

Sustainable Repurposing of Coffee By-Products: A Systematic Review of Bioactive Potential and Safety Risks

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Abstract

This systematic review (2020–2025) synthesizes evidence from recently peer-reviewed studies to evaluate the sustainable repurposing of coffee by-products. The analysis addresses four research questions (RQs) focused on chemical composition, application, safety, and sustainability. Quantitative results for RQ1 (bioactive composition) confirm that 100% of the studies identify high phytochemical density, notably chlorogenic acids, caffeine, and melanoidins. Specific benchmarks include caffeine levels up to around 31 mg/g in silverskin and a 6–10% lipid fraction in spent coffee grounds (SCG). For RQ2 (the application of the by-product) the evidence primarily concentrates on bakery products (bread, biscuits, gluten-free formulations) and beverages (teas, kombucha, soft drinks), followed by dermato-cosmetic formulations like creams and exfoliants. Critically, RQ3 (safety issues) reveals a significant evidence gap; while 10 hazard categories including mycotoxins and acrylamide were identified, standardized toxicological data remains fragmented. Similarly, RQ4 (sustainability aspect) remains conceptually strong but empirically weak, with only less than 15% of studies providing quantitative indicators such as life cycle assessment (LCA) metrics. Despite qualitative support for circular economy integration, the lack of standardized safety protocols and human clinical trials limits regulatory approval. This manuscript integrates compositional value, real-world functionality, regulatory-relevant safety (including microbiology), and decision-useful sustainability into a single PRISMA-guided evidence map, making it a translational assessment rather than a descriptive inventory.

Keywords: antioxidant activity, bioactive compounds, cascara, circular economy, coffee by-products, functional ingredients, safety assessment, silverskin, spent coffee grounds

1. INTRODUCTION

Coffee is a commodity that is among the most traded agricultural products in the world with the production of more than 10 million tons annually which tends to leave a vast amount of organic residues in the agricultural sectors as well as processing, roasting, brewing and processing [1]. One kilogram of green coffee yields various kilograms of by-products: pulp, husk, cascara, mucilage, silverskin and used coffee grounds, many of which remain unexploited or wasted [2][3]. Out of control, these residues are associated with ecological burdens such as soil and water pollution, greenhouse gas, and difficulties in disposing of these residues in their production areas [4].

The growing popularity of coffee across the world is accelerating this waste flow, which explains why there is an urgent need to create valorisation pathways that can contribute to sustainability and resource efficiency. Coffee by-products are the products of different parts of the value chain with various chemical and functional profiles. During wet processing, the fleshy coffee pulp (mesocarp) is removed from the coffee cherry, whereas during dry processing, the dried outer layers are removed during hulling, producing coffee husk [5]. Silverskin is produced in the roasting process and used coffee grounds are produced in the preparation of the beverage [6][7]. Defects or immature beans (a smaller yet still important share) are also deposited in the sorting processes [8]. The phenolic acids, melanoidins, dietary fibre, lipid, protein, mineral and alkaloid content of these materials make them good candidates in food, cosmetic, nutraceutical and packaging applications [9]-[11].

The increased awareness of sustainability in production systems and the circular bioeconomy has increased the amount of research on how to transform coffee by-products into functional high-value products. Cascara extracts, silverskin flours, coffee pulp fibre and spent coffee ground oils have

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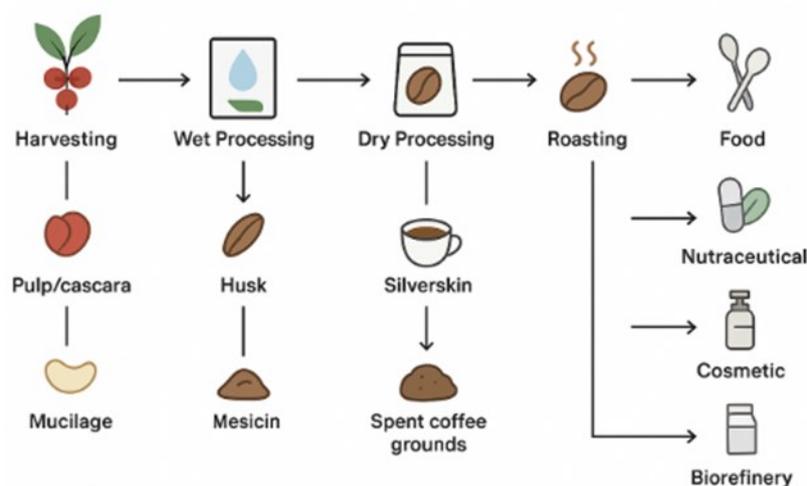


Figure 1. Global coffee production and waste generation context.

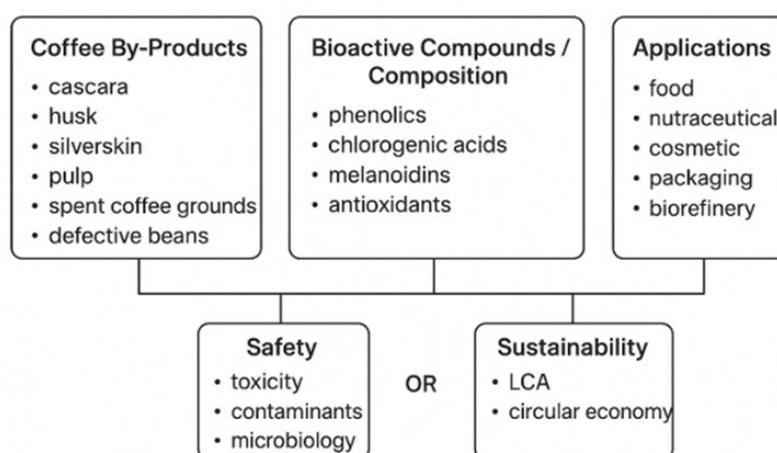


Figure 2. Search strategy conceptual diagram.

been shown to have antioxidant, anti-inflammatory, antimicrobial, and techno-functional properties [12]–[14]. Valorisation pathways go in line with the global sustainability goals of minimizing waste, developing new sources of revenues to the producer, and substituting synthetic additives with natural bioactive compounds [15][16]. The latest developments in the green extraction, nonthermal processing, and biorefinery models help to make the technological innovation in the field even faster [17][18].

Although the number of studies conducted has been increasing rapidly, there is still a lack of evidence on the topic in the spheres of analytical chemistry, food technology, toxicology, and sustainability. Extraction practices, units of reporting, methods of analysis, and the conditions under which they are processed differ across studies making it difficult to compare studies across [7][9]. Safety evaluations are not always communicated:

some reports assess mycotoxins, acryl amide, heavy metals, or genotoxicity [19]–[21], but others only assess the composition and bioactivity, leaving a lot to be desired. Besides, there is a lack of environmental and socio-economic studies on coffee by-product valorisation, and very few studies present the quantitative data on life cycle [11][18]. The synthesis is hence unified, systematic and needs to be made comprehensive to offer clarity between these different streams of evidence.

The present systematic literature review (SLR) will be the synthesis and critical review of the existing evidence on the uses of coffee by-products as functional ingredients in food, nutrition, cosmetic, and other applications. Particularly, the review will be a synthesis of chemical composition and bioactive profiles, technological and sensory use, safety and toxicological discovery, and sustainability framing of the scientific literature in the recent period. The combination of these areas

has a unified basis on which the review can inform future research, product development, regulatory examination, and circular-economy policies.

This flow diagram in [Figure 1](#) represents the key coffee production chain process - harvesting and wet/dry processing, followed by roasting and brewing, and the streams of by-products that result at each of the stages, such as husk, pulp/cascara, mucilage, silverskin, spent coffee grounds (SCG), and flawed beans. The key valorisation pathways that are currently being investigated in the scientific literature are also highlighted in the diagram and include food and beverage applications, the development of nutraceutical and functional-ingredients and cosmetic formulations, packaging materials, and more general biorefinery or circular-economy applications. The diagram gives a comprehensive picture of the movement of waste products in the coffee value chain and where upcycling and the use of the material can be realised. In this review, cascara is used as an ingredient term for dried coffee cherry outer material (skin with variable residual pulp depending on processing), while coffee pulp refers to the wet-processing mesocarp stream. Coffee husk refers to

the dried outer layers from dry processing. Where primary studies use overlapping naming, we retain the authors' term but interpret it within these operational definitions for consistent synthesis.

Recent reviews have made important contributions by consolidating evidence on coffee by-products in specific domains, including food-oriented applications and ingredient development [6][9] and advances in separation and extraction strategies for recovering valuable fractions [10]. Building on these foundations, our manuscript provides a distinct and more systematic contribution by applying a preferred reporting items for systematic reviews and meta-analyses (PRISMA)-guided workflow and focusing on the most recent five-year evidence base (2020–2025), thereby capturing the latest methodological advances and translational trends. We further integrate composition and applications with regulatory-relevant safety (contaminants, toxicology, microbiology) and decision-useful sustainability reporting (system boundaries and comparability), supported by an adapted Joanna Briggs Institute (JBI) appraisal to interpret confidence and translational readiness across the literature.

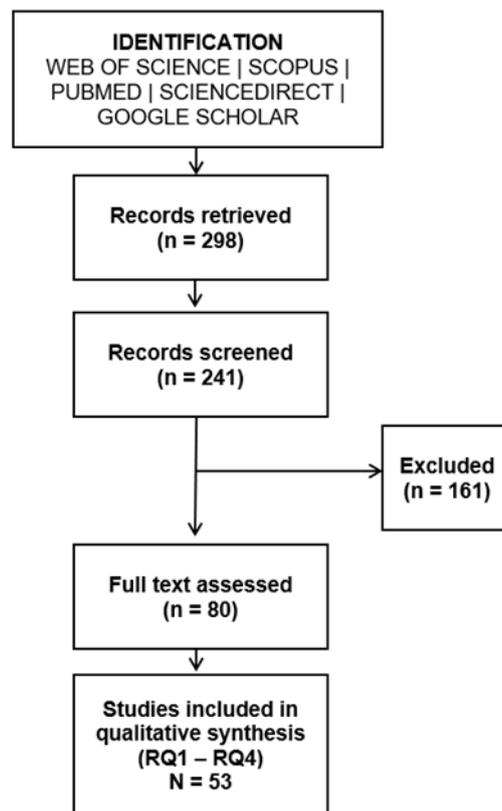


Figure 3. PRISMA flow diagram for study selection.

Table 1. Data extraction form.

Category	Variables Extracted	Description of Data Collected
General information	Author(s), year, country, journal, study type	Bibliometric data and the study design (analytical, experimental, compositional, application-based and sustainability).
Material Details	By-product type, source/origin, Processing method, pretreatment	Coffee-by product type/waste (casca, husk, pulp, silverskin, SCG, defected), source, condition of processing (wet/dry), storage and pretreatment.
Extraction / processing	Extraction technique, Solvent/ conditions, green extraction methods, process parameters	Covering maceration, aqueous extraction, ethanolic extraction, ultrasound, microwave, supercritical CO ₂ , green extraction methods, temperature, time duration and yield.
Chemical composition	Phenolics, chlorogenic acid (CGA), flavonoids, melanoidins, fibre, lipids, alkaloids; Analytical techniques	Confirmation of key phytochemicals; these are used to analyze components (HPLC, LC-MS, GC- diseases in plants, spectrophotometry).
Bioactivity outcomes	Antioxidant activity (DPPH, FRAP, ABTS, ORAC), anti-inflammatory, antimicrobial, UV-protection	Any reported biochemical or functional activity relevant to RQ1, including assay type, units, and key results.
Application findings	Food applications, nutritional improvements, cosmetic formulations, Technological properties	Real life applications (breads, beverages, yogurts, emulsions, creams), influences on physicochemical properties, sensorial features, and stability results (RQ2).
Safety assessments	Toxicity tests, contaminants, microbiological results, regulatory notes	Mycotoxins, heavy metals, acrylamide, microbial count, cytotoxicity/genotoxicity (RQ3).
Sustainability indicators	LCA data, circular-economy framing, waste-reduction metrics, socioeconomic aspects	The implication to environmental modelling, valorisation, waste minimization, rural development and resource-efficiency outcomes (RQ4).

2. MATERIALS AND METHODS

2.1. Protocol and Reporting Framework

The systematic literature review was done in line with the guidelines of PRISMA 2009 of transparent reporting of systematic reviews [22]. To reduce selection bias and the methodological consistency of the review process, the review protocol, research questions, eligibility criteria, search strategy, screening procedures, and data-extraction structure were designed a priori. The protocol established the analytical framework to be used in the evaluation of

evidence with regard to the valorisation of coffee by-products into functional ingredients in food, nutrition, cosmetic, and sustainability areas.

2.2. Research Questions

The four main research questions that were covered in the review were: RQ1: What are the bioactive compositions, antioxidant or other bioactivities of coffee by-products?, RQ2: How have these by-products been utilized in formulating food, nutrition and cosmetics and what are the technological or functional uses or purposes?, RQ3:

What are the chemical, microbiological or toxicological hazards identified or estimated?, and RQ4: What do research reports say about the sustainability or the circular-economy advantages of valorising coffee by-products?

2.3. Eligibility Criteria (PICO Concept)

2.3.1. Types of Materials (Population / Material)

The studies had to be eligible, meaning they had to investigate one or more coffee by-products as identified as husk, cascara/pulp, silverskin, spent coffee grounds (SCG), parchment, or defective/

immature beans used as or proposed to be used as a functional ingredient, extract, or formulation in food, nutrition, cosmetic, or packaging applications. Papers that had only studied green or roasted coffee beans, biofuel production, composting, adsorption materials, construction materials, or other non-ingredient usages were excluded.

2.3.2. Concepts / Interventions

The research studies fulfilled at least one of the following domains: (1) Bioactive profiling/chemical composition (i.e., phenolics, melanoidins, lipids, dietary fibre). (2) Antioxidant or other

Table 2. Quality appraisal criteria used for included studies.

Quality Criterion	Definition	Assessment Focus
Sample characterisation	Reporting on type of by-product, origin, processing, pretreatment, and physicochemical properties are adequate.	Whether the study makes clear the sources of materials, the stage of processing (e.g., cascara, silverskin, SCG), storage conditions and significant compositional descriptors.
Analytical rigour	Relevance, responsiveness, and integrity of methods of analysis applied in quantification of chemical elements.	Validated procedures (HPLC, LC -MS, GC -MS, spectrophotometry), replicates, controls, analytical accuracy and precision.
Methodological transparency	Completeness of methodological reporting allowing reproducibility.	Informativeness of the methods of the extraction, parameters, solvents, experimental conditions, sample preparation, and statistical analysis.
Bioactivity assessment validity	Use of appropriate and reliable assays to determine antioxidant, anti-inflammatory, antimicrobial, or other functional activities.	Proper execution of the assay (DPPH, FRAP, ORAC, ABTS), control addition, standard references, unit reporting and clinical interpretation of the results.
Safety assessment completeness	Extent to which safety-related endpoints were tested and reported.	Screening of contaminants (mycotoxins, heavy metals, acryl amide), toxicological screening (in vitro/ in vivo), microbiological screening, and regulatory contextualisation.
Application-based evaluation quality	Strength of testing done applies formulations that are in food, nutrition, or cosmetic matrixes.	The quality of sensory evaluation, the measures of technology, the stability application, and the relevance of the formulation in practice.
Sustainability and circular-economy reporting	Inclusion and clarity of environmental or socioeconomic data.	LCA parameters, resource-efficiency metrics, waste-reduction indicators, and circular-economy frameworks.
Overall study coherence and bias risk	Intra rater consistency, correct interpretation of results and clarity of limits.	Logical structure, potential conflicts of interest, funding disclosure, and clarity of limitations.

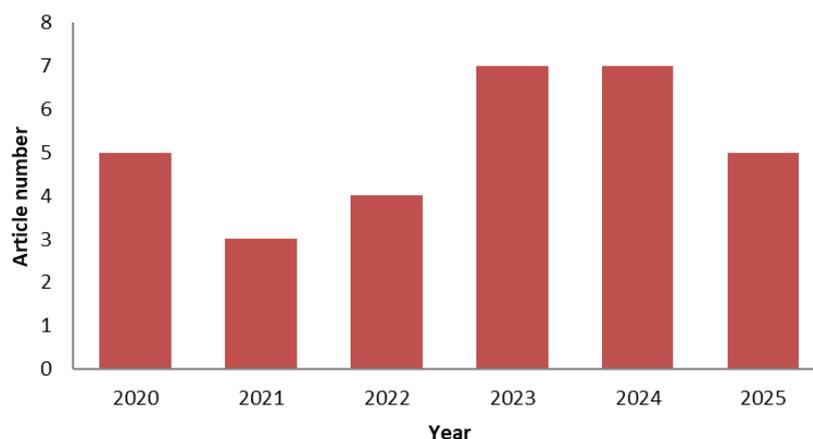


Figure 4. Trends in publications on coffee by-products (2020–2025).

biological characteristics (e.g., DPPH, FRAP, ORAC, anti-inflammatory activity or enzymatic test). (3) The formulations could be food, nutrition, cosmetic or packaging. (4) safety or hazard evaluation (e.g. mycotoxins, acrylamide, heavy metals, toxicology).

2.3.3. Outcomes

The primary outcomes of this review encompassed the quantitative characterization of chemical composition and bioactive constituents, alongside reported antioxidant and other biological activity values. They also included the functional and technological effects observed when these by-products were incorporated into food, nutritional, or cosmetic formulations, as well as any documented contaminants, toxicological indicators, or microbiological parameters relevant to safety assessment. In addition to these core outcomes, the review considered secondary aspects such as environmental evaluations, sustainability metrics, and broader claims related to circular-economy benefits.

2.3.4. Study Design, Language, and Time Frame

Qualifying designs could be any of the following: analytical studies, *in vitro* assays, *in vivo* models, formulations studies or human sensory or safety studies. The only inclusion criteria were original studies; review and proceedings were considered only as citation chasing. Articles published in the English language between January 2020 and December 2025 were taken into consideration.

2.4. Information Sources and Search Strategy

Detailed searches were conducted in Web of science, Scopus, Pubmed/Medline, Science Direct and Google Scholar. Google Scholar was used only for citation chasing and supplementary searches, not as a primary systematic database. The review of reference lists of the included studies and other related reviews were also used to identify additional. The search query involved controlled vocabulary and free-text wording in three boolean logic conceptual blocks:

Block 1: Coffee by-products

("coffee by-product*" OR "coffee byproduct*" OR cascara OR "coffee husk" OR "coffee pulp" OR "coffee silverskin" OR "spent coffee ground*")

AND

(composition OR phytochemical* OR antioxidant* OR application* OR toxicolog*)

Block 2: Bioactives / functions

(composition OR phytochemical* OR "bioactive compound*" OR "chlorogenic acid*" OR phenolic* OR flavonoid* OR caffeine OR diterpene* OR trigonelline OR "fatty acid*" OR "metabolomic*" OR "lipidomic*" OR "chemical profile" OR antioxidant* OR "DPPH" OR "ABTS" OR "FRAP" OR "ORAC")

Block 3: Application context

(application* OR utilisation OR utilization OR "value-added" OR "functional propert*" OR techno-functional OR "food application*" OR "cosmetic*" OR "nutraceutical*" OR ingredient* OR

formulation* OR "bioactive extract*" OR "material application*")

Safety add-on terms:

(safety OR toxicolog* OR hazard* OR contaminant* OR "heavy metal*" OR "pesticide residue*" OR acrylamide OR mycotoxin* OR genotox* OR cytotox* OR "acute toxic*" OR mutagenic* OR allergen*)

Sustainability add-on terms:

(sustainab* OR "circular econom*" OR "life cycle assessment" OR LCA OR "carbon footprint" OR "environmental impact" OR valorisation OR valorization OR "waste valorisation" OR "waste valorisation")

The following conceptual diagram depicts the search strategy, which was followed in this systematic review, and it was based on three main blocks of keywords: (1) coffee by-products, which include cascara, husk, pulp, silverskin, spent coffee grounds, and defective beans; (2) bioactive compounds and compositional terms, including phenolics, chlorogenic acids, melanoidins, alkaloids, fibre and antioxidant activity; and (3) applications, including food, beverage, nutraceutical, cosmetic, packaging, Searches were

narrowed down further with two more modifier blocks: safety and sustainability, which were applied to the searches related to toxicology, contaminants, microbiology, LCA, and circular-economy. The visual representation of the search terms incorporation within databases using Boolean operators (AND / OR) was used to allow thorough search of RQ1-RQ4 relevant literature (Figure 2).

2.5. Study Selection

All records that were retrieved were automatically deduplicated by importing them into a reference-management system. The review was done in two stages: (1) screening against exclusion criteria title and abstract. (2) Methodological relevance, richness of data and alignment of outcomes: Full-text screening. Controversies were solved by unanimity. Reasons of exclusion were due to the article content that consist of absence of pertinent outcomes, inappropriate type of by-products, non-ingredient emphasis, or absence of detail on methods.

The following flow diagram (Figure 3) is a PRISMA summary of the identification, screening, eligibility, and ultimate inclusion processes of this systematic review. A total of five major databases (Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar) were searched using a

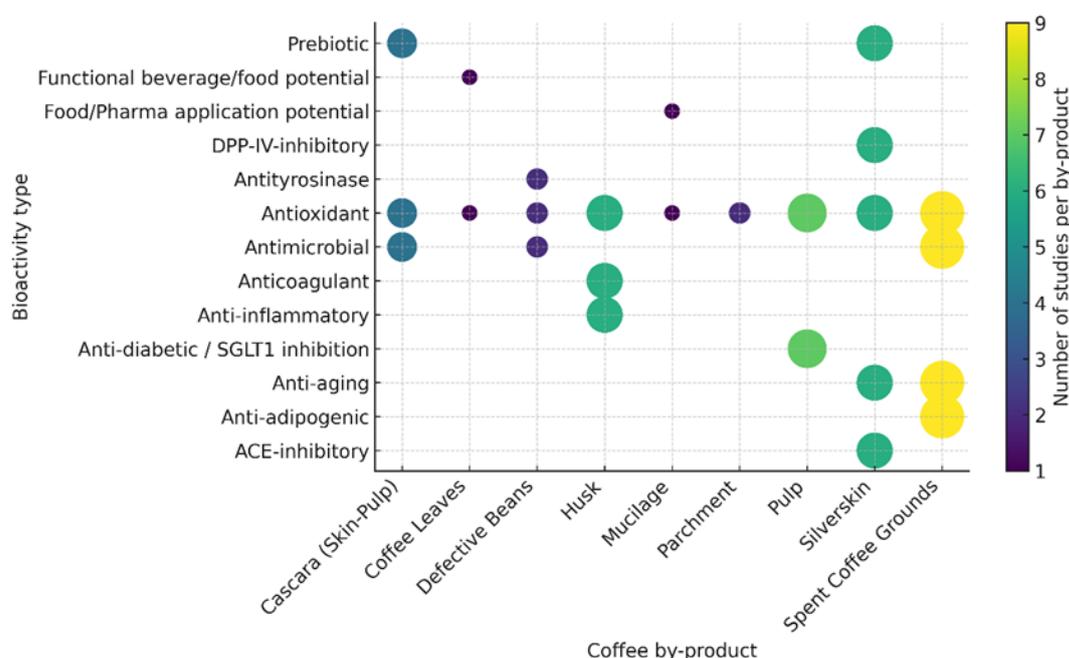


Figure 5. Bubble plot - comparative profile of major bioactive groups in coffee by-products. (Bubble size shows how many studies reported that item, and bubble colour shows the category of outcome (see legend))

structured three-block search strategy of coffee by-products, bioactive composition, and application terms, and modifiers of safety and sustainability. Following the removal of duplicates, titles and abstracts were filtered and then the full-text was scanned using preset eligibility criteria. The diagram specifies the number of records that are discarded at each step and reports the final number of studies that are included in the qualitative synthesis that is related to RQ1–RQ4. The figure follows the PRISMA guidelines of reporting 2009. The full list of excluded studies with reasons for exclusion, together with the stepwise screening workflow, is provided in supplementary data.

2.6. Data Extraction

The process of extracting the desired key variables of all the studies involved was done using the Data extraction form which included general bibliographic data, material properties, extraction and processing data, compositional and bioactivity data, application information, safety evaluations and sustainability measures (Table 1). The framework was developed relying on the PRISMA 2009 concepts and modified to the RQ1-RQ4 analytical framework.

2.7. Quality Appraisal / Risk of Bias

The quality of the methodology of each study was evaluated with the help of an adapted JBI checklist of the experimental, analytical, and in vitro designs. Such criteria as clarity of the aims, sample characterisation, extraction or processing transparency, analytical validity, replication, use of control, statistical reporting, and relevance to ingredient applications were considered (Table 2).

The criteria used in quality appraisal of all the studies included, adapted the known methodological evaluation tools to use in experimental, compositional, application-oriented, and safety-oriented research. Each of the studies was rated according to the clarity of sample characterisation, rigour of analysis and methods, transparency and reproducibility of procedures, validity of bioactivity tests and completeness of safety testing. These were the criteria that were employed in evaluating overall study robustness and risk of bias.

3. RESULTS AND DISCUSSION

3.1. Overview of Included Studies

This systematic literature review included 53 studies which passed the eligibility criteria in the review. These sources encompassed the years 2020 to 2025, meaning that there is the heightened interest of the scientific community in the valorisation of coffee by-products as a functional ingredient. The published sources involved were focused not only on a large number of regions, but the most represented ones were Latin America, Europe, and Asia, which implies that the coffee by-products research is highly uniform across the countries where coffee is produced and those which have developed technologies [4][9]. The types of studies were varied (analytical chemistry and bioactivity tests (e.g., [7][10]), food and beverage formulation studies [13][23], or toxicology/safety studies [19]-[21]). Most studies clearly described the coffee by-product and reported the main results, but a few did not report enough detail on method checks and repeat measurements, so the strength of evidence varies (see Tables S1 – S2).

The most common by-products that were studied included cascara /pulp, spent coffee grounds, silverskin and husk and less on defective beans. This predominance is unsurprising: cascara and pulp have long-standing cultural uses in producing countries [24], while spent coffee grounds are widely available in consumer markets through household and industrial coffee brewing [14]. In contrast, defective beans, parchment, mucilage and coffee leaves were explored far less often, typically in small-scale or exploratory studies. In terms of research focus, chemical composition and antioxidant properties remain the most reported areas. A substantial number of studies also examined techno-functional and formulation-related applications, particularly in food, beverage and cosmetic contexts. Meanwhile, work related to safety, including contaminants and toxicity assessments, and sustainability, such as environmental impact or circular-economy positioning, is increasing but still less developed overall [18].

Trends in the publication of coffee by-products 2020–2025 using the studies incorporated in this systematic review (Figure 4). The figure

Table 3. Key bioactive compositions of coffee by-products according the type of byproducts.

By-Product Type	Coffee Species	Extraction Method/ Fraction Type	Key Bioactive Components Measured	Composition / Bioactivity Values	Antioxidant / Other Bioactivities	References
Pulp	Arabica, Robusta	Aqueous, ethanol, propylene glycol, ultrasound-assisted extraction (UAE), SUPRAS	Chlorogenic acids, caffeine, trigonelline, polyphenols, flavonoids, tannins	TPC: 9.29 mg GAE/g; Caffeine: 3.6 mg/g; Chlorogenic acid: 9.2 mg/g; total flavonoid content (TFC): 58.8 mg QE/g; TTC: 8.7 mg TAE/g	DPPH: 7.6 mg TEAC/g; ABTS: 13.6 mg TEAC/g; FRAP: 10.9 mg FeSO ₄ /g; anti-diabetic (SGLT1 inhibition); increased antioxidant after fermentation	[7][25]-[27] [41]-[43]
Husk	Arabica, Robusta	Ethanol, aqueous, hydrolyzable/non-extractable polyphenols, pressurized liquid extraction (PEF) + microwave-assisted extraction (MAE)	Caffeine, chlorogenic acids, gallic acid, caffeic acid, polyphenols, flavonoids	TPC: up to 6.54 g CAE/100g; Caffeine: 5.36–3787.6 mg/100g; phenolic acids, flavonoids, minerals (K, Ca)	DPPH: up to 3.11 g TE/100g; FRAP: up to 17.68 g FeSO ₄ /100g; anticoagulant, antioxidant, anti-inflammatory	[7][11][27] [28] [37] [44]
Silverskin	Arabica, Robusta	Pressurized liquid extraction, hydroalcoholic, enzyme-assisted, UHPLC-Q-Orbitrap HRMS	Caffeine, chlorogenic acids, feruloylquinic acids, melanoidins, polyphenols, peptides	Caffeine: 6–31.2 mg/g; chlorogenic acids: 0.22–10.6 mg/g; TPC: 52.3–88.4 mg GAE/g; Peptides: 0.3 mg/mL	ABTS: 101.6 µmol Trolox/g; FRAP: 132.3 µmol Fe(II)/g; ACE-inhibitory, DPP-IV-inhibitory, prebiotic, anti-aging, antioxidant	[7][29]-[31] [45][46]
Spent Coffee Grounds	Arabica, Robusta, blends	Hydroethanolic, ethanol, acetone, PLE, supercritical CO ₂ , UAE, solid-liquid extraction	Caffeine, chlorogenic acids, polyphenols, fatty acids, melanoidins, diterpenes	TPC: 15.99–38 mg GAE/g; caffeine: 1.15–6.14 mg/g; chlorogenic acids: 0.83–8 mg/g; oil: 6.3–10.5%; linoleic acid: 39–43%	DPPH: up to 3136 µmol TE/100g; FRAP: up to 4408 µmol TE/100g; anti-adipogenic, anti-aging, antimicrobial, antioxidant	[32]-[36] [47]-[50]
Cascara (Skin-Pulp)	Arabica, Robusta	Aqueous, DART-MS, HPLC-ESI-HRMS, conventional/microwave extraction	Caffeine, chlorogenic acids, polyphenols, flavonoids, organic acids, minerals	93 non-volatile molecules; Caffeine: present; Chlorogenic acids: 17 types; K, Ca, P, S, Mg, Cl; TPC: higher in Arabica	DPPH: 45%; ABTS: 91%; high antioxidant, antimicrobial, prebiotic potential	[10][11][37] [38]
Defective Beans	Arabica	Enzyme-assisted, aqueous, solid-liquid extraction	Caffeine, chlorogenic acids, polyphenols, flavanols, flavonoids, tannins	TPC: up to 6.54 g CAE/100g; caffeine: higher than silverskin; polyphenols: higher than silverskin	DPPH: up to 3.11 g TE/100g; FRAP: up to 17.68 g FeSO ₄ /100g; antioxidant, antityrosinase, antimicrobial	[7][30]

Table 3. Cont.

By-Product Type	Coffee Species	Extraction Method/ Fraction Type	Key Bioactive Components Measured	Composition / Bioactivity Values	Antioxidant / Other Bioactivities	References
Parchment	Arabica	Aqueous, DART-MS	Caffeine, chlorogenic acids, polyphenols, minerals	Caffeine: present; chlorogenic acids: present; K, Ca, P, S, Mg, Cl	Antioxidant, mineral-rich	[7][11]
Mucilage	Arabica	Ethanol, methanol, acetone, UHPLC-DAD-TQ/MS	Hydroxybenzoic acids, vanillic acid, rutin, polyphenols	HBC: higher in husk; vanillic acid: efficient extraction with 80–90% EtOH; Rutin: all solvents	Antioxidant, potential for food/pharma applications	[39]
Coffee Leaves	Arabica	UAE, Taguchi design, RSM	Trigonelline, caffeine, chlorogenic acids, mangiferin, rutin, polyphenols	TPC: 62.1 mg GAE/g; mangiferin: 4.1 mg/g; 5-CQA: 11.4 mg/g; DPPH: 356.9 μ mol Trolox/g	Antioxidant, functional beverage/food potential	[40]

demonstrates the increment of scientific output on the topics of composition, applications, safety and sustainability of cascara, husk, pulp, silverskin, spent coffee grounds and defective beans. Across the included literature, the dominant designs were laboratory-based compositional profiling and extract-driven *in vitro* bioactivity assays, followed by proof-of-concept food/cosmetic formulation studies; comparatively few studies used *in vivo* models, human sensory panels, or regulatory-style safety testing. Major limitations were heterogeneous processing and extraction conditions, inconsistent reporting units and outcome metrics, and incomplete reporting of validation, replication, and statistics. Safety and sustainability evidence was particularly uneven, with scarce microbiological datasets and limited, non-comparable LCA-style assessments.

3.2. Chemical Composition and Bioactive Profiles (RQ1)

Table 3 makes it very clear that coffee by-products are not just “waste”, but a family of matrices with quite different bioactive profiles and levels of scientific maturity. Pulp and husk already sit in a relatively comfortable position: they combine meaningful phenolic content with solid *in vitro* antioxidant activity, and first signs of more specific functions, such as SGLT1 inhibition and improved redox status after fermentation for pulp [7][25]-[27] and anticoagulant or anti-inflammatory effects for husk [7][11][28]. In the bubble plot (Figure 5) this shows up as medium-sized bubbles covering antioxidant plus one or two additional bioactivity categories, so these streams look already validated, but still with obvious space to deepen mechanistic understanding and move beyond *in vitro* endpoints.

Silverskin and spent coffee grounds clearly form the most advanced cluster. Silverskin brings together high phenolic and caffeine levels with peptide fractions that show *in vitro* ACE and DPP-IV inhibition, prebiotic traits and preliminary anti-aging activity [7][29]-[32]. SCG adds another layer, with relevant total phenolic content (TPC), strong DPPH/FRAP values, a lipid fraction rich in unsaturated fatty acids, and reported anti-adipogenic, antimicrobial and anti-aging effects depending on the fraction and formulation [33]-

[36]. In the bubble plot, both by-products show large, dark bubbles spanning several bioactivity types, which reflects not only functional diversity but also the higher number of studies feeding into [Table 3](#). Practically, this means silverskin and SCG are already strong candidates for targeted food, nutraceutical and cosmetic ingredient development rather than just theory or simply research objects. However, it should be noted that the included studies report outcomes in heterogeneous units (e.g., mg/g, g/100 g, $\mu\text{mol TE}$ and related formats), which reduces direct comparability across studies and prevents robust quantitative pooling of results.

The remaining by-products sit more at the edge of the current evidence map, but they are not empty. Cascara has a surprisingly complex non-volatile profile and consistently good antioxidant, antimicrobial and prebiotic signals [10][11][37][38], while defective beans show TPC and caffeine levels comparable to normal beans plus anti-tyrosinase and antimicrobial activities [7][30]. Parchment, mucilage and coffee leaves are more superficially described, but still come with measurable antioxidant capacity and, in the case of leaves, high mangiferin and chlorogenic acid contents that fit well with a functional tea narrative [7][11][39][40]. In the bubble plot these materials appear as small, pale bubbles in one or two bioactivity rows. This is a good visual reminder that they are under-explored rather than uninteresting; the biology is probably richer than what is currently published.

Taken together, [Table 3](#) and the bubble plot tell a simple but useful story. Where research effort has been concentrated and more advanced extraction or fractionation has been applied, we see a broader portfolio of bioactivities and a clearer route to application, as in silverskin and SCG. Where only basic extractions and a few antioxidant assays have been done, we mainly see “antioxidant only” bubbles with low evidence density, as in parchment, mucilage and leaves. For the next wave of work, a sensible strategy is to push the “front-runner” by-products towards concrete product concepts, while deliberately applying the same analytical depth and extraction creativity to the neglected streams to see if they can move from small, single-function bubbles to the multifunctional cluster.

3.3. Applications in Food, Nutrition, and Cosmetics (RQ2)

[Table 4](#) shows the overall applications of coffee by-product in various field. Applications were in food, beverage, nutraceutical, cosmetic and packaging systems. Cascara was completely popular in drinks, teas, kombucha, and bakery use [13][23][24]. Silverskin was added to bread, biscuits and even emulsions, and it even was an additive applied into bread as a natural preservative [51]. SCG was found in bakery, bars, along with functional food prototypes [14]. This was used as an antioxidant extract, preliminary or mechanistic study of anti-inflammatory formulation, exfoliating particle, and photoprotective formulation [12]. Where reported, effects related to gut health or glycaemic modulation are primarily supported by preclinical or animal studies, with limited and non-generalizable evidence in humans.

In applications to bakery and beverages, coffee by-products provided benefits in terms of antioxidant retention, water-holding capacity or fat-binding capacity, as well as in terms of colour intensity owing to natural pigments [7][23]. Silverskin extracts also enhanced the oxidative stability of emulsions and creams, as well as provided natural colouring or fragrance [12][52]. SCG lipids, improved the lipid-based formulations and showed stabilisation properties. The outcomes of senses were encouraging; the inclusion of low to moderate (1-5 percent) was rather acceptable, whereas higher values ranged to bitterness, dark color, or different textures [23][53]. Cascara drinks have demonstrated good complex flavours [24]. The higher quality of dietary fibre and phenolics, the enhanced ability antioxidants in fortified food products were discovered in some of them [7][14]. There were in vivo anti-inflammatory and metabolic benefits [54]. By-products of coffee specifically cascara and silverskin, showed UV-protective anti-inflammatory and antioxidant properties, which could be used as dermato-cosmetics [12]. Silverskin particles were equally used as natural exfoliants [52].

[Figure 6](#) which is related to [Table 4](#), reflecting the usage of the major coffee by-products that include husk, cascara/pulp, silverskin, spent coffee grounds and defective beans as used in the food, nutrition and cosmetic industries. The figure

Table 4. Applications of coffee by-products in food, nutrition, and cosmetic formulations.

By-Product Type	Application Domain (Food / Nutrition / Cosmetic)	Product Type	Ingredient Role	Technological / Functional Effects	Sensory Outcomes	Nutritional / Functional Outcome	Authors' Application Conclusion	Ref.
Husk	Food	Bread, baked goods	Fibre source, antioxidant	Improved structure, colour, oxidative stability	Acceptable at moderate inclusion	↑ fibre, ↑ phenolics	Feasible as functional flour	[7]
Cascara / Pulp	Food	Gluten-free bread, beverages	Dietary fibre source, antioxidant extract	↑ water absorption, ↑ stability	Good acceptability up to 5–10%	↑ antioxidant activity	Suitable for clean-label products	[23] [55]
Silverskin	Food	Fresh-cut produce, bakery	Natural preservative, antioxidant	Extended shelf-life, reduced browning	Neutral flavour impact	↓ oxidation	Effective at low doses	[51] [52]
SCG	Nutrition / Food	Bars, beverages, supplements	Lipid source, antioxidant	↑ stability, ↑ texture, ↑ binding	Acceptable at low %	↑ lipids, ↑ antioxidant capacity	Promising for functional foods	[14]
Defective Beans	Food	Bakery and blends	Phenolic contributor	Minor functional effects	Slight sensory change	Some antioxidant enhancement	Applicable in low ratios	[56]
Cascara	Nutrition	Kombucha beverages	Antioxidant & anti-inflammatory extract	Improved bioactivity & colour	Positive consumer response	↑ intracellular antioxidant effects	Functional beverage potential	[13]
Coffee Berry Pulp	Nutrition	Extract-based supplements	Polyphenol source	Bioactivity enhancement	Not evaluated	↓ metabolic biomarkers	Promising nutraceutical	[54]
Silverskin	Cosmetic	Creams, lotions, exfoliants	Antioxidant, photoprotective agent	Stabilises emulsions	No irritation reported	↑ UV-protection potential	Suitable for dermo-cosmetic uses	[12]
Mixed By-Products	Food / Nutrition	Extracts, powders	Antioxidant, fibre	Stability improvements	Varies	↑ phenolics	High functional versatility	[9]
Cascara	Food	Soft drinks	Caffeine & phenolic source	Improved flavour complexity	High consumer interest	Mild stimulant effect	Viable alternative beverage base	[57]

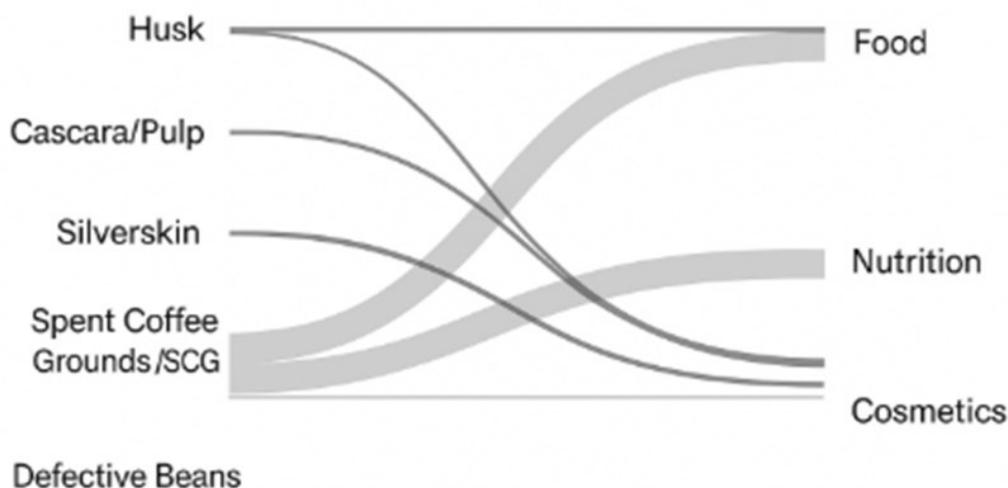


Figure 6. Application domains summary diagram.

(Color intensity indicates the relative frequency of reported applications across studies, while category blocks represent major formulation domains)

illustrates the abundance of each type of by-product in each of the classes of formulations (indicating the most common areas of application e.g., bakery products, beverages, nutraceutical extracts, emulsions, creams) and gives the information of the ways of valorisation of the pathways of each type diversified in recent publications. The most stable functional roles were antioxidant enhancement, fibre enrichment and natural colouration. The best levels of inclusion were typically less than 5% but the extract-based uses were flexible to higher dose levels. In most of the studies, sensory evaluation was also restricted, which indicates the research gap.

The cumulative results relevant to RQ2 provide a great possibility of coffee by-products as natural antioxidants, fibre-based functional ingredients, prebiotic, stabilisers, and sensory-modifying substances. Research on baked goods, beverages, gluten-free recipes, and kombucha show the increase of antioxidant activity, fibre, and occasionally shelf-life [13][23]. However, cascara, pulp, and silverskin are nutritionally, and the authors argue that such products could play important roles in gut health, glycaemic moderation, and oxidative stress management [58]. Cosmetic use is another promising field especially in the use of antioxidant serums, UV-modulations extracts, and exfoliating particles. Ruse et al. [12] make the case around *Coffea arabica* compounds as useful dermatocosmetics, and this practice is in line with industry trends of moving to plant-based

actives. Melanoidin and phenolics of coffee can also be used as natural preservatives and antimicrobials, which support clean-label formulation trends [51].

3.4. Safety and Hazard Findings (RQ3)

As can be observed exhaustively in Table 5, various hazard for safety measure remain to be found in the coffee by-product. Safety evidence in the reviewed literature ranges from regulatory-oriented assessments aligned with novel food or contaminant frameworks to exploratory in vitro toxicological screenings, which differ substantially in evidentiary weight. Mycotoxins [19], acryl amide and Maillard reaction product [2][59], heavy metals [20][58], pesticides, microbiological quality, and in vitro genotoxicity were all covered by safety evidence [21]. Assessments were not uniform among types of by-products: silverskin and cascara were most assessed. Studies of mycotoxins typically provided values that were lower than the regulatory limits, but it varied based on the origin and drying methods [19]. Rasted cascara drinks contained acrylamide but in reasonable quantities [2]. Silverskin levels of heavy metal were low [20]. Occasionally, there was evidence of pesticide residue in some SCG samples although they were generally below maximum residue levels [58]. The extracts of silverskin proved to be not cytotoxic on the tested cell models [20]. Shopping and pulp extracts were genotoxicity risk low, but some in vitro studies gave contradictory results [21].

Table 5. Hazards identified across coffee by-products.

By-Product Type	Hazard Type	Specific Analyte / Toxicological Endpoint	Reported Levels / Findings	Microbiological Safety	Overall Safety Conclusion	Reference
Cascara (Coffee Cherry)	Mycotoxins, process contaminants	OTA, acrylamide, melanoidins	Acrylamide detected at low µg/kg levels; OTA not detected in most samples	Not reported	Safe within tested doses for beverage use	[2][19]
Cascara (Dried Pulp)	Oxidative degradation, contaminants	HMF, CGA degradation products	Drying method influenced HMF formation; CGA retained	No pathogens reported	Suitable for food applications if dried properly	[55]
Silverskin	Toxicological evaluation	Acute/subchronic toxicity, melanoidin reactivity	No toxicity observed in <i>in vivo</i> or <i>in vitro</i> models; melanoidins stable	Microbial counts within safe limits	Considered safe as a novel food ingredient	[20]
Silverskin (Torrefacto & Natural)	Heavy metals, PAHs	Pb, Cd, As; PAHs	Metals within legal limits; PAHs detected at very low levels	Not reported	Safe for tested food applications	[52]
SCG	Chemical contaminants	Lipid oxidation products, residual caffeine	Moderate lipid oxidation; caffeine high but expected	Not reported	Safe with controlled processing	[14]
Coffee Pulp	Toxic elements	Heavy metals, pesticide residues	Metals largely below food safety limits; pesticides minimal	Not reported	Safe for nutraceutical use with monitoring	[59]
Mixed By-Products	Alkaloids	Trigonelline	Toxicological thresholds not exceeded	Not reported	Low risk under normal consumption	[56]
Coffee By-Products (General)	Polyphenol toxicity	CGA and isochlorogenic acids	No adverse effects at intake levels typical of by-products	Not reported	CGAs safe; low toxicity risk	[59]
Coffee By-Products (General)	Genotoxicity	In vitro DNA damage assays	Contradictory: some extracts genotoxic at high doses; others protective	Not applicable	Requires dose-standardized toxicological study	[21]
Cascara Beverage	Process contaminants	Acrylamide, melanoidins	Acrylamide present at low levels; melanoidins safe	Not reported	Safe with controlled roasting/drying	[2][19]

Cascara extracts were shown to have metabolic benefits despite no side effects in animal studies [54]. Contradictory *in vitro* genotoxicity findings likely reflect differences in extraction methods, dose ranges, and model systems rather than definitive evidence of intrinsic genotoxic risk.

Overview of hazards in chemical, microbiological, and toxicological risks of major coffee by-products (husk, cascara/pulp, silverskin, spent coffee grounds, and defective beans) according to the research published in 2020–2025. The table presents the type of contaminants (mycotoxins, process contaminants, heavy metals, pesticide residues), microbiological hazards where possible, the toxicological effect, and the general safety interpretation by the authors of the study.

Figure 7 illustrates the hazard category, it is shown as heatmap of the prevalence of hazard as determined in major coffee by-products, cascara/pulp, husk, silverskin, spent coffee grounds, defective beans, and mixed by-product extracts, when measured by studies published between 2020–2025. The figure presents the frequency and intensity of the hazard reporting in five major categories which are mycotoxins, process contaminants (acrylamide, HMF), heavy metals,

pesticide residues, and toxicological/microbiological. The darker shade shows the greater number of studies that reported a particular hazard category of a specific type of by-product showing gaps and lack of balanced safety data coverage in the literature.

The findings of safety topic (RQ3) show that there is an uneven scenery. A number of studies report relatively low concentrations of heavy metals, pesticides residues, and mycotoxins, but it is occasionally overloaded and has gaps in data which should be approached with caution [19][20]. Acrylamide and melanoidin issues are also present in high temperature processed streams, especially, silverskin and SCG [2]. The *in vitro* research on toxicology provides inconsistent results on genotoxicity, indicating the necessity to conduct additional rigorous and long-term and *in vivo* studies [21]. Regulatory frameworks are slowly changing as noted by EU novel food assessments on silverskin and cascara, but harmonised safety evaluation standards are still missing. The discrepancies witnessed among the studies highlight the need to have a common safety measure to follow before these by-products are incorporated in food and cosmetic markets on a large scale.

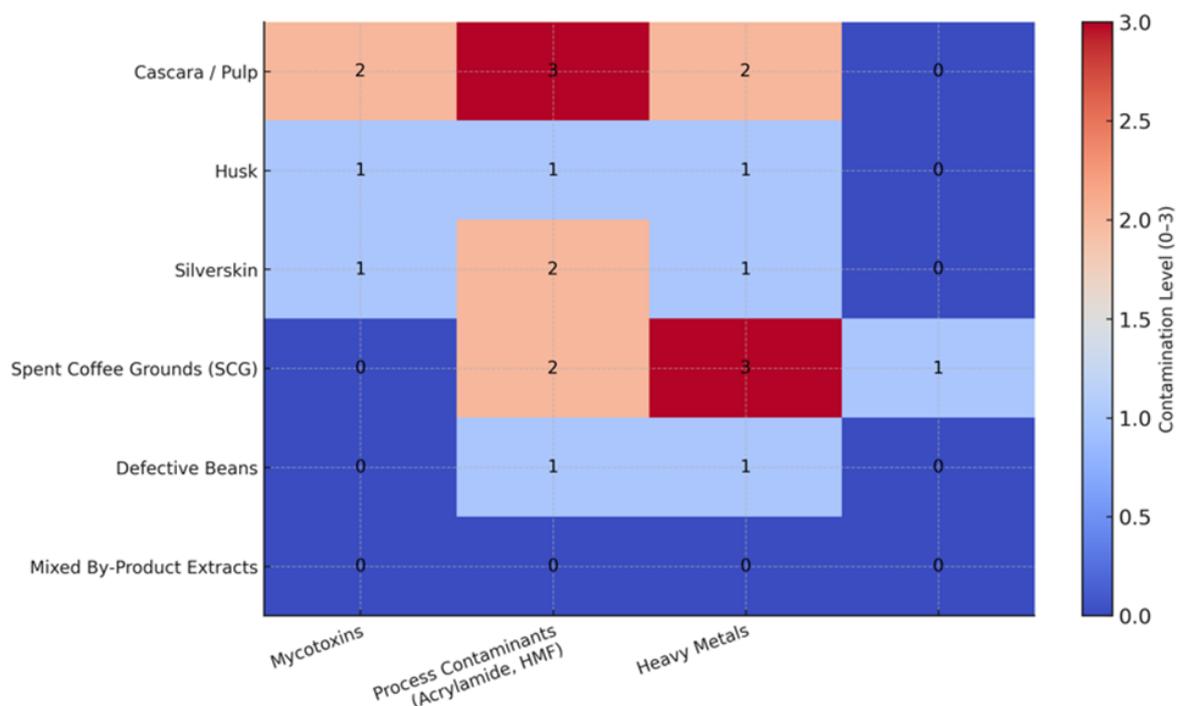


Figure 7. Heatmap of hazard categories vs. by-product type.

(Cell color and the embedded values indicate the relative frequency of reporting in the included studies (0 = not reported, 1 = low, 2 = moderate, 3 = high), with red shading reflecting higher reporting frequency and highlighting gaps in safety coverage)

3.5. Sustainability and Circular-Economy Themes (RQ4)

Table 6 is the synthesis of the environmental indicators (waste reduction potential, energy use, and beneficial compound extracts), socio-economic benefits, and circularity narratives cited in the publications published in 2020–2025 and its implementation in the limited but still emerging quantitative sustainability data. Related to Table 6, Figure 8 is an illustration of coffee processing steps and its related valorisation pathways which connected to their respective beneficial output in the context of sustainability issues. In the literature as listed in Table 6, valorisation of coffee by-products was always associated with the decrease in wastes, resource conservation, and the process of cyclic integration [15][16]. The authors indicated the opportunities of replacing synthetic contents, product diversification, and green manufacturing. Quantitative environmental indicators were only used in a few studies. According to Nutrizio et al. [18], LCA-based evaluation of green extraction technologies recorded lower energy and emissions. Bojorquez-Quintal et al. [11] had community-level sustainability advantages.

Other studies emphasized increment of farmer income, local hiring, as well as rural growth in case the by-products are up-cycled instead of being down-cycled [11][15]. Still other ones stressed that costs of waste-management will be less and the resources will be more circular [16]. The current sustainability evidence base remains insufficient for regulatory evaluation or industrial decision-making because it is often qualitative, non-comparable across studies, and frequently lacks the methodological elements required for decisions e.g., clearly defined functional units, transparent system boundaries, complete inventories, and appropriate baselines or counterfactual scenarios.

Illustrated in Figure 8, a sustainability value chain conceptual map depicting the flow of the coffee by-products in primary production and processing (farm, wet/dry milling, roasting) through waste stream generation (husk, pulp/cascara, silverskin, spent coffee grounds, defective beans), and then by valorisation routes (food, nutraceuticals, cosmetics, packaging materials, biorefinery processes) and then environmental and socioeconomic benefits (waste reduction,

integration into a circular economy, reduced emissions, new sources of income, rural development, resource efficiency). The diagram focuses on the role of each of the stages on a circular bioeconomy model.

In the literature, the positive effects of the sustainability aspect are greatly highlighted but are hardly ever measured. Whereas the qualitative assertion prevails, the few LCAs to be found have pointed to positive environmental results. The socioeconomic analyses are not developed. The valorisation of coffee by-products contributes to the goals of the circular-economy through minimising agricultural wastes, creating alternative economic sources, and lowering the usage of virgin resources. Several reports highlight the socioeconomic possibilities of the decentralised, place-based valorisation models specifically among rural populations and smallholder farmers [11]. Green extraction further helps in upcycling the waste materials, thereby lowering the degradation of the environment [17][18]. In spite of these optimistic signs, sustainability arguments are much more of a qualitative nature. The quantitative LCA data are restricted and not always complete thus they cannot be compared to conventional ingredients strongly. Circular economy claims and policy or industry integration should be supported with much more detailed environmental modelling such as GHG emissions, water footprint, and potential waste reduction.

3.6. Synthesis of the Overall Findings

It is a systematic review that presents a synthesis, compositional, functional, safety, and sustainability evidence on significant coffee by-products, including cascara, pulp, husk, silverskin, spent coffee grounds (SCG), and defective beans. Throughout the studies included, there is a general consensus that these materials are rich in phenolics, chlorogenic acids, melanoidins, alkaloids, dietary fibre, and other antioxidant compounds, and that they are biochemically rich and can be used as functional ingredients. New developments in mechanistic health effects also show potential technological, nutritional, and cosmetic applications, which have been incorporated into bread, beverages, emulsions, kombucha-based products, and dermatocosmetic formulations [12]

Table 6. Sustainability framing and LCA evidence for coffee by-product valorisation.

By-Product Type	Sustainability Framing in the Study	Environmental Indicators Reported (LCA / LCI)	Socioeconomic or Circular-Economy Claims	Overall Sustainability Interpretation	Reference
Cascara / Coffee Pulp	Waste valorisation, reduction of solid residues	Not a full LCA; mentions energy savings from drying optimisation	Added value for farmers through cascara beverages	Positive potential but lacks full quantitative assessment	[2][55]
Silverskin	Upcycling into food & cosmetic ingredients	Not LCA-based; environmental benefit inferred from substituting synthetic antioxidants	Supports circular economy by integrating roasting waste	Strong sustainability framing, evidence qualitative	[20][12]
Spent Coffee Grounds (SCG)	Biorefinery and zero-waste utilisation	Some studies report energy balance/processing efficiency	Potential income through local reprocessing	Positive impact but fragmented quantitative data	[14]
Coffee Husk	Circular reuse in food applications	No LCA values; environmental benefits described conceptually	Added value in rural regions where husk disposal is a problem	Promising but lacking numerical validation	[7]
Coffee Pulp / Berry	Sustainability through polyphenol extraction	Not full LCA; mentions low processing impacts for aqueous extracts	Provides low-cost, high-value nutraceutical ingredients	Evidence supportive but preliminary	[54][58]
Defective Beans	Waste minimisation, alternative use	No environmental metrics	Helps reduce losses in processing; supports circularity	Sustainability argument weak without LCA	[56]
Mixed By-Products	Upcycling and resource efficiency	Some energy and environmental efficiency metrics available	Local circular chains for SMEs	Shows promising sustainability potential	[9]
Coffee By-Products (General)	Circular bioeconomy positioning	Reviews identify lack of full LCAs	Highlights potential socioeconomic benefits	Field recognised as promising but under-quantified	[2][59]

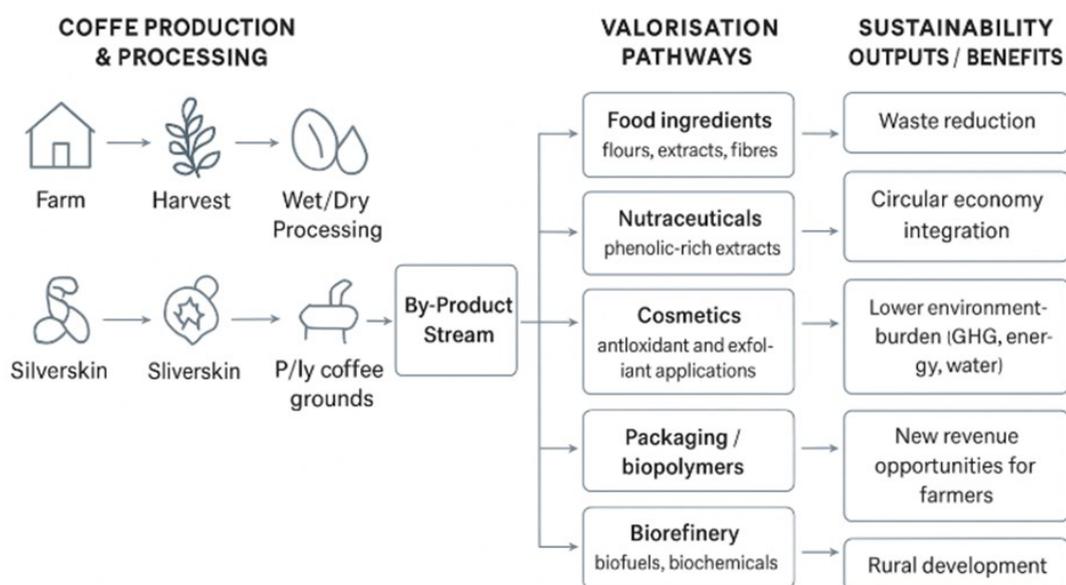


Figure 8. Sustainability value chain for coffee by-product valorisation.

[23][53]. Evidence on safety is still more fragmented. Although several chemical pollutants, toxicological endpoints, and microbial factors have been analyzed especially in silverskin, SCG, and cascara, the data is not consistent between studies, with some significant differences in the scope of hazard assessments [21][20]. The sustainability themes are also clearly expressed at the conceptual level, and several studies also connect by-product valorisation with the framework of the circular economy; nevertheless, the quantitative environmental measurements are not frequent, which does not allow concluding about the environmental performance in the firm [15][16]. On the whole, the review illustrates the existence of an fast-growing, yet disproportionate body of evidence, with abundant biochemical and application-focused data being opposed to severe gaps in safety and sustainability studies.

The most convincing evidence to support the reuse and valorisation of coffee by-products show up in RQ1, in which compositional and bioactivity analyses, including HPLC, LCMS, GCMS, spectrophotometry, and antioxidant analysis, are repeatedly used to confirm the high phytochemical density coffee by-products [7][9]. These research are sound in terms of their methodology and sustainable throughout different regions and processes. Application-oriented research (RQ2) also exhibits the growing rigour, particularly sensory

research, physical-chemical modelling of food matrices and dermatological formulations. Conversely, the weakest pillar is safety (RQ3). Quantitative contaminant analysis is also presented in only a subset of studies, and toxicological studies are usually based on initial in vitro endpoints as opposed to full-scale, multi-tier endpoints [56][58]. There is a lack of microbiological, allergenicity, and chronic toxicity. The conceptual appeal of sustainability evidence (RQ4) is empirically weak, with the limited LCA-based analyses of the topic suggesting positive trends but insufficient harmonisation in the approaches [18]. Therefore, the composition and application research is maturing, whereas the safety and sustainability evidence is characterized by fragmentation in its methodology, which restricts the confidence of cross-domain inferences.

3.7. Implication and Research Agenda for the Future

To continue the scientific and commercial development of coffee by-products, it is necessary to coordinate the development in a number of fields. Standardisation of extraction protocols is necessary to facilitate comparability of findings of compositional and bioactivity of the findings since present heterogeneity clouds mechanistic insight. Equally, the harmonised bioactivity reporting standards such as common antioxidant assays,

reference compounds and units would radically enhance the synthesis of evidence in food, nutrition and cosmetic applications. The safety issue in the long term is a knowledge gap. The future work ought to put more emphasis on chronic toxicity tests, microbiological risk-tests and multi-tier toxicological tests to create regulatory confidence particularly on the populations that are vulnerable. Sustainability claims and high impact upcycling pathways require strong life-cycle assessment and socioeconomic impact analysis. Where life-cycle assessments were reported, system boundaries were often limited (e.g., partial or gate-to-gate approaches) or insufficiently described, preventing robust comparison across studies and underscoring the need for standardized LCA frameworks in future research. Lastly, new evidence of nutritional and other functional benefits should be subjected to human clinical studies, especially to validate antioxidant, metabolic or dermatological benefits and permit functional labelling laws to be approved.

4. CONCLUSION

The present systematic review provides an integrated synthesis of compositional, functional, safety, and sustainability evidence on major coffee by-products, including cascara, pulp, husk, silverskin, spent coffee grounds, and defective beans. Across the reviewed literature, these materials consistently show high contents of phenolics, chlorogenic acids, melanoidins, alkaloids, dietary fibre, and other bioactive compounds, supporting their potential use as functional ingredients in food, nutrition, and cosmetic applications. Application-oriented studies demonstrate promising technological performance, including antioxidant enhancement, fibre enrichment, and functionality in bakery products, beverages, emulsions, and dermatocosmetic formulations. These findings align with current industry interests in clean-label, plant-based, and multifunctional ingredients, particularly for valorising agri-food residues. In contrast, evidence related to safety and sustainability remains uneven. While several studies report low to moderate levels of chemical contaminants and largely non-toxic profiles under tested conditions, safety assessments are fragmented and often limited to selected

endpoints, with scarce data on microbiological safety and long-term exposure. Similarly, sustainability is frequently discussed within circular-economy frameworks, yet quantitative life-cycle assessments are rare and methodologically heterogeneous, limiting robust environmental comparison. Overall, the literature indicates that coffee by-products hold substantial potential as value-added ingredients, but their broader adoption will depend on improved methodological standardisation, more comprehensive safety evaluations, and harmonised sustainability assessments. Addressing these gaps will be essential to support regulatory confidence, industrial scalability, and evidence-based integration of coffee by-products into food, nutrition, and cosmetic value chains.

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Conflicts of Interest

The authors declare no conflict of interest.

SUPPORTING INFORMATION

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DECLARATION OF GENERATIVE AI

During the preparation of this work, the authors used Large Language Model tools (Google Gemini) to improve the readability, grammar, and flow of the English language. Additionally, AI-assisted reference management software was used to organize citations and ensure formatting consistency. The authors affirm that these tools were used exclusively for editorial and formatting purposes; no AI tool was used to generate scientific concepts, data, or interpret results. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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