differences between varieties such as Arabica and Robusta and regional variations according to cultivation altitude, soil, and climate conditions. In addition, safety, bioavailability, related regulations, and industrial applicability are discussed, and sustainable valorization strategies for realizing a circular economy are suggested. The potential of coffee by-products as functional food raw materials for simultaneously promoting human health and environmental sustainability is highlighted, and key tasks for future research and industrial applications are proposed.

Key words: Coffee by-products; functional food ingredients; bioactive compounds; circular economy; sustainable valorization.

1 INTRODUCTION

Coffee is the second largest trade after petroleum in the world, and enormous amounts of by-products are generated in the entire process of cultivation, harvesting, processing, and distribution (Gokavi & Kishor, 2020). Coffee cherry pulp, mucilage, parchment, husk, and silver skin account for more than 40% of the total yield, and most of them are simply landfilled, incinerated, or used for feed and compost only on a limited basis, causing environmental pollution and treatment costs (Klingel et al., 2020). However, these by-products are not just wastes, but they are rich in physiologically active ingredients that are beneficial to human health, such as chlorogenic acid, caffeine, trigonelline, various polyphenols, dietary fibers, and minerals, which have the potential to be used as raw materials for high value-added functional foods (Rebollo-Hernanz et al., 2023). Recently, as resource depletion, climate change, and the food industry's sustainability demand increase, research is actively being conducted to use coffee by-products in the development of functional foods, and it is attracting attention as a strategy to realize a circular economy and improve human health (Iriondo-DeHond et al., 2020). Coffee Science has already published a Use of products generated in the processing of the coffee industry: A review that comprehensively deals with by products generated in the coffee industry. This prior paper provided basic academic and industrial data by broadly summarizing the types of by products generated from coffee cherry processing and the possibility of industrial recycling,

and suggesting various application plans such as fertilizer, feed, and bioenergy. However, despite the growing body of research on the valorization of coffee processing by-products, the nutritional and health aspects directly relevant to their use as functional food ingredients remain insufficiently characterized (Gokavi & Kishor, 2020). Recent systematic and narrative reviews have primarily focused on compositional profiling and technological utilization (Lee et al., 2023), while providing limited integration of factors critical for food development and commercialization, including processing-induced changes in bioactive components, regional variability associated with coffee varieties and cultivation environments, human health effects and safety, and bioavailability of key compounds (Ramírez et al., 2023). As a result, existing evidence remains fragmented (Navajas-Porras & Castillo-Correa, 2025), hindering the translation of coffee by-products into scientifically substantiated functional food applications. In fact, the functionality and nutritional value of coffee by-products are not simply determined by the chemical composition of raw materials. The nutritional value of coffee by-products is not solely determined by the chemical composition of raw materials, but is strongly influenced by a series of post-harvest and processing steps (Kitzberger et al., 2020). Fermentation can induce enzymatic hydrolysis (Silva et al., 2025) and microbial metabolism (Vale et al., 2022), leading to the release or transformation of phenolic compounds (Myo et al., 2021), including chlorogenic acids and other polyphenols, while simultaneously modulating

antioxidant activity (Wahyu, 2022). Drying conditions affect moisture removal (Al-Ghamdi et al., 2024) and oxidative stability, with elevated temperatures often associated with partial degradation of heat-sensitive bioactives (Rendón-Mera et al., 2025). Roasting promotes Maillard reactions (Costa et al., 2023) and thermal degradation (Honda et al., 2022), resulting in a decrease in chlorogenic acids but an increase in melanoidin formation, which contributes to antioxidant capacity and flavor development. Storage duration and conditions further influence the retention or loss of caffeine, polyphenols, dietary fiber functionality, and volatile flavor compounds through oxidation and moisture uptake. Collectively, these processing variables act as key determinants of the final quality, bioactivity, and potential health effects of coffee by-products used as food raw materials (Bastian et al., 2021; Koskinakis et al., 2025). In addition, regional factors such as genetic differences, cultivation, soil, rainfall, and temperature patterns of varieties such as Arabica and Robusta also influence the chemical properties and physiologically active ingredient contents of by products (Urugo et al., 2024). Examples include reports that high-altitude Arabica contains high levels of certain antioxidants and flavor components, and studies that Robusta is rich in caffeine and some phenols. However, systematic considerations on how these varieties and regional variations and processing processes interact and change the functionality and nutritional quality of by products are still insufficient (Martinez Gelvez, 2021). The scientific evidence necessary to prove its practical value as a functional food raw material such as human health effects, safety, bioavailability, regulatory and industrialization strategies was also insufficient. Many studies reported to date remain at the in vitro level, and animal experiments or human application tests are limited. Practical studies such as safety assessment of long term intake of by products, international regulatory response, standardized processing and storage guidelines, and consumer acceptance analysis are still in the early stages. The purpose of this paper is to fill this research gap and to present a scientific basis and action plan to convert coffee by products into functional food raw materials. Classification of major coffee by products and physiologically active ingredients are summarized through the latest research, and the effect of processing processes such as fermentation, drying, roasting, and storage on chemical composition and health effects is analyzed in depth (Hu et al., 2020). In addition, it comprehensively reviews the chemical composition and functional differences according to soil and climate conditions in cultivars and cultivated areas such as Arabica and Robusta, and comprehensively discusses the effects of promoting human health, bioavailability, safety, related regulations, and industrial applicability. Through this approach, we would like to present a strategic roadmap to

simultaneously achieve health oriented food development and environmental sustainability beyond simple recycling of coffee by products (Torres-Valenzuela et al., 2020).

2 MATERIAL AND METHODS

This review employed a combined systematic and narrative approach to comprehensively evaluate the potential utilization of coffee by-products as functional food ingredients, covering literature published between 1979 and 2025. Major international databases, including Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar, were searched using combinations of the following keywords: “coffee by-products”, “coffee pulp”, “coffee husk”, “coffee silverskin”, “spent coffee grounds”, “bioactive compounds”, “functional food”, “processing methods”, “fermentation”, “drying”, “storage”, “health effects”, “valorization”, and “sustainability”. The search and selection process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guideline and was conducted in three stages. During the identification stage, a total of 172 records were retrieved from databases and grey literature sources. In the screening stage, 55 duplicates were removed, and 10 records unrelated to coffee by-products, bioactive compounds, processing, or health effects were excluded based on title and abstract screening. In the eligibility stage, 13 additional studies were excluded after full-text review due to limited relevance, insufficient compositional or bioactivity data, or geographic contexts unrelated to coffee production. Ultimately, 94 studies were included in the final analysis. Data were systematically extracted and organized according to the type of by-product (pulp, mucilage, husk, parchment, silverskin, and spent coffee grounds), post-harvest and processing steps (fermentation, drying, roasting, storage), key bioactive compounds (chlorogenic acids, caffeine, polyphenols, dietary fibers, melanoidins), varietal and environmental factors (altitude, climate, soil), health-related effects (antioxidant, anti-inflammatory, metabolic regulation, gut microbiota modulation), safety and toxicological findings, and potential industrial or regulatory applications. Priority was given to the most recent publications from 2020 to 2025, while earlier foundational studies from 1979 to 2010 were also included to establish historical and scientific context. Based on the compiled evidence, this study critically discusses the biochemical characteristics of coffee by-products, the influence of processing and cultivation factors on bioactivity, the prospects for their functional food applications, and strategies for sustainable valorization. The methodological process was designed in accordance with the transparency and reproducibility principles required by *Coffee Science*, and the overall literature selection process is summarized in the PRISMA flow diagram (Figure 1).

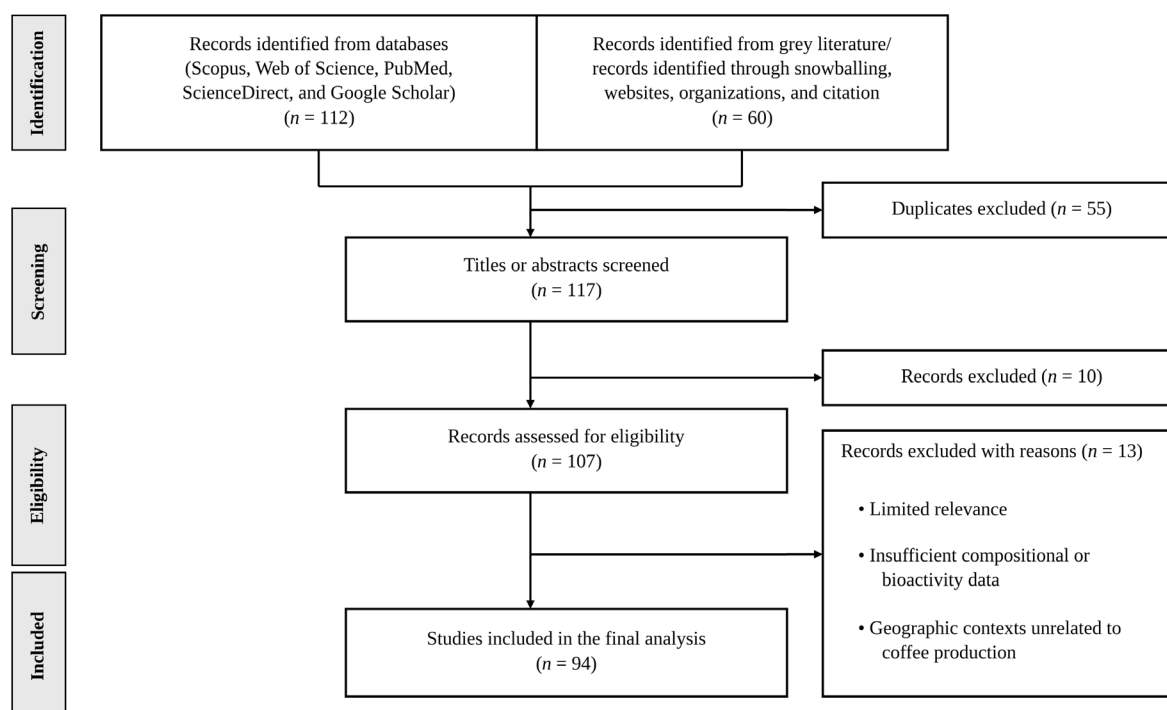


Figure 1: Records retrieval process using the PRISMA flow diagram.

3 RESULTS

3.1 Composition and Bioactive Potential of Coffee By-products

By-products generated in the coffee process vary in chemical composition and physiologically active ingredients depending on the type. Representatively, there are pulp, mucilage, husk, parchment, and silver skin, and each by-product accounts for about 30-40% of the dry weight, accounting for the largest proportion of the coffee industry by-products. These by-products are rich in carbohydrates, proteins, dietary fibers, and minerals, as well as physiologically active compounds that are beneficial to human health such as chlorogenic acid, caffeine, trigonelline, polyphenols, and melanoidin (Machado et al., 2023) (Table 1) (Figure 2). Pulp and mucilage are derived from coffee cherry peel and mucilage layers and are the first by-products to be separated after harvest, and more than 60% of the total solids are carbohydrates (pectin, cellulose, hemicellulose) and are rich in proteins and minerals. In particular, the high concentration of antioxidant components such as chlorogenic acid, flavonoids, and anthocyanins can contribute to antioxidant and anti-inflammatory activity. In addition, it has been reported that these layers contain a large amount of soluble dietary fibers that exhibit prebiotic effects, which has the potential to have a positive effect on the regulation of intestinal microorganisms (M. Machado et al.,

2024). Husk and parchment are formed in the process of drying and threshing and are mainly rich in insoluble dietary fiber and minerals. Caffeine and phenolic compounds remain in the husk to maintain antioxidant activity, and parchment also contains polyphenols and trace amounts of caffeine. These are highly applicable as food supplementation fiber sources, natural antioxidants, and functional packaging materials (Palanisamy et al., 2025). Silver skin is a thin shell separated from the surface of the beans during roasting, and although the amount of production is relatively small, it is one of the most notable by-products because protein, amino acids, and melanoidin and chlorogenic acid with excellent antioxidant activity are concentrated. In a recent study, it has been reported that the silver skin extract has a positive effect on inhibiting lipid oxidation, controlling blood sugar, and maintaining the balance of intestinal microorganisms. These chemical compositions and physiological active components vary greatly depending on the breed and cultivation environment (Arya et al., 2022) (Table 2). Arabica generally has a low caffeine content and is rich in flavor components and specific polyphenols, while Robusta has a strong antioxidant power due to its high concentration of caffeine and chlorogenic acid. In addition, environmental conditions such as cultivation altitude, soil characteristics, precipitation, and temperature can influence the biochemical composition of coffee, including phenolic and chlorogenic acid profiles (Urugo et al., 2024; Rusinek et al., 2025). For example, Arabica grown in highlands tends to be

more concentrated with certain antioxidant components and aromatic compounds due to the influence of a cool climate and daily temperature difference (Rusinek et al., 2025). Microbial communities immediately before and after processing can also cause changes in the components of by-products. Microbial types and metabolites in natural and starter fermentation control the organic acid, polyphenol, and amino acid contents of pulp and mucilage, which affect not only taste but also health function. Therefore, in order to maximize the physiologically active components of by-products, not only the selection of varieties and cultivation sites, but also the management of microorganisms after harvest must be considered (Zhang et al., 2019). Coffee by-products have their own nutritional and functional components, and varieties, cultivation environment, and initial microbial communities work in combination to determine the final chemical composition. These basic data are essential to discuss the component changes, health functions, and industrial applications of each processing process, which will be covered in later chapters, and provide a scientific basis for converting coffee byproducts into high value-added functional food raw materials (Obieze et al., 2025).

3.2 Effects of Processing and Storage

The functionality and nutritional value of coffee byproducts vary greatly depending on the various processing methods and storage conditions applied after harvest. Physical, chemical, and microbiological changes that occur during fermentation, drying, roasting, and storage processes act as key factors that determine the content and composition of major physiologically active ingredients such as chlorogenic acid, caffeine, polyphenol, dietary fiber, and melanoidin, as well as antioxidant and anti-inflammatory activity and flavor characteristics (Cao et al., 2022). In the fermentation stage, the enzymatic activity and metabolites of microorganisms greatly influence the component change of the byproduct. Natural fermentation is led by indigenous microorganisms, and lactobacillus, yeast, and acetic acid bacteria decompose sugars and proteins to produce organic acids and various aromatic compounds. In this process, partial decomposition and recombination of chlorogenic acid and caffeine occur, resulting in changes in antioxidant activity and flavor profile (Shen et al., 2024). On the other hand, controlled fermentation inoculated with starter microorganisms can increase the reproducibility of quality and physiologically active ingredients by maintaining

Table 1: Chemical composition and key bioactive compounds of major coffee by-products.

By-product	Major carbohydrates (g/100 g)	Protein (g/100 g)	Total dietary fiber (g/100 g)	Key bioactives (mg/100 g)
Pulp	Pectin, cellulose (~60)	~8	~25	Chlorogenic acids, flavonoids, anthocyanins (~200–500)
Mucilage	Soluble polysaccharides (~55)	~6	~20	Chlorogenic acids, pectic oligosaccharides (~150–400)
Husk	Cellulose, hemicellulose (~65)	~5	~55	Caffeine, phenolic compounds (~100–300)
Parchment	Cellulose, hemicellulose (~70)	~3	~60	Phenolic acids (~50–150)
Silverskin	Cellulose, melanoidins (~40)	~18	~60	Melanoidins, chlorogenic acids, caffeine (~300–600)

Table 2: Varietal and regional differences in bioactive profiles of coffee by-products.

Variety/Region	Notable bioactive trend	Supporting references
Arabica, high altitude	↑ specific phenolics, ↑ aroma precursors	Rusinek et al. (2025); Hu et al. (2024)
Arabica, low altitude	Moderate phenolics, balanced caffeine	Worku et al. (2018); Van der Vossen, Bertrand and Charrier (2015)
Robusta	↑ caffeine, ↑ chlorogenic acids	Vignoli et al. (2014); Ludwig et al. (2014)
Dry tropical region	↑ sugars and Maillard precursors	Perrone, Farah & Donangelo (2012); Morales, Somoza & Fogliano (2012)
Humid tropical region	↑ polyphenols with antioxidant potential	Benitez et al. (2019)



Figure 2: Coffee processing chain and generation of major by-products.

a constant fermentation rate. Recent studies have reported strategies to minimize the loss of antioxidant components through fermentation period and temperature control, and to strengthen polyphenols and prebiotic dietary fibers with specific microbial combinations (Pereira et al., 2020). The drying process also has a significant impact on the nutrition and functionality of by-products. Traditional sun drying is low in cost and natural, but heat and oxidation-sensitive components such as polyphenols and vitamin C may decrease when exposed to high temperatures and long periods of time. On the other hand, hot-air drying enables uniform drying in a short time, reducing microbial contamination, and it is reported that maintaining a specific temperature range can effectively preserve chlorogenic acid and antioxidant activity (López-Parra et al., 2024). In addition, the latest technologies such as vacuum drying and freeze drying are attracting attention as a way to optimally maintain color, aroma, and physiologically active ingredients. In the roasting step, some of the by-products silver skin are subjected to strong heat to form melanoidin and Maillard reaction products. These compounds have strong antioxidant and antibacterial activity, but excessive roasting can rapidly reduce heat-sensitive polyphenols such as chlorogenic acid (Górska et al., 2020). The correlation between component changes and antioxidant activity according to roasting degree (light, medium, dark) is an important criterion for the development of functional raw materials for silver skin. Component stability also depends on the storage and transportation stages after harvest. High relative humidity and temperature increase the risk of mold growth and mycotoxin production, and antioxidant activity may decrease due to oxidation and polymerization of polyphenols. Vacuum packaging, nitrogen substitution packaging, and refrigeration and low-temperature storage are effective in maintaining physiologically active ingredients and flavors by inhibiting oxidation and microbial growth (Bassey et al., 2022). In order to stably preserve antioxidant activity and dietary fiber content even during long-term storage, the barrier properties of packaging materials, oxygen removal level, and temperature management are presented as key management indicators (Table 3). The processing process and storage conditions do not act alone but determine the final quality of the by-product through interaction. It has been reported that using a specific microbial strain in fermentation and drying quickly at a low temperature afterwards improves antioxidant activity and taste simultaneously (Oliveira et al., 2021). In addition, optimizing the packaging and storage strategy before and after roasting can maintain the balance of chlorogenic acid and melanoidin. The functionality and nutritional value of coffee by-products vary greatly throughout the processing process, such as fermentation, drying, roasting, and storage, and their interactions (De Oliveira Silva et al., 2025). Precise control of process-specific conditions can maximize health-active

ingredients such as chlorogenic acid, caffeine, polyphenols, and melanidine and minimize quality degradation and safety issues. This scientific basis is an essential strategy for developing and industrializing coffee by-products as functional food raw materials (Torres-Valenzuela et al., 2020).

3.3 Health Implications and Safety

Coffee by-products have the potential to exhibit a variety of human health promotion effects thanks to their abundant physiologically active ingredients. Recent studies have reported that ingredients extracted from pulp, mucilage, husk, parchment, and silver skin can have a positive effect in various aspects such as antioxidation, anti-inflammatory, metabolic health improvement, and intestinal microbial control. First of all, antioxidant action is one of the most well-proven effects. Chlorogenic acid, caffeine, flavonoids, and melanoidin remove free oxygen and inhibit lipid peroxidation to prevent cell damage. Animal experiments and human cell studies have reported that pulp and silver skin extracts significantly reduce lipid oxidation and oxidative stress in the blood (Castro-Díaz et al., 2025). These antioxidant effects can contribute to reducing the risk of cardiovascular disease (Kobylińska et al., 2025), diabetes, and aging-related diseases. Anti-inflammatory effects are also noteworthy. Research is increasing that polyphenols and melanoids of coffee byproducts inhibit the expression of inflammatory cytokines by regulating NF- κ B and MAPK signaling pathways. In particular, the combination of melanoidin of silver skin and caffeine and chlorogenic acid of husk has been reported to be effective in alleviating the inflammatory response of macrophages (Table 4) (Ontawong et al., 2023). In terms of improving metabolic health, chlorogenic acid and soluble dietary fiber can help control blood sugar and manage weight (Singh et al., 2023). Chlorogenic acid delays glucose absorption in the small intestine and inhibits gluconeogenesis in the liver, relieving blood sugar rise. Soluble dietary fiber can increase insulin sensitivity and improve fat metabolism by producing short-chain fatty acids through intestinal fermentation (Zhang et al., 2023). In some animal models, coffee pulp and mucilage extracts suppressed weight gain and improved blood lipid levels. Improving the balance of intestinal microbes is also considered an important effect (Bhandarkar et al., 2021). The prebiotic properties of pulp and mucilage promote the growth of beneficial bacteria such as *Bifidobacterium* and *Lactobacillus* and increase the production of short-chain fatty acids to strengthen intestinal health (Kassem et al., 2021). This process can contribute to the prevention of metabolic diseases and immune control. It is noteworthy that these health effects are closely linked to process-specific treatment. Fermentation can increase the antioxidant and anti-inflammatory effect by increasing specific organic acids and phenolic metabolites, and melanoidin produced through roasting gives strong antioxidant

Table 3: Impact of processing and storage on key bioactive compounds of coffee by-products.

Processing / Storage	Key variables	Main effects on bioactive compounds	Representative references
Fermentation	Temperature, duration, microbial starter	Modulates chlorogenic acids and phenolics; can enhance antioxidant activity	Shen et al. (2024)
Drying	Sun vs. hot air vs. vacuum	High temperature can degrade polyphenols; controlled drying preserves phenolics and caffeine	López-Parra et al. (2024); Pyrzynska (2024)
Roasting	Degree (light/medium/dark)	Formation of melanoidins; partial loss of chlorogenic acids and some phenolics	Perrone, Farah & Donangelo (2012); Morales, Somoza & Fogliano (2012)
Storage	Temperature, humidity, oxygen level	Proper control maintains antioxidants and polyphenols; poor storage promotes oxidation and mycotoxin risk	Iriondo-DeHond et al. (2019); Rodrigues, Oliveira and Alves (2023)

Table 4: Reported health-related effects (primarily based on in vitro and animal studies) and safety considerations of coffee by-products.

By-product	Major bioactive compounds	Key demonstrated health effects*	Potential safety concerns	Representative references
Pulp & Mucilage	Chlorogenic acids, polyphenols, dietary fiber	Antioxidant, anti-inflammatory, glycemic control	Mycotoxin risk if poorly dried	Jiménez-Zamora et al. (2015); Klingel et al. (2020)
Husk & Parchment	Caffeine, phenolics, insoluble fiber	Antioxidant, prebiotic effects	Possible caffeine excess, ochratoxin risk	M. Machado et al. (2024); Klingel et al. (2020)
Silverskin	Melanoidins, chlorogenic acids	Antioxidant, anti-inflammatory, lipid oxidation inhibition	Acrylamide formation if over-roasted	Jiménez-Zamora et al. (2015)

Note: Most reported health-related effects are derived from in vitro or animal studies, while evidence from human clinical trials remains limited.

and antibacterial activity (Borrego-Ruiz & González-Domenech, 2024). On the contrary, high-temperature drying or excessive roasting can lower health effects by losing some heat-sensitive polyphenols, so precise control of the processing process is important. On the other hand, in order to use coffee by-products as functional foods, safety verification is essential. When mold is contaminated in raw materials, mycotoxins such as aflatoxin and ochratoxin A may be produced, which may seriously harm human health (Gao et al., 2022). In addition, some of the polyphenol oxidation or Maillard reaction byproducts during high-temperature drying or long-term storage can have potential toxicity (Geng et al., 2023). Therefore, multi-layered safety management such as post-harvest hygiene management, appropriate drying and storage conditions, and regular toxicity tests is required. In addition, the intake of caffeine and chlorogenic acid should be considered. Caffeine has the effect of promoting awakening and metabolism at an appropriate amount, but excessive intake may cause side effects such as insomnia, blood pressure rise, and promotion of gastric acid secretion (Sharma et al., 2023). Chlorogenic acid is also generally evaluated as safe, but it can cause gastrointestinal disorders in sensitive people (Lu et al., 2020). Therefore, when developing functional foods using coffee by-products as raw materials, it is necessary to standardize caffeine and chlorogenic acid contents and present intake guidelines. In addition to safety, the issue of bioavailability is also an important task. Many polyphenols and melanoidins have low metabolic and absorption rates during

digestion, making it difficult to reach effective concentrations in the body (Lorenzo et al., 2021). In order to improve this, various processing technologies such as microencapsulation, nanoemulsion systems and fermentation pretreatment have been proposed, and future studies require precise identification of the human metabolic pathway and development of technologies to increase the actual absorption rate (Li et al., 2023). Coffee byproducts have great potential to provide various health benefits such as antioxidant, anti-inflammatory, metabolic health, and intestinal microbial improvement through abundant chlorogenic acid, caffeine (Machado et al., 2023), polyphenol, melanodin, and prebiotic dietary fibers. However, in order to commercialize coffee by-products as functional food ingredients (Bevilacqua et al., 2023), it is essential to ensure safety by controlling microbial contamination, toxic metabolites such as mycotoxins, and excessive caffeine intake, as well as by improving bioavailability. These safety considerations are typically evaluated against established regulatory thresholds, including maximum caffeine intake levels and permissible mycotoxin limits (Duncan et al., 2024), within existing food safety frameworks such as those defined by the European Food Safety Authority (EFSA, 2015), the U.S. Food and Drug Administration (FDA) including GRAS notifications (Vettorazzi et al., 2020), and Japan's Foods for Specified Health Uses (FOSHU). Incorporating these regulatory perspectives strengthens the scientific basis for the safe utilization of coffee by-products in functional food

applications. These scientific grounds and management strategies will be the basis for industrial and regulatory applications to be discussed later (M. Machado et al., 2024).

3.4 Industrial and Regulatory Perspectives

Coffee by-products have various industrial applications due to their abundant physiologically active ingredients and functional potential (Iriondo-DeHond et al., 2020). As the global market for health-oriented foods and functional beverages grows, prebiotic drinks using pulp and mucilage, antioxidant teas with husk extracts, high-fiber and antioxidant-enhanced bakery products using silver skin, and snack bars are already being commercialized (Salazar-Bermeo et al., 2021). Coffee by-products are also being applied to polyphenols and dietary fiber-reinforced powders, natural antioxidant packaging materials, and cosmetic raw materials, and these products contribute to the establishment of a circular economy in the coffee industry by converting simply discarded by-products into high value-added resources (Dong et al., 2020). Coffee by-products are also being applied to polyphenol- and dietary fiber-reinforced powders, natural antioxidant packaging materials, and cosmetic raw materials. For instance, coffee silverskin has been utilized as a functional fiber ingredient in baked goods and snack bars, while coffee husk-derived extracts have been explored for antioxidant-active packaging applications (Franca et al., 2024; Cantele et al., 2022; Dauber et al., 2024). In terms of economics, by-products have the advantage of relatively easy mass acquisition and low price, but there is a limitation that decomposition is fast due to large seasonal and regional variations in the harvesting and processing stages and high moisture content. Therefore, an efficient collection, storage, and pretreatment system is considered a key factor in commercial success. For example, technology to standardize quality by quickly drying and fermenting pulp and mucilage, or to prevent oxidation and contamination by collecting and storing silver skins immediately after roasting is important to ensure product stability and

uniformity. For commercialization, each country's food safety regulations and functional labeling requirements must be met. These regulatory requirements are generally aligned with international food safety and functional food evaluation frameworks, including those established by the European Food Safety Authority (EFSA) (Anastassiadou et al., 2025), the U.S. Food and Drug Administration (FDA), and Codex Alimentarius Commission guidelines (Onel et al., 2019). In the European Union (EU), coffee by-products are likely to be classified as Novel Food (Kull et al., 2023), and toxicity, allergic, and nutritional safety evaluations and submission of human application test data for each product are required (Klingel et al., 2020). In the United States, FDA's generally recognized As Safe (GRAS) recognition must be obtained or a Dietary Supplement report must be filed (Shimizu, 2020), Japan must obtain permission as a specific health functional food (FOSHU) (Ali, Elfalleh, & Smaoui, 2025), and Korea must obtain permission as an individual recognized health functional food (Sato et al., 2025). In particular, quantitative standardization of caffeine and chlorogenic acid content, and safety verification during long-term intake are key requirements common in all major markets (Table 5). In addition, sufficient scientific evidence, including a systematic literature review (Kamioka, 2023) and human clinical trials, is required to substantiate functional claims such as antioxidant, anti-inflammatory, and metabolic health effects. Quality and safety management are also key to industrialization success (Stratton et al., 2023). International standards such as HACCP, ISO 22000, and GMP must be applied to prevent mold contamination, mycotoxin formation, acrylamide production during roasting, oxidation and polymerization during storage (Rampal et al., 2020). At the same time, it is also important to introduce low-carbon and eco-friendly processes to minimize the environmental burden that may occur during the collection and processing of by-products, and to secure sustainability by utilizing recycling and energy-saving technologies (Wibisono et al., 2025). This eco-friendly strategy goes beyond just

Table 5: Regulatory frameworks and key requirements for commercialization of coffee by-products.

Region/Country	Key regulatory body	Main approval pathway	Specific points for coffee by-products
EU	EFSA (European Food Safety Authority)	Novel Food authorization	Requires toxicological data, human clinical evidence, maximum caffeine limits
USA	FDA	GRAS notification or Dietary Supplement	Evidence of safety and substantiation of structure-function claims
Japan	MHLW (Ministry of Health, Labour and Welfare)	FOSHU (Foods for Specified Health Uses) approval	Demonstrated health benefit and long-term safety
Korea	MFDS (Ministry of Food and Drug Safety)	Individually recognized health functional food approval	Scientific evidence for function and safety, caffeine content control
Brazil	ANVISA	Novel food / functional ingredient registration	Standardization of caffeine and polyphenol content, toxicology evaluation

environmental protection and provides direct value to securing consumer trust and corporate ESG (environmental, social and governance) management (Nugroho et al., 2024). Looking at the future, in order to recognize coffee by-products as major sources of functional ingredients, technology for accumulating scientific evidence and standardizing quality will become more important (Duran-Aranguren et al., 2021). Research on improving the stability, bioavailability of physiologically active ingredients, and taste and aroma through advanced processing technologies such as microencapsulation, nanotechnology, and fermentation pretreatment is expected to expand (Pateiro et al., 2021). In addition, large-scale human clinical trials and longterm intake safety evaluations that prove the health effects of byproducts should be conducted at the same time, and a unified regulatory framework and circular economic incentives are also required in the international market (Enriquez & Sánchez-Triana, 2020). Coffee by-products have the potential to develop into sustainable and highvalue-added functional food raw materials beyond simple waste (Peluso, 2023). If strategies such as securing scientific evidence, standardized quality control, international regulatory response, and eco friendly production are combined, coffee byproducts will create new markets in the functional food industry and establish themselves as key resources to benefit both the environment and human health (Bekavac et al., 2025).

4 DISCUSSION

Based on the reviewed studies, coffee processing by-products such as pulp, mucilage, husk, parchment, and silverskin show potential as functional food ingredients due to their bioactive compounds. (Franca & Oliveira, 2022). Pulp, mucilage, husk, Parchment, and silver skin contain abundant physiologically active ingredients such as chlorogenic acid, caffeine, polyphenol, melanoidin, and prebiotic dietary fibers, so it has great potential to contribute to improving human health, such as antioxidants, anti inflammatory, improved metabolic health, and maintaining a balance of intestinal microbes (Santos et al., 2021). However, in order to completely convert this potential into commercial and industrial value, there are still many challenges to be solved in terms of science, technology, and regulation. Above all, the lack of evidence for human application is pointed out as a key research gap. Most of the health effects reported so far are limited to cell experiments or animal models, so scientific evidence through large scale and long term human clinical trials and meta analysis is needed for functional labeling and safety approval (Zoccatelli & Ciulu, 2025). It is also important to precisely identify the metabolic pathways and bioavailability in the body of major components such as chlorogenic acid, melanoidin, and dietary fiber, and to strategies to increase the actual absorption rate through

advanced processing technologies such as microencapsulation, fermentation pretreatment, and nanoemulsion (Lu et al., 2020). Research that comprehensively interprets the interaction mechanisms of cultivation environments and processing processes on ingredient composition and health effects is also essential for future development. Standardization of quality and safety is the key in the industrialization stage. International hygiene and safety management standards such as HACCP, ISO 22000, and GMP should be applied to prevent potential hazards such as mold contamination, mycotoxin production, acrylamide formation during roasting, oxidation and polymerization during storage (Chen et al., 2020). At the same time, it is necessary to secure sustainability by introducing low carbon and eco friendly processes that minimize the use of energy and water resources during collection, storage, and processing, which are directly linked to consumer trust and enhancing corporate ESG (environmental, social and governance) value. In terms of regulation and policy, functional and health claims based on scientific grounds should also be clearly presented. Major markets such as Novel Food in the European Union, GRAS in the United States, FOSHU in Japan, and individual recognized health functional foods in Korea all require toxic, nutritional and clinical data, especially quantitative standardization of caffeine and chlorogenic acid contents and long term intake safety verification (Shan et al., 2025). At the same time, policy support that reflects the cyclical economic value and environmental protection effect of coffee by products in the regulatory framework will also become increasingly important. Taken together, coffee by products have sufficient scientific and industrial foundation to develop into sustainable and high value added functional food raw materials, not just industrial waste. If future research and technology development, regulatory response, and market strategy are organically combined, coffee by products will be positioned as key resources in the next generation of functional food industries that improve human health and realize a resource circulation economy (Krishnan & Devarajan, 2025).

5 CONCLUSIONS

Coffee by-products are rich in chlorogenic acids, polyphenols, melanoidins, and dietary fibers, exhibiting strong antioxidant, anti-inflammatory, and metabolic health benefits. Optimizing processing strategies to improve the bioavailability of key bioactive compounds is essential for maximizing the functional value of coffee by-products. In parallel, long-term safety assessments and the establishment of stability and standardization criteria are critical prerequisites for their successful commercialization as functional food ingredients. With growing demand for sustainable functional foods, coffee by-products hold great potential as valuable resources contributing to human health and circular economy development.

6 AUTHOR CONTRIBUTIONS

Conceptual Idea: Park, E.; Kwon, K.H.; Methodology design: Park, E.; Kwon, K.H.; Data collection: Park, E.; Data analysis and interpretation: Park, E.; Kwon, K.H.; and Writing and editing: Park, E.; Kwon, K.H.

7 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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