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Spent Coffee Grounds

Beyond the Brew:
The Hidden Potential of Spent Coffee Grounds

CENTER FOR CIRCULAR ECONOMY IN COFFEE

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For more information, contact:
C4CEC info@circulareconomyincoffee.org

Street address: Via Bologna 32, Turin, Italy
Postal address: 10152, Italy
E-mail: info@circulareconomyincoffee.org
Website: www.circulareconomyincoffee.org

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Beyond the Brew: *The Hidden Potential of Spent Coffee Grounds*

Founding members and Strategic partners

Fondazione Lavazza

Politecnico di Torino

Università di Scienze Gastronomiche di Pollenzo

International Coffee Organization

International Trade Centre

UNIDO
United Nations Industrial Development Organization

Acknowledgement

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The report was prepared by Mariamawit Solomon, Projects and Operations Lead at C4CEC, who led the research, content development, editorial work, and overall strategic design, with guidance and oversight from Dario Toso, Head of the Scientific Board, Katherine Oglietti, Coffee Guide Network Coordinator at ITC and Co-Coordinator at C4CEC and Ariana Ocampo, Junior Economist at ICO. All original graphics and layout were developed by Fabiana Rovera, PhD candidate at PoliTO, Sara De Menech, Research Fellow at PoliTO, Erica Lombardo, Research Fellow at PoliTO and Maira Campanella, Research Fellow at UNISG.

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The paper leverages findings from a 2025 assessment conducted on scalable circular opportunities using coffee byproducts in Ethiopia, conducted in partnership by C4CEC, Women in Coffee Ethiopia (WICE), and International Trade Centre (ITC), with funding from The Spanish Agency for International Development Cooperation (AECID) and the Ministry of Foreign Affairs of the Netherlands. It also includes findings from a global coffee sector survey, distributed through multiple channels, including the C4CEC membership network and The International Trade Centre (ITC) Coffee Guide Network community. We hope this white paper motivates participants across the global coffee value chain to work with business, technical, and development partners to accelerate the shift from a linear to a circular model.

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Abstract

This white paper examines the potential to transform spent coffee grounds (SCGs), an estimated 11 million tons of annual coffee waste into a strategic resource for the circular bioeconomy. It analyzes SCGs composition and valorization pathways across agriculture, food, cosmetics, energy, and advanced materials, highlighting their potential to reduce greenhouse gas emissions by up to 76% compared to landfill disposal. Drawing on scientific evidence, primary and secondary research, market insights, and policy frameworks, the paper identifies opportunities for business innovation and socio-economic inclusion, alongside barriers such as fragmented collection systems, high moisture content, and regulatory ambiguity. Case studies illustrate real-world success stories, while market demand analysis and impact estimates offer data-driven perspectives for scaling solutions. It concludes with actionable recommendations to align policy, finance, and collaboration, enabling integrated biorefineries, localized processing hubs, and cascading use strategies that position SCGs as a cornerstone of a circular coffee economy.

Executive Summary

The value of coffee goes beyond the beverage. The entire coffee plant contains valuable bioactive compounds and characteristics sought after in a variety of industries. Yet when we brew a cup of coffee, less than 5% of the original coffee cherry remains in our cup. The remaining 95% of the coffee cherry can become either a waste management problem with real environmental implications, or an opportunity to generate new business, improve agricultural productivity, and mitigate climate change.

Spent coffee grounds (SCGs) are the primary solid residue remaining after the brewing of roasted, ground coffee. They represent one of the largest waste streams in the coffee consumption phase, generated daily across industrial, commercial, and domestic contexts. Today, the coffee sector generates 11 million tons of SCGs annually, making it one of the largest food-related waste streams worldwide. When discarded in landfills, SCGs emit more than 700 kg of CO_2 equivalent per ton, primarily in the form of methane, a greenhouse gas 25 times more potent than CO_2. With coffee consumption rising, the stakes are clear: we must rethink SCGs not as waste, but as a renewable feedstock for sustainable growth.

The Circular Opportunity

SCGs are rich in cellulose, lignin, lipids, proteins, and antioxidants—compounds that make them valuable across multiple industries. From organic fertilizers and mushroom substrates in agriculture to fiber-rich food ingredients, caffeine-based skincare, biofuels, and even textiles and bioplastics, SCGs offer a pathway to transform waste into wealth. Circular models built around SCGs valorization can unlock new income streams for women and youth, addressing structural inequities in the coffee sector while creating jobs and fostering innovation.

Environmental Gains

Valorizing SCGs delivers measurable climate benefits. Life cycle assessments show that SCGs transformation can reduce emissions by up to 76% compared to landfill disposal. When SCGs are used for bioenergy, greenhouse gas emissions can be reduced by up to 50% compared to fossil fuels. Beyond emissions, circular strategies conserve water and resources, helping maintain balance within planetary boundaries, countering coffee's resource intensity. It takes approximately 140 liters of water to produce a single cup of coffee, and the carbon footprint of each cup is estimated at 0.45 kg CO_2 equivalent.

Unlocking the Value of SCGs

SCGs are not merely waste; they represent a significant source of bioactive and structural compounds. Their composition and potential applications are shown in *Table 1*. These compounds make SCGs a versatile feedstock for industries ranging from agriculture to advanced materials.

Challenges to Scale

Despite their potential, SCGs valorization faces challenges. The high moisture content of fresh SCGs (often exceeding 60%) complicates storage, transportation, and retention of desirable properties, requiring energy-intensive drying or stabilization. Collection logistics remains a major barrier due to the dispersed nature of coffee consumption, where waste

SCGs components	*Chemicals*	*Property*	*Application*
Cellulose & Hemicellulose	Sugars	Substrate for fermentation	Bioplastics, textiles, packaging
Lignin	Phenolic polymers	Antioxidants, mechanical strength, binding, thermal stability	Cosmetic formulations, bio-based chemicals and energy systems, bioplastics
Proteins	Acids	Antioxidant, antimicrobial	Bio-stimulants, nutraceutical, animal feed, food ingredient, soil amendment
Lipids	Oleic acids Linoleic acids Palmitic acids Tocopherols	Antioxidant, antiaging	Bio-oils & emulsions for cosmetics
Phenols & Bioactive Compounds (including residual caffeine)	Chlorogenic acids Caffeic acids Flavonoids	Antioxidant, anti-inflammatory	Pharmaceutical, nutraceutical, cosmetics
Nitrogen Compounds and Minerals	Nitrogen and Minerals including magnesium, potassium, phosphorus, calcium, and iron	Support plant fertility	Agricultural use as soil amendment and biofertilizer, food

Table 1. Composition and potential of SCGs

generation occurs diffusely across households and cafés rather than centralized facilities. Compositional heterogeneity is another barrier. SCGs composition varies depending on coffee species, brewing method, and roasting conditions, leading to inconsistencies in functional properties and safety profiles. Such variability complicates the standardization of extraction protocols and quality control for food-grade applications. Finally, regulatory ambiguity further limits progress. These materials occupy a complex regulatory space that intersects waste management, food safety, cosmetics legislation, and renewable energy policy. Lack of harmonized waste classifications, end-of-waste criteria, and clear safety protocols continues to act as a structural barrier to progress. Effective valorization strategies therefore depend not only on technological feasibility but also on the legal re-classification of SCGs from "waste" to "secondary raw material" or "by-product" under national and supranational legislation.

Call to Action

Unlocking SCGs potential requires coordinated action:

- ***Policy Alignment** to harmonize waste classifications and end-of-waste criteria*
- ***Financing and IP Strategies** to de-risk investments and support innovation*
- ***Collaboration** among coffee producers, innovators, and policymakers to scale circular solutions globally*

With supportive frameworks and investment in scalable technologies, SCGs can become a cornerstone of the circular bioeconomy — turning coffee waste into a driver of climate resilience, social inclusion, and green innovation.

Key Takeaways

- SCGs are generated in three main contexts: industrial, commercial, and domestic.
- **Controlled collection and pre-processing to stabilize SCGs is essential** in order to prevent contamination from food residues and contaminants, especially in a cafe, restaurant, or mixed waste environment.
- Coffee generates **11 million tons of SCGs annually**, one of the largest food-related waste streams.
- **Landfilling SCGs emits over 700 kg CO_2 per ton**, while life cycle assessments demonstrate that valorization can reduce these emissions by up to 76%.
- **For every kilogram of instant coffee, 2 kg of wet SCGs are produced**, underscoring industrial-scale waste.
- SCGs contain valuable properties including **cellulose, lignin, lipids, proteins, and antioxidants**, enabling applications in agriculture, food, cosmetics, textiles, and energy.
- The lipid component can be recovered as **coffee oil**, an ingredient of increasing interest in the cosmetic and pharmaceutical industries.
- Residual caffeine in SCGs, though lower than in raw coffee beans, remains valuable for topical products targeting circulation, supporting anti-cellulite and firming cosmetic formulations.
- Circular models create **new income streams for women and youth** in coffee producing countries, promoting equity and inclusion.
- **Moisture content and fragmented collection** remain major logistical challenges.
- **Regulatory ambiguity** and waste classification limits scaling; reclassification is essential particularly for food and cosmetics applications.
- **Local processing hubs and reverse logistics** can cut costs and emissions.
- Financing and IP strategies are critical to **scale circular innovations and attract investment**.

Introduction

Unavoidable food waste refers to food components not intended for human consumption, such as eggshells and spent coffee grounds (SCGs) (Lee et al., 2024). While avoidable **food waste can be minimized through education**, **awareness**, and **improved management**, unavoidable food waste requires different strategies centered around efficient collection, handling, and transformation.

SCGs are the residual material left after brewing coffee, regardless of the method used. Globally, **the coffee sector produces approximately 11 million tons of SCGs each year** (ICO, 2024). From 1 ton of green coffee, roughly 650 kg of dry SCGs are generated, while producing 1 kg of soluble (instant) coffee results in about 2 kg of wet SCGs (Forcina et al., 2023; Drewnowski et al., 2025). With global coffee consumption steadily rising, **the volume of SCGs continues to grow**, creating both environmental challenges and untapped resource opportunities.

The Food and Agriculture Organization of the United Nations (FAO) emphasizes **minimizing unrecycled biowaste** as a critical step toward building a sustainable, green, and circular bioeconomy (Gebreeyessus, 2022). The **need for transformation in the coffee sector is increasingly evident**, with circular economy practices offering sustainable opportunities for cost savings, income generation, job creation, and workplace inclusion, while mitigating waste and avoiding environmental degradation. A **circular approach** plays a **critical role** in addressing mitigating climate change, biodiversity loss, and pollution, while opening equitable and inclusive economic opportunities, helping to maintain balance within planetary boundaries. By eliminating waste, keeping materials in use, and restoring natural systems, circular economy presents a framework for integrating environmental, social and economic solutions, with the coffee industry serving as a clear example.

Transitioning the coffee sector toward circularity is driven by **three major imperatives**:

SOCIO-ECONOMIC VALUE CREATION

Circular economy models not only reduce waste but also unlock new business opportunities by repurposing SCGs into value-added products such as biofertilizers, animal feed, cosmetics, and bioplastics. These innovations open new market segments not only for established corporations but also for smallholder farmers, women, and youth, who have historically been excluded from higher-value activities in the coffee sector. Globally, women account for 25–30% of the coffee workforce, yet their participation in ownership, training, and decision-making remains constrained. Despite performing up to 70% of manual labor at critical stages such as harvesting, sorting, and processing, women own only about 20% of the land used for coffee production (Everest, 2019; Eser, 2025). Youth face similar barriers: the average coffee farmer is now in their 60s, while most of the population in coffee-growing regions is under 30. Many young people perceive coffee farming as economically unviable and are leaving the sector altogether (Reuters, 2016; FAO, n.d). Without deliberate inclusion, the circular transition risks replicating these structural inequities.

Inclusive design is therefore essential. Localized recycling centers and SCGs processing facilities established near production or consumption hubs can create employment and entrepreneurship opportunities at the community level. Such models ensure that the economic and social benefits of circularity do not remain concentrated among multinational firms but instead uplift marginalized groups across the supply chain. Participation in circular initiatives has already shown promise: inclusive coffee programs have enabled women and youth to assume new roles in business development, gaining access to skills and income streams previously out of reach.

Evidence from advanced economies reinforces this potential. Between 2012 and 2018, employment linked to the circular economy in the European Union increased by 5%, reaching nearly 4 million jobs (European Commission, 2020). Similar approaches could translate into improved livelihoods, generational renewal, and greater social resilience for emerging markets. In this sense, the model is not only a sustainability add-on but a socially and economically viable engine for long-term development.

ENVIRONMENTAL GAINS: EMISSIONS REDUCTION AND RESOURCE EFFICIENCY

The urgency of reducing waste is amplified by coffee's resource intensity. It takes approximately 140 liters of water to produce a single cup of coffee, and the carbon footprint of each cup is estimated at 0.45 kg CO_2 equivalent (Kilgore, 2023). Allowing such a resource-intensive product to end as waste magnifies environmental costs, underscoring the importance of circular strategies that valorize SCGs.

Disposing of SCGs in landfills poses significant risks. Similar to other organic waste, SCGs release methane and carbon dioxide during decomposition, both of which accelerate climate change. When discarded in landfills, SCGs emit over 612 kg of CO_2 equivalent per ton. Methane is particularly harmful, with a global warming potential 25 times greater than carbon dioxide over a 100-year (Forcina et al., 2023) period. Recognizing these risks, the FAO (2020) identifies the reduction of unrecycled organic waste as a core pillar of a sustainable bioeconomy.

Composting offers one pathway, but it underutilizes the chemical richness of SCGs, which contain valuable compounds such as polyphenols, lipids, cellulose, and lignin. More advanced valorization options such as pyrolysis or biochemical extraction for building biological batteries can significantly amplify environmental benefits. Life cycle assessments demonstrate that SCGs transformation can reduce emissions to air by up to 76% compared to landfill disposal (Forcina et al., 2023). Furthermore, when SCGs are used for bioenergy, greenhouse gas emissions can be reduced by up to 50% compared to fossil fuel use (Eser, 2025).

The effectiveness of these approaches depends not only on waste valorization but also on logistics. Transport distances play a decisive role: local collection and processing models maximize environmental benefits by minimizing emissions along the supply chain. Thus, circularity is not simply a waste

EMISSIONS REDUCTION POTENTIAL OF SCG VALORIZATION

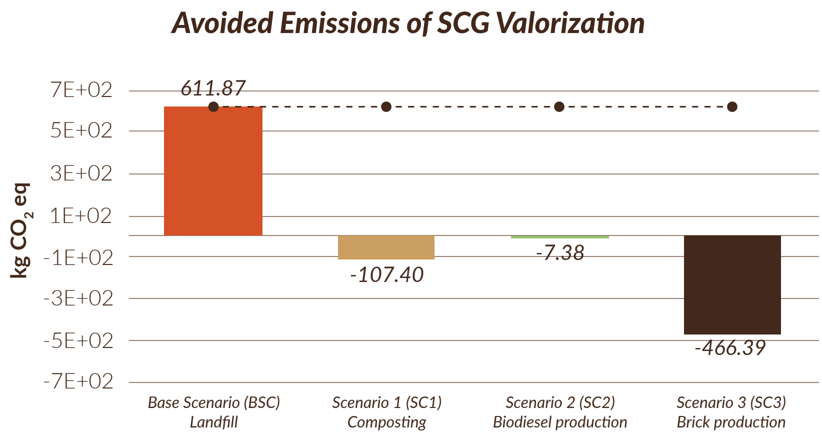


Figure 2. Avoided impacts related to the considered scenarios.

Adapted from Forcina et al., 2023

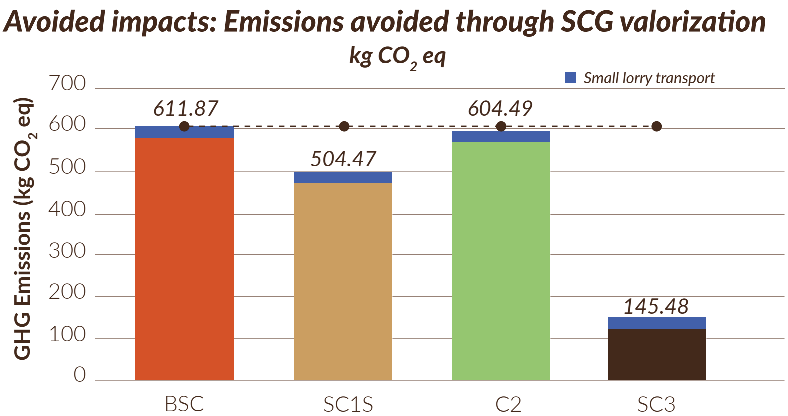


Figure 3. Environmental impacts of SCGs valorization systems: emission to air.

Adapted from Forcina et al., 2023

management solution, it is an essential mechanism for reducing emissions, conserving resources, and strengthening climate resilience.

BUSINESS INNOVATION AND ECONOMIC OPPORTUNITIES

The third imperative underpinning the transition toward circularity in the coffee sector is the creation of new business opportunities across diverse industries. SCGs, once discarded as waste, are increasingly recognized as a versatile raw material with applications in agriculture, textiles, food, energy, and advanced materials. This diversity highlights circularity not only as an environmental measure but as a catalyst for industrial innovation and economic growth.

In farming systems, SCGs are valued as an organic fertilizer, providing nitrogen, potassium, phosphorus, and micronutrients. SCGs have also been used as a growing medium for mushrooms, where their natural moisture content eliminates the need for additional drying, reducing costs and inputs while supporting circular agricultural models.

In the food sector, SCGs are being repurposed into new culinary applications. Dried SCGs can replace artificial coffee flavorings and colorants in confectionery and snacks, while also providing dietary fiber, protein, and caffeine. Local cafés can use this product to transform their waste into baked goods or sweets, fostering community-level circularity.

The fashion industry has also embraced SCGs as a novel material by integrating them into polyester or nylon filaments. These fabrics offer unique properties such as natural odor control, making them well-suited for sportswear and footwear. Beyond yarns, SCGs are also used as a natural dye, offering a sustainable alternative to synthetic dyes.

Beyond food and fashion, SCGs continue to hold promise in high-value technical applications. With a carbon content exceeding 50%, SCGs can be processed into activated carbon for use in filtration systems or nanostructured carbon for electrochemical devices such as supercapacitors and batteries (Mendes dos Santos et al., 2021; Hamedani et al., 2022; Lionetti et al., 2025). Their naturally porous structure, formed during brewing, reduces the need for intensive treatment, lowering processing costs while supporting the transition to renewable energy systems.

Collectively, these applications illustrate the breadth of economic opportunities unlocked through new industries and markets by valorizing SCGs.

Characterization of Spent Coffee Grounds

SCGs are a dark brown to black granular residue generated during the coffee brewing process. Because coffee is consumed on a global scale, SCGs are produced almost everywhere, from small cafés to large-scale industrial operations. This ubiquity makes **SCGs one of the most widely available organic by-products**. Their chemical and physical characteristics vary based on several factors, including the origin of the coffee, the degree of roast and the brewing or processing method. Moisture content and particle size also differ depending on extraction conditions, resulting in a highly heterogeneous material.

Despite this variability, **SCGs consistently exhibit high concentrations of organic matter**. Approximately 45–55% of their dry mass is carbon, and 2–2.5% is nitrogen, making them rich in bioactive and nutrient-dense compounds (Mendes dos Santos et al., 2021; Choe, 2025). Dietary fiber dominates the composition, primarily hemicellulose (~35–40%) and cellulose (8-15%), which together account for nearly half the total mass (Mendes dos Santos et al., 2021). Proteins, measured via nitrogen content, contribute around 10%, although this figure may include nitrogenous compounds formed through Maillard reactions during roasting and brewing (Choe, 2025). Lipids, which are largely retained during water-based extraction, make up 15–20% of the total composition, depending on coffee type and brew strength (Kresna et al 2024). These lipids include linoleic, palmitic, oleic, and stearic acids, and carry diterpenes like cafestol and kahweol, compounds known for both their health benefits and valorization potential (Vu et al., 2021; Iriondo-DeHond et al., 2019).

Chemical Components	Value
Total carbon (%,dwt)	61.13, 47.8 - 69.5
Total nitrogen (%,dwt)	2.91, 1.9 - 2.3
Carbon/nitrogen (C/N ratio) (wt)	21.00: 1, 19.80:1
Cellulose (Glucose) (g/100 g)	12.40±0.79, 36.7±5.0
Hemicellulose (g/100 g)	39.10±1.94, 36.7±5.0
Arabinose (g/100 g)	3.60±0.52, 1.7
Mannose (g/100 g)	19.07±0.85, 21.2
Galactose (g/100 g)	16.43±1.66, 13.8
Lignin (g/100 g)	23.90±1.70
Insoluble (g/100 g)	17.59±1.56
Soluble (g/100 g)	6.31±0.37, 1.6 - 1.7
Klason lignin (%, dwt)	30.9 - 31.9
Total dietary fiber (g/100 g)	60.46±2.19
Insoluble (g/100 g)	50.78±1.58
Soluble (g/100 g)	9.68±2.70
Lipids (wt%)	10 - 15
Protein (w/w)	13.60
Non-protein nitrogeous compounds (%)	3.70
Total sugars (mg/kg)	8.50±1.20
Total polyphenols (%, dwt)	1.50±1.00
Caffeine (%, dwt)	0.02 - 0.4526
Minerals (mg/kg)	-
Potassium (mg/kg)	11,700±0.01, 3549.00
Calcium (mg/kg)	1200±0.00, 777.40
Magnesium (mg/kg)	1900±0.00, 1293.30
Ashes (%,dwt)	0.43 - 2.20

Table 1. Characterization of spent coffee grounds.

Adapted from Drewnowski et al. (2025).

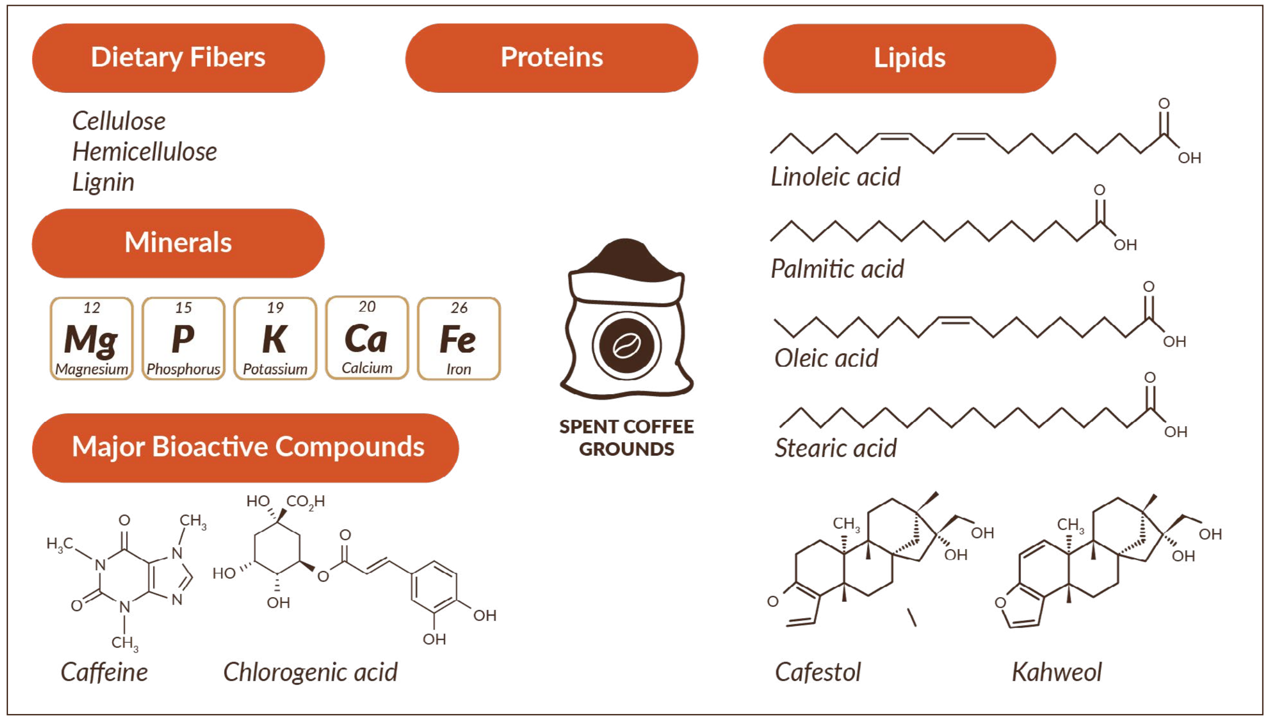


Fig. 4 Composition of SCGs

Adapted from Choe, 2025

SCGs also retain **notable amounts of caffeine** (typically <0.5% post-brewing) and **chlorogenic acids** (~2.3%), both of which are recognized for their antioxidant and anti-inflammatory properties (Mendes dos Santos et al., 2021, Vilas-Boas et al., 2020). In roasted coffee, caffeine varies by species and roast level. Arabica contains 0.0779–0.0909 mg/g (light to dark roast), while Robusta holds higher levels of 0.1399–0.2115 mg/g (Farikha et al., 2025). Despite partial solubilization during brewing, caffeine remains in SCGs as a bioactive compound valued in food, pharmaceutical, and cosmetic applications. Trace alkaloids such as theobromine, theacrine, and theophylline further enrich the SCGs biochemical profile (Choe, 2025).

Minerals including magnesium, potassium, phosphorus, calcium, and iron are also retained, enhancing the material's value as a soil amendment or input for nutrient recovery systems. Beyond primary compounds, SCGs contain secondary bioactives such as catechins, quinic acid, and a variety of phenolic acids: caffeoylquinic, ellagic, trans-ferulic, gallic, and p-coumaric acids, each offering potential use in nutraceutical and bioproduct formulations (Yusufoğlu et al., 2024).

Among **the most industrially significant components is lignin**, which makes up 20–25% of dry SCGs biomass (Drewnowski et al., 2025). As the second most abundant organic polymer on Earth after cellulose, lignin is gaining renewed interest for applications across material science, bio-based energy systems, and even advanced technologies such as aluminum-air batteries, where it enhances electrolyte performance and corrosion resistance (Arias et al., 2023).

The **carbohydrate content** of SCGs, particularly galactomannans (GMs) and arabinogalactans (AGs), **contribute to physical properties such as viscosity and foam formation in SCGs**. These polysaccharides are valuable for applications in food texture modification and encapsulation technologies. Their presence in SCGs opens possibilities for secondary use, especially given their resilience through the brewing process (Lopes et al., 2020).

Cellulose, the dominant structural polysaccharide, is another key SCGs component with high application potential. Traditionally sourced from wood and plant fibers, cellulose is increasingly being extracted from agricultural waste to address deforestation and sustainability concerns. **SCGs offer an eco-friendly, biodegradable alternative source of cellulose** suitable for packaging, textiles, and biomedical uses (Seki̇,2025).

However, **the practical value of this biomass is often limited by its biochemical instability**. Once brewed, exposure to oxygen and moisture accelerates the breakdown of key compounds such as caffeine, chlorogenic acids, and lipids. SCGs typically retain high levels of residual water, though the precise amount varies depending on the brewing method and handling post-extraction. Espresso-derived SCGs, for example, are compacted and therefore contain less surface moisture. In contrast, drip-brew and French press residues retain much higher levels of both free and bound water. This greater moisture content makes them inherently less stable.

This **variability in moisture is more than a compositional detail**; it directly dictates microbial stability, shelf life, and odor formation. **Moist environments foster rapid microbial proliferation**, including mold and bacteria, which in turn generate mycotoxins and degrade volatile aromatic compounds. Elevated water activity accelerates hydrolytic reactions in the lipid fraction of SCGs, liberating free fatty acids that are prone to oxidation, thereby producing rancid odors and undermining chemical integrity (Kresna et al., 2024). These changes reduce both the functional and sensory value of SCGs, limiting their use in higher-value applications such as food additives, cosmetics, or bio-based materials unless immediate stabilization methods (e.g., drying) are applied.

Additional contamination from food residues, cleaning chemicals, and oils, especially in SCGs collected from cafés, restaurants, or mixed-waste environments, further complicates valorization. Controlled collection and pre-processing are therefore required, which raises both operational costs and technical barriers.

Even so, **SCGs retain functional chemical groups such as carboxyl** (-COOH), **hydroxyl** (-OH), and **sulfur-containing moieties**. These groups enable SCGs to bind with heavy metals like lead, copper, and cadmium in aqueous environments, making them effective and low-cost adsorbents for wastewater treatment and environmental remediation (Choe, 2025).

Circular Economy Applications for SCGs

As Circular Economy principles gain traction, **SCGs valorization is emerging as a cost-effective and sustainable strategy**.

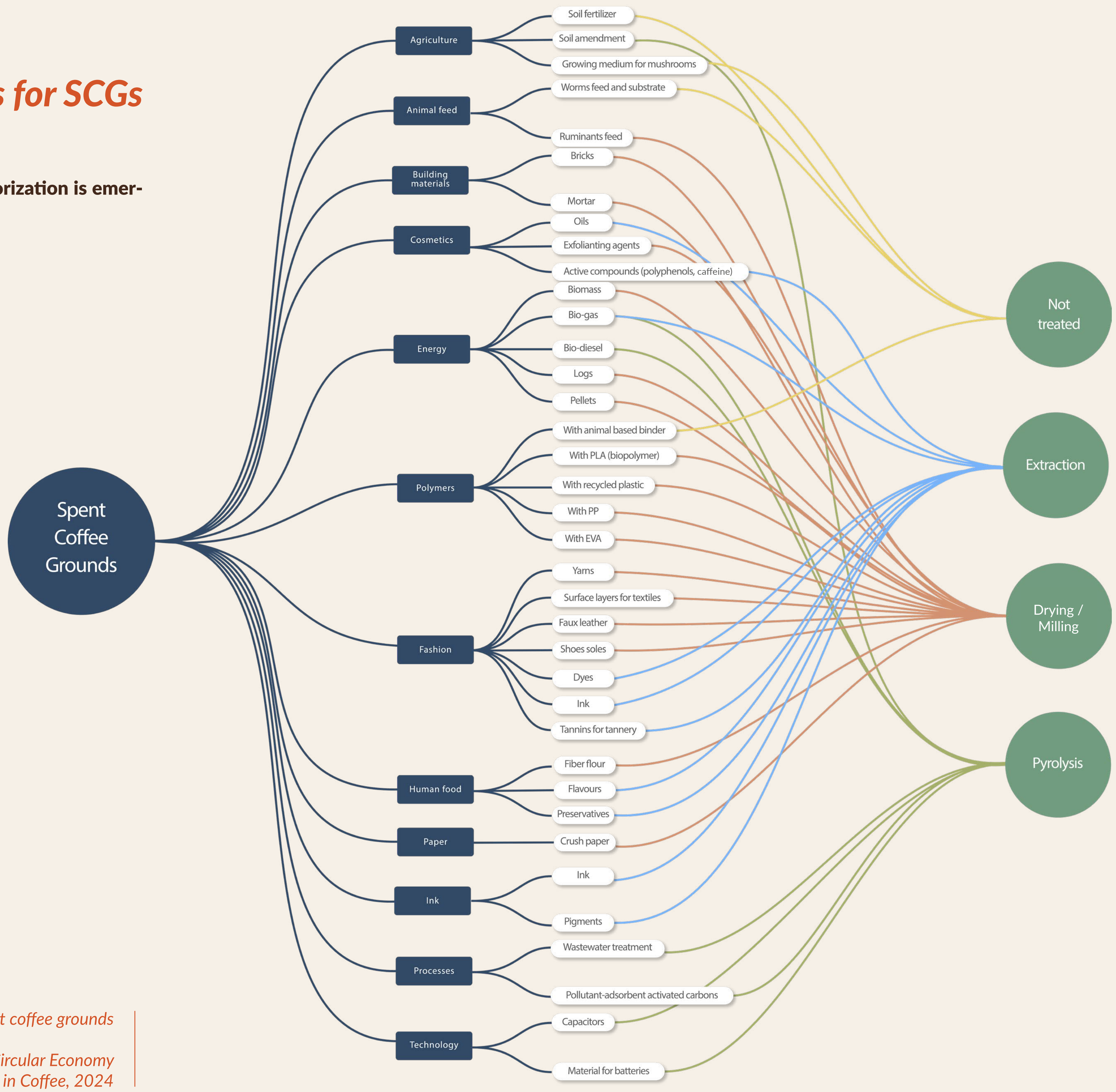


Figure. 5 Value addition uses for spent coffee grounds

Source, Adapted from ITC Coffee Guide Network's Circular Economy Working Group and Center for Circular Economy in Coffee, 2024

AGRICULTURE APPLICATIONS

In agriculture, SCGs have long been recognized **as a nutrient-rich organic amendment**. The effects of SCGs on soil fertility, however, are strongly influenced by the form in which they are applied. Fresh SCGs contain readily decomposable carbon, which can stimulate soil biological activity but may also lead to short- to medium-term nitrogen immobilization and greenhouse gas emissions. SCGs can also be used **as mulch**, where they regulate soil temperature, retain moisture due to their high water-holding capacity, and increase nutrient availability for plants (Bomfim et al., 2023). Processing helps mitigate these drawbacks: vermicomposting yields a stable, nitrogen-rich material suitable for direct fertilization without immobilization (Cervera-Mata et al., 2022). Beyond soil fertility, SCGs exhibit **bioactive properties**: they bind pesticide residues and heavy metals, limiting their mobility in soils, and contain compounds such as caffeine, tannins, and phenolics that can act as natural pest deterrents (Bomfim et al., 2023).

Case Study 1

Ruwawa Multi Generation Farm

Country:
Kenya

Year launched:
-

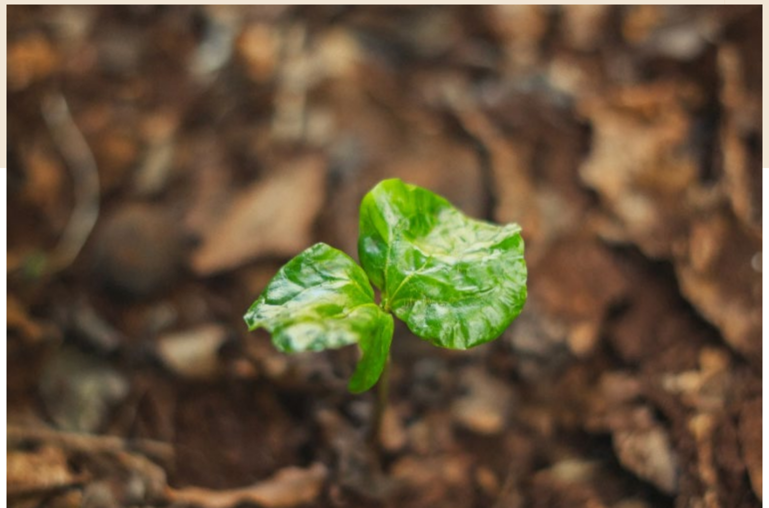
Industry/Sector:
Regenerative Agriculture

Input:
SCGs

Output:
Bio-Pesticides

Smallholder farmers in Kenya face a dual challenge: managing the vast amounts of coffee waste generated from production and finding cost-effective, eco-friendly pest control solutions. With 20 smallholder farmers participating in Kiambu and Githunguri, Ruwawa Coffee Farm launched a pilot project to explore SCGs as a natural pesticide offering farmers an affordable alternative to chemical pesticides. The project began by collecting SCGs from local coffee shops. These grounds, rich in bioactive compounds such as caffeine, tannins and phenols were processed into a natural pesticide. Farmers then applied the SCGs-based solution over a three-month period to manage common pests, including ants, slugs, and aphids. Application around the soil near coffee bushes proved most effective against ants, while treating the leaves worked best for slugs and aphids.
The following results were observed within the pilot:

- Pest infestations were significantly reduced, with a 40% decline in slug and aphid populations.
- Soil quality improved, showing increased organic matter and nitrogen levels, contributing to overall crop health.
- Farmers responded positively, highlighting the affordability and ease of application compared to synthetic pesticides.



Estimated Valorization Percentages for SCG-Based Pesticides

Final Product	Valorized SCG Percentage	Notes
Liquid Organic Pesticide	30–50%	Depends on the extraction process and additional solvents/ingredients used.
Solid Fertilizer or Repellent	70–90%	SCGs are blended directly or composted, with minimal material loss.
Mulch or Soil Amendment	90–100%	SCGs are applied to the soil with no additional processing, maximizing resource recovery.
Activated Carbon for Pesticide	20–40%	SCGs are converted to activated carbon, with material loss during pyrolysis.

Table 2. Estimated Valorization Percentages for SCG-Based pesticedes

The percentages above are based on the following assumptions: **for 1 ton of fresh spent coffee grounds (SCGs), the drying process reduces the weight by 50%.** Then, **during extraction**[1]**, the yield is further reduced by another 50%**. In numerical terms, this means: 1000 kg of wet SCGs becomes 500 kg after drying, and then extraction results in approximately 200–250 kg of bioactive compounds for the liquid pesticide. This brings the **total valorization approximately up to 20–25% of the initial 1000 kg of wet SCGs**. However, if the residues are composted or used as fertilizer, the combined valorization could increase to 60–80%.

However, scaling this solution requires overcoming supply chain challenges, increasing farmer awareness, and advocating for supportive agricultural policies. With the right collaborations and continued research, SCG-based pesticides could help bridge the gap between sustainability and agricultural productivity, fostering a more circular economy in Kenya's coffee sector.

[1] In this context, extraction refers to the process of isolating bioactive compounds such as polyphenols, lipids, and caffeine from the dried SCGs using solvents or other recovery methods.

Case Study 2

The Nãm Urban Mushroom Farm

Partner(s):
Delta Cafés

Country:
Portugal

Year launched:
2020

Industry/Sector:
Food&Agriculture

Input:
SCGs

Output:
Mushrooms

Nãm's business model is based on upcycling coffee waste from food and drink businesses. On one side, the process of collecting coffee waste is created between the coffee producer and Nãm, who uses this waste material to grow mushrooms.

Nãm collects used coffee grounds from vending machines to grow mushrooms, which are then sold to cafes, restaurants, hotels, high end grocery shops, food markets, reaching directly end consumers.

Once the mushrooms are harvested, a rich fertilizer is left, which is then collected by the municipality of Lisbon, Portugal to enrich the soil of local gardens. Nãm aims to promote healthy soils, rebuilding soil organic matter with the introduction of active mycelium and thus increasing soils' capacity for CO_2 sequestration. This process indirectly helps to mitigate rising atmospheric CO_2 levels, one of the primary drivers of climate change. By applying CE principles, Nãm returns to the land what was extracted from it, closing the natural loop cycle. Other problems addressed are the vulnerability and external reliance of urban food systems as well as the lack of local and fresh mushrooms to supply urban consumers.

Agricultural circularity also finds expression in urban farming models. In Portugal, Nãm Urban Mushroom Farm (Nãm Mushroom | UrbanFarm) founded in partnership with Delta Cafés has developed a closed-loop system that transforms SCGs into a substrate for growing mushrooms. Once the mushrooms are harvested, the residual biomass becomes organic fertilizer for gardens.

Similarly, SCGs serve as a protein-rich input in vermiculture systems. Worms fed on SCGs mixed with other organic by-products generate high-quality vermicompost. The worms themselves can be processed into protein flour for animal feed, as shown by the UK-based company Entocycle.

SCGs have also been **successfully integrated into livestock diets**; in one study, dairy ewes with 10% SCG in their feed showed improved milk production and composition without negative impacts on digestion (De Otalora et al., 2020). Starbucks Japan has piloted similar programs integrating SCGs processed with lactic acid bacteria into feed for cattle and compost.

Case Study 3

Country:
Japan

Year launched:
1984

Industry/Sector:
Alternative Chocolate industry

Input:
SCGs

Output:
Coffee-based chocolate bars (COLEHA)

SOI

SOI employs koji, a filamentous fungus traditionally used in Japanese fermented foods such as soy sauce and sake, to biotransform SCGs into a stable, consumable product. This method does not require energy-intensive drying and can be conducted in existing fermentation facilities, offering a low-impact, scalable approach to valorize SCGs into food ingredients.

In experimental trials, SCGs collected from a local café were mixed with water and inoculated with koji, then pasteurized and processed into solid coffee-based bars (COLEHA) that are similar in taste and texture to chocolate bars.

Laboratory analyses show that fermenting SCGs with koji increases the amount of amino acids in the resulting paste to about three times that found in raw coffee beans. This happens because the enzymes produced by koji, called proteases, break down the proteins in the coffee grounds into amino acids.

SPECIALTY FOOD APPLICATIONS

The food industry has also embraced SCG valorization. Connecting Grounds, a women-led startup in Denmark, created Coffee Base, a dried SCG ingredient used in snacks and confections. It functions as a flavoring, coloring, and functional ingredient rich in caffeine, fiber, and protein and even replaces all-purpose flour in gluten-free recipes. Similar initiatives are active in Canada (GroundUp Eco Ventures, RFine Biomass Solution) and the U.S. (The Kawa Project), and Japan (SOI) where SCGs are used to produce chocolate alternatives and beverage ingredients.

Case Study 4

Country:
Greece

Year launched:
_2018_

Industry/Sector:
Cosmetics & Biobased Plastics

Input:
SCGs

Output:
Skincare products & bioplastics

Coffeeco Upcycle S.A.

Coffeeco Upcycle S.A. is a circular economy company pioneering a dual-stream valorization model for SCGs, transforming waste into both bioactive skincare and fiber-reinforced bioplastics. Through its consumer brand Auraskin, Coffeeco has developed a proprietary extraction process that yields a 10% coffee-derived active clinically tested for safety and microbiome compatibility. These ingredients are formulated into skincare-to-go products such as lip balm, hand cream, and facial sunscreen, sold at the exact points where the waste is generated — coffee shops, gyms, and transport hubs — creating a direct, visible circular loop for consumers.
Simultaneously, Coffeeco creates a bioplastic by blending polypropylene / polyethelene with up to 15% coffee fiber, producing reusable 350 ml cups, soap dispensers, and hospitality-grade trays certified for food contact and industrial dishwashing. These are manufactured in collaboration with Greek industry partners and supplied back to the same venues for everyday use, closing the loop across multiple touchpoints.
A critical element of the model is the collection of SCGs. Coffeeco set up reverse logistics in partnership with coffee chains, offices, and corporate campuses such as Coffee Island and Pfizer. SCGs are collected weekly via existing delivery routes, reducing additional transport emissions. The material is stabilized within 48 hours to avoid spoilage, ensuring it remains fresh for high-value applications.
What distinguishes Coffeeco's approach is the simultaneous use of SCGs in two distinct industries. One ton of SCGs can yield up to 2,000 skincare products and 3,000 reusable cups. By addressing both consumer retail and business-to-business markets, the company maximizes the return on a single waste input and demonstrates the potential of multi-sector valorization.
The model has gained traction beyond Greece. Operations have expanded to Cyprus, Romania, the UK, and the US, where pilots include collaborations with fitness chains such as Rumble Boxing.
In 2025, Coffeeco was selected for the Amazon Sustainability Accelerator, an acknowledgment of the scalability and replicability of its dual-stream system.

COSMETICS APPLICATIONS

The cosmetics industry, too, has found high-value applications for SCGs. Bioactive compounds found in SCGs such as caffeine and polyphenols offer antioxidant, anti-inflammatory, and skin-toning properties. SCGs extracts are used in anti-aging formulations, moisturizers, soaps, and scruns where the grounds also serve as natural exfoliants. Kaffee Bueno, Eco-Bean, Coffeeco Upcycle, More 2 Coffee, Coffee Resurrect, and many others exemplify this application, sourcing SCGs for antioxidant extraction used in skincare products.

Case Study 5

Country:
Poland

Year launched:
2018

Industry/Sector:
Industrial Coffee Processing Technology

Input:
SCGs

Output:
High-value chemicals (e.g., coffee oil, antioxidants, lignin, rare sugars)

EcoBean

EcoBean has developed a technological approach for the comprehensive valorization of SCGs, aiming to extract multiple functional compounds from the waste stream. These compounds include coffee oil, antioxidants, rare sugars, and lignin, which can be repurposed for applications in food, cosmetics, and packaging.

A key aspect of EcoBean's approach is the implementation of an industrial, on-site biorefinery. Rather than relying on a centralized collection of small SCG batches, the system is designed to process SCG at locations where large volumes are generated, such as instant coffee production plants.

The biorefinery is modular and plug-and-play (SKID-based), enabling integration with existing production lines. The units are designed for local assembly, allowing deployment in diverse geographic locations and facilitating scalable valorization of SCG within industrial settings.

The technology is compatible with various coffee production processes, including spray drying, freeze drying, and cold brewing, which produce SCGs with differing characteristics.

Case Study 6

S.Café® Technology

Actors:
SINGTEX® Industrial Co., Ltd.

Country:
Taiwan

Year launched:
2008

Industry/Sector:
Textile / Functional Apparel

Input:
SCGs and recycled polyester

Output:
Functional yarns and textiles for fashion and sportswear

S.Café® is a textile that utilizes SCGs as a raw material for functional yarn and fabric production. Through a patented low-temperature, high-pressure process, the SCGs are transformed into nano-scale particles and blended with recycled polymer to create a masterbatch. This masterbatch is then spun into yarns using various techniques, producing fabrics with tailored hand feel, structure, and performance characteristics.
The porous structure of coffee grounds plays a critical role in the material's functionality. The resulting textiles exhibit enhanced properties such as odor control, UV protection, and accelerated drying times. These performance features are inherent to the material, derived from the high surface area and absorbent capacity of the embedded coffee particles, and are maintained throughout the lifecycle of the garment, even after repeated washing and wear. S.Café® yarns are integrated into a range of apparel applications, particularly in activewear, outdoor gear, and lifestyle clothing. The company also developed ICE-CAFÉ™, a specialized variant that incorporates cooling properties by reducing skin temperature up to 2°C, offering thermoregulation for sports and warm environments. In addition this, S.Café® has introduced an additional line that combines coffee grounds with recycled ocean plastic and ocean-bound waste, expanding the circular potential of their materials.

Case Study 7

Coffeefrom SRL

Partner(s):
Politecnico di Milano, Bearplast

Country:
Italy

Year launched:
2021

Industry/Sector:
Composite materials

Input:
SCGs and recycled polyester

Output:
Additives and fillers for polymeric materials for fashion and sportswear

Coffeefrom is a social enterprise that transforms industrial SCGs, typically disposed of in landfills, into polymeric composite materials. The company currently processes approximately 600 tons of SCGs per year, incorporating them into thermoplastic matrices at proportions ranging from 10% to 20%. Five material families have been developed for specific applications:

- Coffeefrom® Bio: 100% biodegradable material combining SCGs with PLA.
- Coffeefrom® Eco: Recycled LDPE with SCGs, flexible and lightweight.
- Coffeefrom® Strong: HDPE with SCGs, rigid and heat-resistant.
- Coffeefrom® Texture: PP with SCGs, rigid, heat-resistant, and food-contact certified.
- Coffeefrom® PBS: Bio-based material with good tensile strength and ductility, suitable for injection molding.

Primary manufacturing currently uses injection molding to produce products such as espresso cups, mugs, and tableware. A key feature of these materials is that they meet stringent food-contact certifications, and, when required, a protective resin is applied to allow products to withstand industrial dishwashing.

SCGs are further valorized through component extraction. Oil and polyphenols are recovered via NADES extraction, while the remaining solid residue is processed to extract nanocellulose following a patented method developed with Politecnico di Milano. Nanocellulose can be used as an additive in packaging and cosmetics, and the post-extraction residue can enhance the mechanical properties of composite materials.
Trials are currently underway to increase the SCGs content in Coffeefrom materials to 30–50%, using nanocellulose to maintain or enhance mechanical performance. In parallel, 3D printing has been successfully tested for large-format applications, including furniture components and architectural elements.

MATERIALS APPLICATIONS

SCGs are also gaining momentum in the fashion and textile industries. They are being transformed into materials such as yarn and fabric, offering unique properties like natural odor control, UV protection, and quick-drying performance making them well-suited for activewear and casual apparel. Beyond clothing, SCGs are used to produce natural dyes that offer warm, earthy tones as a sustainable alternative to synthetic colorants. Coffee-based textiles are even being explored as an eco-friendly substitute for leather, reducing dependence on animal-derived materials. Eecoff and S.cafe exemplify this application, sourcing SCGs for yarns.

Beyond garments, SCGs are increasingly recognized as a renewable feedstock for sustainable material production. A promising example is eco-brick manufacturing, where substituting just 3% of clay with SCGs enables a single ton of waste to yield more than 30 tons of bricks (Kumar et al., 2025). SCGs are also being explored in biocomposites and biodegradable packaging. When incorporated into biodegradable polymers, SCGs oil enhances both antioxidant properties and biodegradability, creating viable alternatives to petroleum-based plastics (Choe, 2025). In the paper industry, companies such as Favini have experimented with blending SCGs and silverskin into paper products, thereby reducing reliance on virgin cellulose.

ADVANCED PROCESSING AND TREATMENT OF SCGS

Thermal treatments of SGCs, such as pyrolysis and hydrothermal carbonization modifies the chemical and physicochemical properties of SCGs, producing biochars and hydrochars with distinct effects on carbon and nitrogen cycling. **Converting SCGs into biochar through pyrolysis offers a more stable and impactful solution**: the resulting carbon-rich material improves soil fertility, sequesters carbon, and reduces the need for synthetic fertilizers. Compared to traditional fertilizers, biochar-amended soils can cut fertilizer demand by one-third and lower nitrous oxide emissions (Matrapazi et al., 2020). These findings highlight that while **SCGs are a source of carbon and nutrients**, their agronomic value is contingent upon appropriate processing to optimize nutrient availability and soil health outcomes.

Pyrolysis also generates bio-oil and biogas, though the latter's calorific value is notably lower than natural gas. Nevertheless, such processes may contribute meaningfully to the decarbonization of agriculture. Some valorization pathways go even further. For example, **activated carbon** derived from SCGs has been tested in double-layer capacitors[2] and shows strong performance during charge-discharge cycles (Kikuchi et al., 2013). Advanced technologies are now exploring **SCGs applications in accumulators and batteries** like the work undertaken by CNR Nanotec. This high-tech angle demonstrates the versatility of coffee waste beyond traditional resource recovery.

Rising coffee consumption has created a steady supply of SCGs, making them an attractive raw material. However, **research shows that the economics only work when biorefineries are positioned near instant coffee plants, HORECA channels, or municipal waste collection centers**. Despite this abundance, experts caution that focusing SCGs on a single end-use, particularly energy recovery, is not cost-effective. Cascading models, where bioactive compounds are first extracted and energy recovery follows, are more aligned with both environmental and financial goals (Arias et al., 2023).

As demonstrated in the case studies, **bioactive compounds** from SCGs carry strong commercial potential across **pharmaceutical, cosmetic, and food applications**. Realizing this opportunity depends on developing scalable, eco-efficient extraction technologies that align with the 12 Principles of Green Chemistry.

[2] *Double-layer capacitors, also known as supercapacitors, are energy storage devices that store electrical energy physically by accumulating ions at the interface between an electrode and an electrolyte forming what's called an electric double layer.*

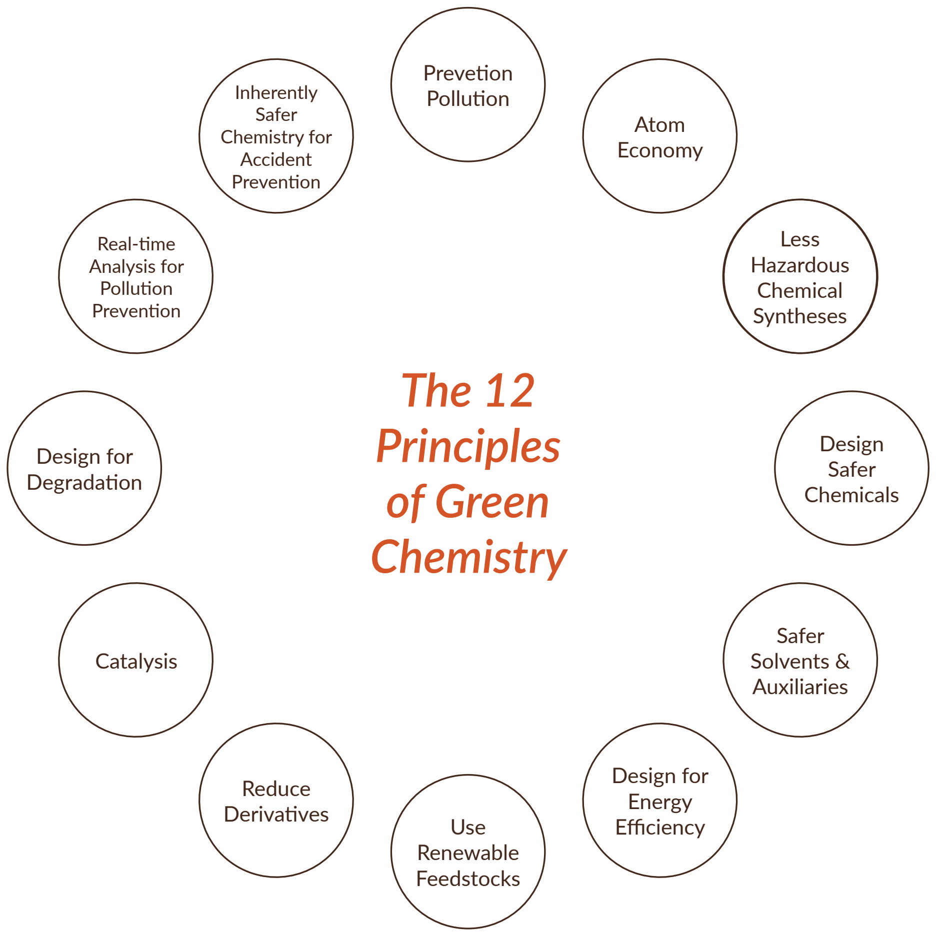


Fig. 6 The 12 Principles of Green Chemistry

Adapted from: Anastas, P. & Warner, J. (1998).

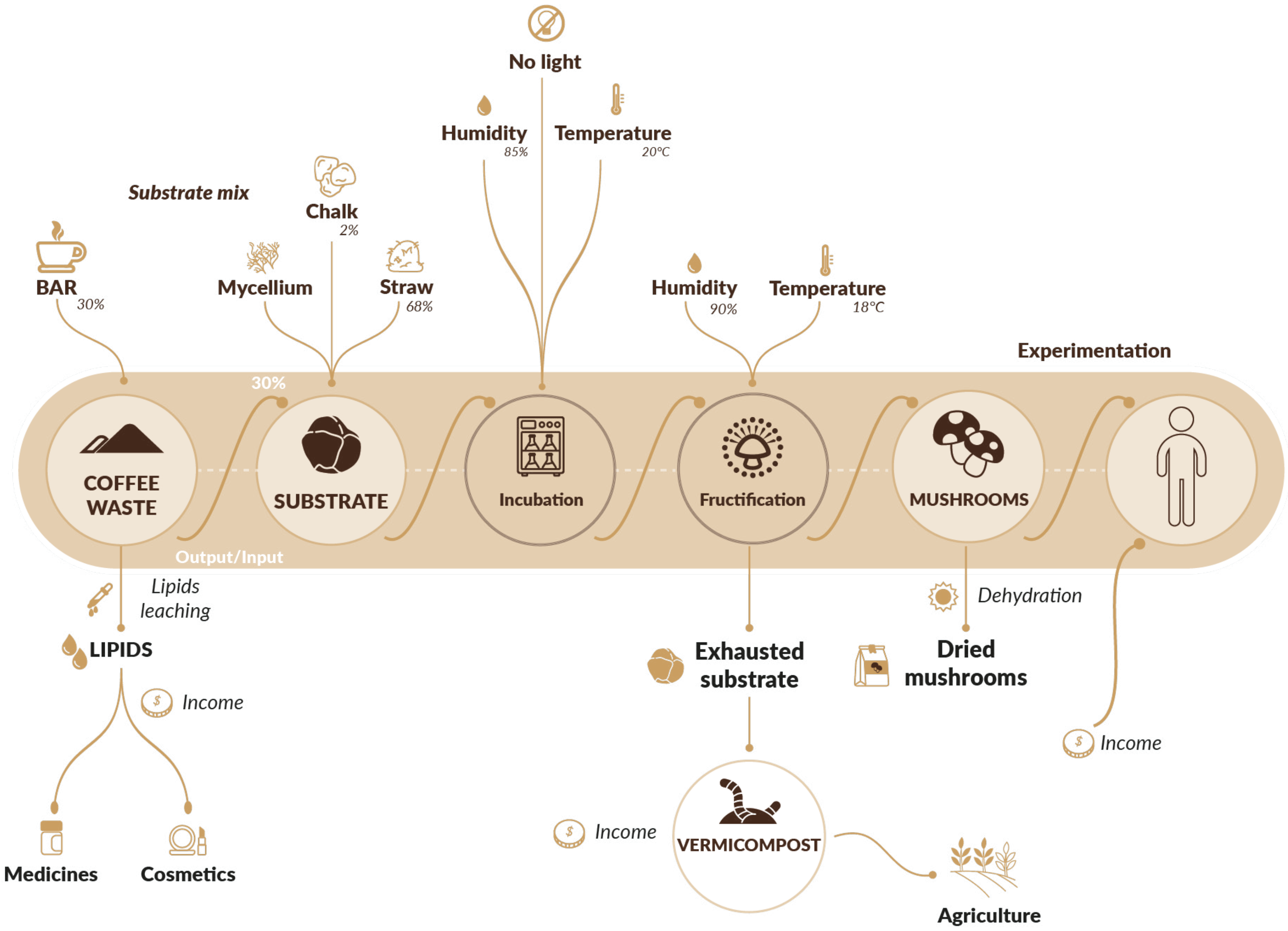


Fig. 7 Creating value from coffee waste

Adapted from Barbero, S., & Toso, D. (2010).

The broader opportunity lies in integrated biorefinery concepts. These systems are designed to capture multiple value streams: bioactives, bioenergy, biopolymers, and construction materials from the same feedstock (Dari et al., 2025). Seen through this lens, SCGs are no longer a waste product but a platform for innovation, regeneration, and enterprise. With supportive policy frameworks and investment in scalable technologies, SCGs have the potential to become a cornerstone of the circular bioeconomy.

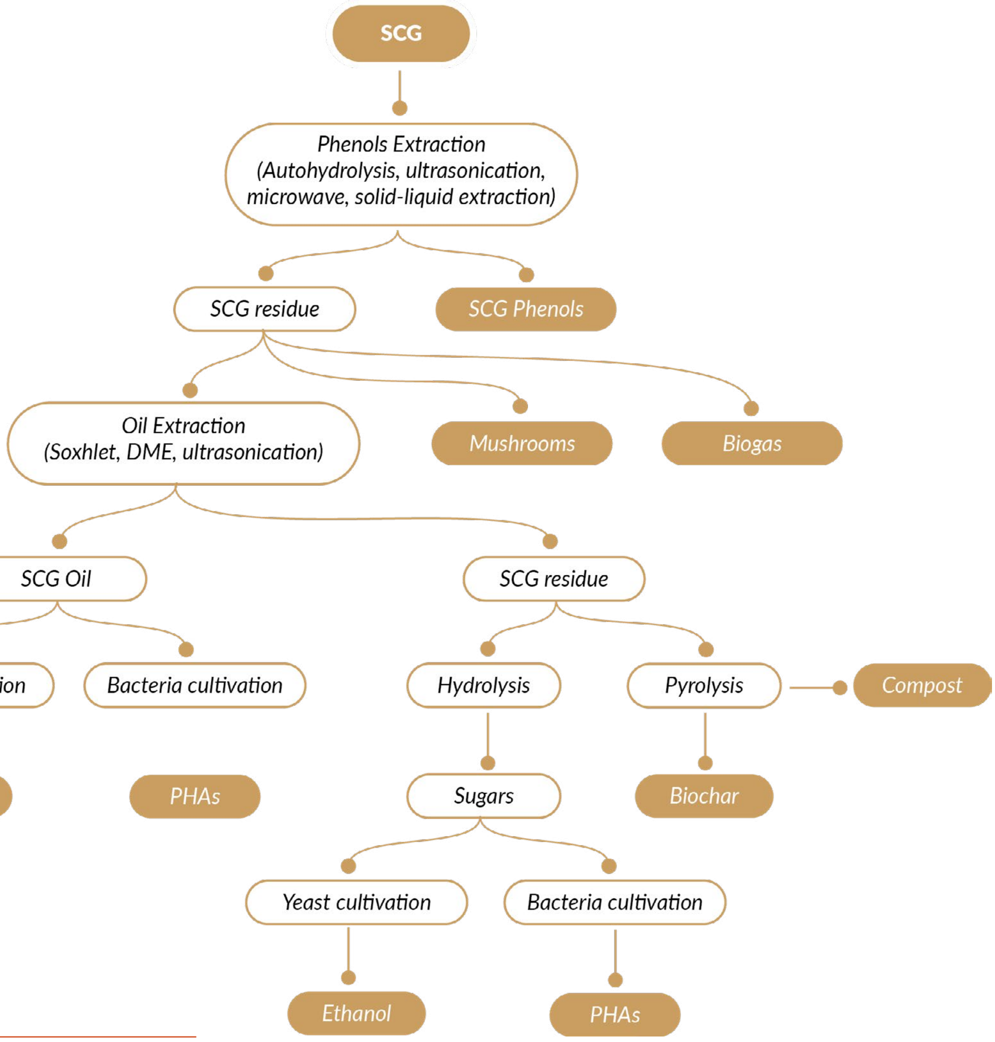


Fig. 8 Scheme illustrating an integrated biorefinery approach for the valorization

Adapted from Kourmentza et al. (2017).

Collection and Utilization of SCGs

SCGs can be **generated and recovered in three** main **contexts**: **industrial**, **commercial**, and **domestic**. Each of these settings presents specific characteristics that influence not only the composition and quantity of the material produced but also its potential regulatory classification.

Each ton of green coffee produces around 650 kilograms of dry SCGs. Therefore, the global output of this by-product is estimated to reach 11 million tons annually (Forcina et al., 2023; Coffee Development Report, 2024, Drewnowski et al., 2025).

In an **industrial context**, SCGs **typically originate from large-scale coffee production or processing facilities**. In such cases, the generated material is generally considered an industrial waste stream. The production of instant coffee, for example, generates significant quantities of SCGs, an industrial by-product that does not appear in the final consumer product. On average, processing 1 kilogram of instant coffee results in approximately 2 kilograms of wet SCGs. The instant coffee industry alone accounts for approximately 4.5 million tons of SCGs each year, underscoring the scale of waste generated by this sector (EcoBean, n.d). In addition to instant coffee producers, industrial cold brew and ready-to-drink coffee companies contribute significantly to global generation. As these sectors continue to grow, SCGs production at this scale is estimated to exceed 4 million metric tons annually (EcoBean, n.d).

Moving to the **commercial context**, SCGs **arise as a by-product of coffee preparation in the HORECA sector** (hotel, restaurant, and cate-

Italian Espresso

Coffee dose: ~7–8 g
Beverage volume: 20–25 ml
SCGs produced: 6–7 g

Ratio ~1:3

Drip Coffee

Coffee dose: ~10–12 g
Beverage volume: 180 ml
SCGs produced: ~10 g

Ratio ~1:15

(La Marzocco Home, 2014)

The difference in SCGs is due to the different amount of ground coffee used, not directly to the beverage volume (20–25 ml vs 180 ml) or the brewing method itself.

Fig. 9 SCGs produced:
Italian Espresso versus Drip Coffee

ring). Research suggests that about 50% of all SCGs come from coffee shops, restaurants, and household consumption (Ahmed et al., 2024). The magnitude of generation at the commercial level can be illustrated with a few examples. A single office building with 100 employees, each consuming an average of two cups of coffee per workday, generates approximately 1.0 to 1.8 metric tons of SCGs annually.

This estimate is based on the standard brew ratio of 55 g of coffee per liter of water, as recommended by the Specialty Coffee Association, which corresponds to ~11 g per 200 mL cup and ~13.75 g per 250 mL cup, across 260 workdays per year, and adjusted for the typical moisture content of SCGs (Specialty Coffee Association, 2022). In cafés, production scales exponentially: a small coffee shop serving 250 cups daily would generate nearly 1.3 metric tons of SCGs annually.

In contrast, **domestic** generation of SCGs **occurs through household coffee preparation**. Although collectively significant, household production is highly fragmented and yields very small amounts per site, making large-scale collection logistically complex and costly. For this reason, domestic consumption is not considered in this white paper. Instead, **the focus will be on industrial and food service recovery streams**, where collection is more concentrated and practical.

Together, these generation patterns determine the characteristics of the SCGs available for recovery. **Their origin whether industrial, commercial, or domestic directly affects their composition, stability, and potential for reuse**. Accordingly, efficient utilization depends on four key factors that influence their chemical and physical properties. The following **parameters** are **critical** when collecting and processing SCGs:

1 *FRESHNESS AND PURITY*

Freshness and purity determine whether SCGs can be transformed into a reliable feedstock or degrade into a source of risk. When collected immediately after brewing, SCGs still contain significant levels of bioactive compounds such as caffeine, chlorogenic acids, and lipids, and their chemical and microbial profiles remain relatively stable. Once the material is left to sit, however, it begins to lose nutrients, develop acidity, and create favorable conditions for microbial growth.

This contrast between fresh and stale grounds is especially important for food safety. With a moisture content of around 65%, SCGs provide an ideal environment for fungi if they are not dried or stabilized quickly. Contamination by Aspergillus species is particularly concerning, as these fungi can produce dangerous mycotoxins (Kumar et al., 2025). Such toxins pose well-documented risks to human health and make the grounds unsuitable for any food-related or high-value applications. In these cases, what could have been a renewable resource instead becomes a liability.

The handling of SCGs immediately after brewing greatly influences these outcomes. Grounds mixed with residues from milk, sugar, or oils are more prone to microbial growth and yield inconsistent products. By contrast, pure SCGs are easier to stabilize, exhibit predictable nutrient and pH levels, and are safer to channel into valorization routes where consistency is essential.
Storage further determines whether SCGs maintain or lose value. When kept in sealed containers or under cool conditions, they retain nutrients and preserve their bioactive compounds. When stored openly or in humid environments, they tend to acidify to a pH below 5, which accelerates mold growth and fermentation. If temperatures rise, microbial populations can expand exponentially, generating short-chain fatty acids such as acetic, butyric, and formic acids, while lipids oxidize and further degrade the material. These changes undermine both quality and safety.

To minimize these risks, SCGs should be collected frequently, separated from food residues, and dried to a residual moisture content of 10%, or temporarily refrigerated, within 24 to 48 hours. At scale, monitoring pH and moisture content is essential to ensure that safety and stability are maintained. Without such practices, microbial spoilage and chemical degradation quickly erode the economic and practical potential of valorization.

In sum, maintaining freshness and purity is not a minor technical detail but rather a foundational requirement for preserving the bioactive compounds in SCGs, protecting against microbial hazards, and unlocking their potential across applications ranging from fertilizers and soil amendments to other bio-based products.

2 ROAST LEVEL AND GRIND SIZE

Roast level has a pronounced effect on the balance between native phenolic compounds and secondary antioxidants. Light roasts preserve higher levels of chlorogenic acids, which are heat-sensitive but valuable for antioxidant recovery (Hečimović et al., 2011, Ahanchi et al., 2024). This makes lightly roasted SCGs more promising when the goal is to extract bioactives such as chlorogenic acids or caffeine for nutraceutical and functional applications. In contrast, darker roasts undergo greater thermal degradation of these native phenolics, resulting in significantly reduced chlorogenic acid content. Caffeine, by comparison, is relatively stable during roasting, and differences in caffeine yield across roast levels are more strongly influenced by bean density and extraction efficiency than by thermal breakdown (Hečimović et al., 2011).

At the same time, darker roasts generate higher levels of Maillard reaction compunds, including melanoidins, which contribute to antioxidant activity and can improve lipid stability (del Castillo et al., 2002; Ahanchi et al., 2024). As a result, while dark roasts sacrifice some native bioactives, they gain phenolic-like fractions that support oxidative stability and may enhance shelf life in certain food applications.

Grind size further determines how effectively these compounds can be accessed. Finely ground SCGs present a larger surface area, increasing nutrient bioavailability during extraction or composting (Mussatto et al., 2011). This makes fine grounds particularly useful when rapid recovery of caffeine or antioxidants is desired. Coarse grounds, by contrast, decompose more slowly and may be advantageous in applications such as soil conditioning, where gradual nutrient release is beneficial.

Together, roast level and grind size define the balance between immediate bioactive recovery and slower nutrient release. Lightly roasted, finely ground SCGs are optimal for extraction-focused applications, whereas darker, coarser grounds are better suited to uses emphasizing stability, gradual nutrient availability, or antioxidant activity from Maillard-derived compounds (Ahanchi et al., 2024).

3 *GENETICS AND TERROIR*

Soil quality, climate, and agricultural practices all shape the nutrient and bioactive content of the beans, which in turn influences the profile of the residue left after brewing (Ahanchi et al., 2024). These differences carry direct implications for potential applications. SCGs rich in total phenolic content (TPC) and antioxidant activity (AA) are promising for nutraceuticals and functional foods, where extracts may be incorporated into antioxidant-rich formulations. Similar antioxidant fractions can be harnessed in the cosmetic industry, where they contribute to skin care products, or in food supplements, where they provide concentrated bioactives that may help protect against oxidative stress.

Species and terroir further drive compositional variability. Arabica SCGs, especially those sourced from higher altitudes, often exhibit higher levels of nitrogen and potassium, making them suitable for use as fertilizers. For instance, some high-altitude Kenyan

Arabica samples have been reported with elevated potassium and phosphorus contents, which can enhance compost quality. Robusta SCGs, in contrast, tend to be lower in nitrogen but richer in lipids, offering advantages for bioenergy production through biodiesel conversion (Ballesteros, Teixeira, & Mussatto, 2014).

Comparative analyses confirm these distinctions. Data compiled from roasted Arabica and Robusta SCGs show that Arabica typically retains higher carbohydrate fractions (up to 52.5%) and slightly greater chlorogenic acid content, while Robusta contains more caffeine (1.9–2.2% compared to 1.0–1.1% in Arabica) and a somewhat higher lipid fraction (around 7%) (Buone previsioni dai fondi di caffè (n.d); Lavazza - From bean to cup (n.d)). These compositional shifts explain why Arabica residues may be more suited for antioxidant recovery, whereas Robusta residues hold greater potential in lipid-based valorization routes.

Practical applications also reflect these findings. Ahanchi et al. (2024) demonstrated that incorporating SCGs into bread formulations increased antioxidant capacity, with Robusta SCGs delivering slightly higher phenolic content than Arabica at equivalent inclusion levels.

Such outcomes reinforce the importance of carefully considering species and origin when selecting SCGs for nutraceutical or food applications, as compositional differences influence both efficacy and functionality. These variations highlight the need for targeted characterization and application-specific sourcing, ensuring that the potential of SCGs is matched to the most appropriate valorization pathway.

However, these values are not universal; differences are shaped by species, origin, and brewing conditions, and reported percentages cannot be generalized across all sources. A practical approach for industry is therefore to conduct compositional analysis of representative SCGs lots measuring nitrogen, phosphorus, potassium, lipids, and ash rather than relying on canonical averages.

4 *BREWING METHOD*

The brewing method used to prepare coffee strongly influences the chemical composition of the resulting SCGs. Because each method extracts bioactive compounds to different extents, the residual material varies in moisture, organic carbon, caffeine, chlorogenic acids, and phenolic content, all of which determine the suitability of SCGs for valorization (Kumar et al., 2025).

Espresso brewing, which uses high

pressure and very short extraction times, typically produces SCGs with a residual moisture often 50–60% (Johnson et al., 2022). Due to reduced extraction efficiency compared to filter coffee, espresso SCGs contain a notable fraction of soluble, bioactive compounds that were not fully extracted during brewing, including caffeine, chlorogenic acids (CGAs), trigonelline, melanoidins, proteins, and smaller amounts of soluble sugars. Drip or filter brewing, by contrast, rely on longer contact times and a gravity-driven flow, which extract a larger portion of these solubles into the beverage. As a result, SCGs produced from drip or filtered coffee typically have a higher moisture content (up to 70%) but a lower caffeine and CGA content, and a more depleted nutrient profile (Kumar et al., 2025). However, it must be emphasised that due to the high variability in the roasted coffee used for extraction, caused by different cultivars, growing conditions, processing, storage and roasting profiles, the amounts of constituents in SCGs are subject to significant fluctuations, both between different extraction methods and within the same method, particularly with regard to caffeine, CGA and minerals.

The same patterns are observed with chlorogenic acids and total phenolic content. Filtered brews generally deplete more chlorogenic acids from the beans, yet SCGs from light filtered roasts may still contain significant residual fractions (up to 7.25 mg /g 3-CQA and 13 mg/g combined CQA and di-CQA). Drip brewing produces intermediate levels of phenolics in SCGs, while mocha and infusion methods consistently result in lower values, suggesting more efficient extraction of these compounds into the beverage. Despite the degradation of native chlorogenic acids, dark roasted SCGs often show higher antioxidant activity due to the formation of Maillard reaction products such as melanoidins (Kumar et al., 2025).

Beyond household preparation, industrial brewing processes produce distinct SCGs streams with compositions that differ substantially from those of cafés or domestic settings. Instant coffee manufacturing, for example, relies on high-temperature, high-pressure extraction, which removes most soluble bioactives. The resulting SCGs are instead enriched in insoluble fractions such as coffee oils, polysaccharides, and lignin. Reported oil content in such residues ranges widely, from about 10-35%, depending on the process and feedstock, while lignin typically accounts for 25 - 30 % (Ballesteros et al., 2014). Cold-brew extraction, carried out at low temperatures over extended periods, yields yet another profile, often retaining a different balance of acids, volatiles, and bioactive compounds in

the residue. These variations highlight the importance of treating industrial SCGs streams as distinct feedstocks, each requiring characterization before valorization.
Taken together, the brewing method is a decisive factor in determining SCGs composition. Longer and hotter extractions, such as filtered brewing, yield grounds depleted in native chlorogenic acids but enriched in caffeine and Maillard-derived antioxidants, while shorter or cooler methods leave behind different residuals. In valorization strategies, paying close attention to the brewing method allows processors to align the characteristics of SCGs with the most suitable reuse pathway.

In an **ideal scenario**, SCGs would be sourced from **a single or limited number of suppliers**, such as instant coffee or cold brew manufacturers that consistently use the same coffee beans. **This controlled sourcing would enable straightforward analysis and characterization of SCGs**, ensuring uniformity in composition and properties. However, **in practice, SCGs is often collected from diverse sources**, including various coffee shops. This results in a highly heterogeneous mixture of drip coffee and espresso, derived from beans of different origins, varieties, and roasting profiles ranging from very light to deep dark. Such variability presents a significant challenge, as the quality and properties of the upcycled material are directly influenced by the raw material's composition.

From a technical perspective, **analyzing the composition of SCGs should ideally be a prerequisite for upcycling processes**. However, given the inherent variability in sourcing, this is rarely feasible in practice today. As the upcycling industry continues to develop, **the importance of standardization and material characterization may increase**, particularly as more sophisticated applications emerge. Scientific research and insights, such as those referenced above, are crucial for fostering innovation in this field.

Despite these challenges, circular economy initiatives in the coffee industry remain in their early stages. **In real-world operations, the factors influencing SCGs composition often play a minimal role compared to the logistical and economic priorities of companies engaged in SCGs valorization.** For most businesses in this sector, the primary concern is securing the highest possible quantity of SCGs with minimal logistical effort, rather than ensuring consistency in its composition.

Besides the above parameters, **logistics and regulations over the collection and use of SCGs pose as the major challenges** for businesses entering this upcycling field.

Logistics

Logistics is one of the most critical factors in SCGs valorization and a major driver of its carbon footprint. Unlike conventional food waste disposal methods such as incineration, bio digestion, or landfill, SCGs collection requires higher frequency and specialized handling, which drives up costs. Compounding this challenge, SCGs has a high moisture content typically 60–65%, that makes it highly prone to microbial growth, particularly mold.

From a logistical standpoint, the high water content amplifies both physical and economic challenges. Moisture increases bulk density and weight, inflating transportation costs and tipping fees (charges based on weight in disposal scenarios). When SCGs are produced in small, scattered volumes such as in cafés, restaurants, or offices, the added weight becomes a barrier to centralized collection and valorization.
Sustainability and marketability considerations further complicate collection. Quality depends heavily on storage and handling: microbial contamination or poor storage can limit usability in high-value applications such as food or cosmetics. In some cases, organic certification may be necessary, particularly for industries prioritizing sustainable sourcing, though certified organic SCGs remains scarce. The intended end use dictates the level of quality control: food and cosmetic applications require strict standards, while uses such as fertilizers or manufacturing materials allow more flexibility.

To reduce environmental impact and costs, processing facilities should be located as close as possible to SCGs sources. Reverse logistics, integrating collection into existing delivery routes can improve efficiency, while co-transportation with other waste streams, the use of electric cargo bikes or vans in cities, and centralized route hubs can cut emissions further. Life cycle assessments show that poorly managed transport can erode the sustainability gains of diverting SCGs from landfills (Forcina et al., 2023).

One effective mitigation strategy is sourcing SCGs in bulk directly from vending machine operators, HORECA outlets, or instant coffee plants; ideally after on-site stabilization through drying.

Industrial partners produce large, uniform volumes that reduce contamination risks and minimize pre-processing. This model also improves economics: many industrial producers are willing to pay for collection and valorization, converting a disposal cost into a managed by-product. This may even allow them to benefit financially from SCGs valorization.

Still, logistics remain a limiting factor. SCGs are often generated in small, dispersed quantities, making centralized collection labor- and resource-intensive. Transport distances strongly influence the environmental performance of SCGs reuse. Effective collection also depends on proper handling at the source: staff must be trained in sorting, storage, and hygiene practices. Finally, local regulations may constrain collection and processing methods, shaping the feasibility of logistics solutions and determining whether SCGs are treated legally as waste or as a secondary raw material.

Case Study 8

Partner(s):
Retail and industrial producers of SCGs

Country:
Canada

Year launched:
2022

Industry/Sector:
Technology, Food & Agriculture

Input:
Wet SCGs

Output:
Food and Feed ingredients

RFine Biomass Solutions

RFINE Biomass Solutions is a Canadian clean technology company addressing the challenge of stabilizing spent coffee grounds at scale. Recognizing that wet SCGs spoil rapidly due to high moisture content and microbial activity, RFINE developed a patented drying technology that enables on-site stabilization at the point of generation, primarily coffee shops, quick-service restaurants, and industrial coffee producers.

By drying the SCGs shortly after they are produced, RFINE prevents spoilage, reduces weight and volume, and creates a shelf-stable input for further processing. The dried material is then transported via backhaul logistics, leveraging existing food delivery networks to regional facilities for transformation into food-grade ingredients.

RFINE produces high value food and feed ingredients developed from stabilized SCGs. Through rigorous testing and collaboration with food product development partners, RFINE has demonstrated functional and sensory performance of their food ingredient in a wide range of food and beverage applications.

Highlights:

- On-site stabilization: Patented drying equipment reduces spoilage, emissions, and transportation costs.
- Food-grade process: Enables use of SCGs as an input for upcycled ingredients compliant with human consumption standards.

Integrated logistics model: Utilizes reverse logistics to minimize carbon footprint and operational costs.

By addressing the perishability and logistical hurdles associated with SCGs collection and reuse, RFINE enables circular economy practices in the coffee sector. Their technology improves the economics and environmental performance of SCGs valorization, offering scalable solutions to reduce landfill waste and create high-value, low-emission food ingredients.

Policy and Regulatory Framework for SCGs

The global momentum toward **Circular Economy frameworks** has fostered increasing **interest in the valorization of agro-industrial residues, including SCGs**. These materials occupy a complex regulatory space that intersects waste management, food safety, cosmetic legislation, and renewable energy policy. Effective valorization strategies therefore depend not only on technological feasibility but also on the **legal re-classification of SCGs from "waste" to "secondary raw material" or "by-product" under national and international legislation**.

While **EU legislation has introduced both mandatory and voluntary measures** addressing product sustainability, **inconsistencies persist in how waste streams especially organic by-products are classified, collected, and regulated**. For **SCGs**, this results in **ambiguity**: some Member States classify them as municipal waste rather than bio-waste, restricting their valorization.

Globally, the situation is even more uneven. **Policies governing coffee by-products differ widely across countries**, with food safety standards, labeling requirements, and product classifications varying from one jurisdiction to another. **These inconsistencies make cross-border trade and innovation difficult particularly for SMEs and producers in developing regions.** For instance, SCGs intended for food applications in the United States must undergo safety evaluations due to their exclusion from the Generally Recognized as Safe (GRAS) list, whereas in Europe, their integration as dietary fiber is permitted, thanks to EFSA's confirmation that SCGs are not a novel food (Choe, 2025).

In short, while circular economy rhetoric is widespread, **the regulatory environment remains insufficiently developed to enable scalable SCGs valorization**. Lack of harmonized waste classifications, end-of-waste criteria, and clear safety protocols continues to act as a structural barrier to progress.

High-Level Assessment of SCGs Governance

This section presents a high-level **policy mapping and analysis** of how SCGs are addressed or overlooked within **regulatory and policy frameworks across three key regions**: the **European Union**, **United States of America** and **Korea**. The review examines whether SCGs are specifically referenced, how they are classified within waste systems, and how policies influence their collection, handling, and valorization.

The assessment draws on **official policy documents, national waste strategies, and circular economy roadmaps.** Emphasis is placed on regulatory clarity, alignment with circular economy principles, and the presence of enabling or inhibiting factors for SCGs reuse. Key analytical lenses include:

- Waste classification (e.g., municipal vs. biowaste)
- Regulatory barriers to valorization (e.g., food safety, end-of-waste criteria)
- Policy support mechanisms (e.g., incentives, funds, public-private partnerships)

The goal is to understand **how policy landscapes shape SCGs valorization potential**, highlight regulatory gaps, and identify pathways for more integrated circular governance.

European Union

In the European Union, **policy support for circular economy practices has expanded significantly** in recent years. At the center of the regulatory frameworks lies the Waste Framework Directive (2008/98/EC, amended by Directive (EU) 2018/851), which establishes **the waste hierarchy** as a guiding principle across all Member States. According to this hierarchy, **waste prevention is the top priority**, followed by preparation for reuse, recycling, other recovery operations (such as energy recovery), and finally disposal as the least preferred option. **The Directive also provides the legal definitions for "waste", "by-product", and "end-of-waste criteria"**. These concepts are essential for determining whether a material such as SCGs can exit the status of waste and re-enter the market as a usable input for new production cycles such as in biofuels, bioplastics, fertilizers, or cosmetics.

The European waste governance system operates in close connection with a set of high-level strategic frameworks designed to guide the Union's transition towards climate neutrality, resource efficiency, and sustainable growth. These frameworks include the **European Green Deal** (2019), the **Circular Economy Action Plans** (2020), the **EU Bioeconomy Strategy** (2018), and the **Common Agricultural Policy** (CAP). Each of these policy pillars provides a different yet complementary approach to the valorization of bio-based materials and organic residues, including those derived from coffee processing and consumption.

Although SCGs are not specifically referenced in any of these strategic documents, their inclusion within the broader categories of agri-food waste, biowaste, and renewable bio-based resources makes them a relevant case for the practical implementation of these frameworks.

1 THE EUROPEAN GREEN DEAL

Launched in 2019, the European Green Deal represents the overarching policy roadmap for achieving climate neutrality in the EU by 2050. It establishes an integrated vision linking environmental, industrial, agricultural, and social policies under the **shared principle of sustainability through circularity**.

The Green Deal explicitly promotes the development of bio-based value chains, encouraging the conversion of organic residues into high-value materials such as biochemicals, biofertilizers, and bioenergy. While the Green Deal does not detail sector-specific measures for coffee waste, it provides the political and strategic impetus for downstream instruments, such as the Circular Economy Action Plan and the Bioeconomy Strategy, that operationalize this vision within agro-industrial contexts. In practice, initiatives converting SCGs into biofuels, bioplastics, or soil improvers directly contribute to the Deal's objectives on carbon neutrality, waste minimization, and industrial symbiosis.

2 CIRCULAR ECONOMY ACTION PLAN (CEAP)

The Circular Economy Action Plan (CEAP), first introduced in 2015 and subsequently renewed in 2020 under the Green Deal, serves as the EU's principal implementation mechanism for circularity. The 2020 CEAP focuses on designing out waste, keeping materials in use, and regenerating natural systems, emphasizing product durability, reuse, repair, and recycling. For bio-based and food-related sectors, the CEAP highlights the need to develop sustainable value chains capable of transforming organic waste into secondary raw materials. Although coffee residues are not explicitly mentioned, they fall under the "biowaste" category targeted for improved separate collection and valorization. The Plan encourages Member States to strengthen their systems for biowaste collection and processing, notably through composting, anaerobic digestion, and bio-based conversion technologies. This framework directly supports the creation of markets for SCGs-derived products such as biofertilisers, bioenergy, and biopolymers, especially when these materials meet the regulatory standards defined by the EU Fertilising Products Regulation (2019/1009) and the Waste Framework Directive's end-of-waste criteria.

3 EU BIOECONOMY STRATEGY

The EU Bioeconomy Strategy, first adopted in 2012 and updated in 2018, provides the conceptual and operational framework for the sustainable use of biological resources, residues, and wastes. It defines the bioeconomy as encompassing "the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy."

This strategy places particular emphasis on valorising agricultural and agro-industrial residues, promoting cascading uses of biomass and supporting the integration of circular principles into the bioeconomy. Even though coffee residues are not directly referenced, they perfectly fit within the strategy's target categories of biowaste and agricultural by-products. Under this framework, the valorization of SCGs can be interpreted as an example of bio-based innovation, where an abundant organic residue from the food service and roasting industry is transformed into renewable materials or energy carriers.

4 COMMON AGRICULTURAL POLICY (CAP)

The Common Agricultural Policy (CAP), revised for the 2023–2027 programming period, remains the primary financial and regulatory instrument supporting sustainable agriculture and rural development within the EU. Although traditionally focused on primary agricultural production, the reformed CAP integrates the objectives of the Green Deal and the Bioeconomy Strategy, particularly through its eco-schemes and rural development measures.

Within this new orientation, the CAP promotes sustainable resource management, reduction of waste, and valorization of agricultural by-products. For example, support is provided for investments in circular practices such as biogas production, composting, nutrient recovery, and residue-based product development. Coffee residues, as part of the broader agri-food waste category, can benefit from these enabling conditions, especially when valorization activities are implemented at local or regional scales through bio-refinery models or short supply chains. The CAP's emphasis on innovation, cooperation, and value-added diversification offers a potential framework for integrating SCGs valorization into rural or territorial bioeconomy strategies, bridging the gap between waste management and agricultural sustainability.

Table. 3
Main European strategies & directives addressing organic waste materials

Regulatory Intersections: Food, Feed, Packaging, Cosmetic, and Chemical Frameworks

The **valorization of coffee residues into food and non-food applications** necessitates alignment with **a diverse set of EU regulations beyond waste law**.
Transforming SCGs into food ingredients or animal feed components requires compliance with Regulation (EC) No 178/2002 (**General Food Law**), Regulation (EC) No 767/2009 (**Feed Marketing**), and Regulation (EU) 2015/2283 (**Novel Foods**). In addition, **when valorized byproducts are used for packaging, coatings, or functional additives production, and thus are intended to come into contact with food, compliance with Regulation (EC) No 1935/2004** on materials and articles intended to come into contact with food is mandatory. These frameworks ensure safety, traceability, and consumer protection while providing a pathway for market authorization of novel valorized products derived from coffee residues. National authorities may additionally require toxicological and nutritional assessments to verify suitability for human or animal consumption.
When valorized into cosmetics or bio-based chemicals, coffee residues fall under Regulation (EC) No 1223/2009 (**Cosmetics**) and the **REACH Regulation** (EC No 1907/2006). These laws govern the registration, safety assessment, and labeling of substances and mixtures placed on the market. Extracts from SCGs used as antioxidants, exfoliants, or emollients must therefore demonstrate both safety and compliance with chemical inventory requirements.

Law / Directive	*Reference*	*Scope / Objective*	*Relevance*
Waste Framework Directive	2008/98/EC (amended by Directive (EU) 2018/851 and 2025/1892)	Establishes waste hierarchy and legal definitions of waste, byproduct, and end-of-waste criteria. Enables organic residues like SCGs to re-enter production cycles.	All waste streams; valorization of organic residues
Circular Economy Action Plan (CEAP)	EU Action Plan 2020	Provides strategic guidance for transforming organic waste into secondary raw materials; promotes industrial symbiosis and market creation for bio-based products.	Biowaste and agro-industrial residues; bio-based conversion technologies.
EU Bioeconomy Strategy	2012 (updated 2018)	Defines sustainable use of biological resources and promotes cascading valorization of biomass, including agricultural and agro-industrial residues.	Food, feed, bio-based products, bioenergy; organic residues such as SCGs.
Common Agricultural Policy (CAP)	EU CAP 2023–2027	Provides financial and regulatory support for sustainable agriculture, waste reduction, and valorization of agricultural by-products.	Residue-based product development, biogas, composting, nutrient recovery.
EU Fertilising Products Regulation	Regulation (EC) No 2019/1009	Harmonises rules for placing fertilising products on the market; includes criteria for by-products and recovered materials	Bio-based fertilizers, composts, soil improvers from organic residues.
General Food Law	Regulation (EC) No 178/2002	Ensures food safety, traceability, and consumer protection; basis for market placement of food ingredients derived from residues.	Food products, SCGs-derived dietary fibers, extracts, antioxidants.
Feed Marketing Regulation	Regulation (EC) No 767/2009	Sets marketing, labelling, and traceability rules for feed materials.	Animal feed including SCGs-derived protein or nutrient components.
Novel Foods Regulation	Regulation (EU) 2015/2283	Governs authorization of novel foods not significantly consumed in the EU before 1997.	SCGs-derived ingredients for human consumption (e.g., functional additives, protein powders).
Food contact	Regulation (EC) No 1935/2004	Regulates materials and articles intended to come into contact with food	Plastic / paper packaging in contact with food and containing SCGs
Cosmetics Regulation	Regulation (EC) No 1223/2009	Governs safety, labelling, and marketing of cosmetic products.	SCGs extracts used as antioxidants, exfoliants, or emollients.
REACH Regulation	Regulation (EC) No 1907/2006	Regulates registration, evaluation, and authorization of chemical substances; applies to bio-based chemical extracts.	SCGs-derived chemicals or biobased compounds marketed as substances or mixtures.

Case Study: Italy's Regulatory Framework

Italy's regulatory framework largely mirrors EU directives, with additional provisions on by-product management and end-of-waste status. The national system includes legislative decrees, ministerial guidance, and regional initiatives, which are relevant for the collection, treatment, and valorization of residues such as SCGs.

However, no specific regulation or policy currently exists in Italy that explicitly addresses the management of SCGs generated in commercial or domestic settings. The treatment of these residues therefore falls under the broader categories of organic or municipal waste, depending on their source and quantities.

Despite the absence of a dedicated legal framework, a number of pilot projects, local initiatives, and case studies have emerged in recent years, demonstrating practical approaches to the separate collection, recovery, and valorization of coffee residues, mostly related to the management of coffee capsules.

These experiences provide valuable operational insights and highlight potential regulatory pathways for integrating SCGs management with a dedicated system. They also suggest that, under specific conditions, the creation of dedicated collection schemes or partnerships between public authorities, waste managers, and private operators can facilitate the sustainable recovery and reuse of spent coffee grounds at both local and regional scales.

SCGs generated in commercial contexts typically fall within the broader category of municipal or municipal-like waste. In these settings, SCGs are produced in relatively small and scattered quantities by cafés, restaurants, and offices, are therefore generally managed through standard urban waste collection systems.

From a regulatory perspective, SCGs become waste at the moment the user decides to remove them from the coffee machine and discard them in the bin. As long as they remain inside the brewing system, they can still be regarded as a raw material, as an integral component of the coffee preparation process. Although no specific legal provision explicitly addresses this point, previous interpretative rulings have clarified the distinction between product, by-product, and waste in this context.

In this regulatory context, some commercial operators and coffee-related businesses have undertaken the administrative procedure to classify SCGs as a by-product. This process involves the preparation of technical documentation demonstrating compliance with the four criteria, followed by notification and registration with the competent Chamber of Commerce. Once recognized, the by-product status enables a simplified management regime, exempting the material from waste legislation and thus facilitating its direct transfer to recovery and valorization chains.

However, one of the critical aspects in the qualification of SCGs as a by-product concerns the need to ensure material stability over time. Fresh SCGs typically exhibit very high moisture content which promotes microbial growth and rapid degradation, thereby compromising both the hygienic and functional quality of the material. To meet the legal and technical conditions for by-product status, drying and stabilization treatments are therefore indicated to reduce moisture, prevent spoilage, and guarantee that the material remains suitable for its intended recovery use.

United States

The regulatory landscape for organic waste management in the United States is highly decentralized, reflecting the country's governance structure. In the absence of a national law specifically addressing SCGs, regulatory competences are primarily assigned to state and municipal authorities. As a result, a patchwork of legislative approaches has emerged, ranging from comprehensive mandatory collection systems to incentive-based and voluntary programs.

Despite the lack of a dedicated federal framework, SCGs are generally included within the broader category of organic waste or food waste and are thus subject to the same collection and treatment obligations as other biodegradable materials. In recent years, several states and municipalities have strengthened their waste diversion policies, introducing explicit targets for reducing landfilled organic waste and promoting composting, anaerobic digestion, and material recovery.

At the state level, California represents the most advanced and comprehensive example. The Senate Bill 1383 (SB 1383) mandates all jurisdictions to implement organic waste collection systems, explicitly including coffee grounds, with a 75% reduction target in landfilled organics by 2025. Other states, such as New York, Massachusetts, Vermont, Connecticut, Rhode Island, and Minnesota, impose mandatory separation requirements only on large generators, defined according to specific quantitative thresholds (e.g., one or two tons of organic waste per week). Conversely, states like Oregon, Washington, Maine, New Jersey, and Colorado have adopted softer frameworks, based on partial obligations or incentive schemes encouraging voluntary participation.

These mechanisms promote composting and bio-based valorization, while providing technical guidance and funding for municipalities and private operators.

At the municipal level, several large cities (including San Francisco, Seattle, Austin, and New York City) have introduced universal obligations for households, businesses, and institutions to separate organic waste, including SCGs. These systems are typically supported by curbside collection programs, local composting facilities, and enforcement measures such as fines for non-compliance.

The table below summarizes the main regulatory instruments currently in place across selected U.S. states and municipalities, indicating the legal status, scope, and relevance for spent coffee grounds management.

Jurisdiction	Regulation type	SCGs Included	Obligation Applies To	Description
California	Mandatory for all	Yes	All generators	SB 1383 obliges all jurisdictions to implement organic waste collection programs, including coffee grounds, with a 75% reduction target by 2025.
New York	Mandatory for large generators only	Yes	Large generators (>2 tons/week)	Businesses must separate food waste, including coffee grounds, for composting or donation.
Massachusetts	Mandatory for large generators only	Yes	Large generators (>1 ton/week)	Obligation to separate and compost organic waste or deliver it to authorized facilities; includes coffee grounds.
Vermont	Mandatory for large generators only	Yes	Large generators (>2 tons/week); incentives for others	Large generators must separate and recycle organic waste, including coffee grounds; smaller producers are incentivized to compost.
Connecticut	Mandatory for large generators only	Yes	Large generators (>52 tons/year)	Businesses must separate food waste, including coffee grounds, for composting or recovery.
Rhode Island	Mandatory for large generators only	Yes	Large generators	Composting obligation for large generators; includes coffee grounds.
Oregon	Weak / incentive-based law	Yes	Large generators; guidance for others	Some large cities have mandatory organics collection; state provides incentives and guidelines for others; includes spent coffee grounds.
Washington	Weak / partial obligation	Yes	Large generators; incentives for small users	Partial ban on landfilling organic waste; obligations for large generators and incentives for smaller ones; includes coffee grounds.
New Jersey	Weak / incentive-based law	Yes	Large generators	Voluntary programs and incentives for composting or donation of food waste; includes coffee grounds.
Colorado	Weak / incentive-based law	Yes	Large generators	Voluntary and incentive programs for composting or donation; includes coffee grounds.
Maine	Weak / partial obligation	Yes	Large generators; incentives for others	Landfill ban for large food waste generators; incentives and guidelines for household composting; includes coffee grounds.
Minnesota	Mandatory for large generators only	Yes	Large generators	Large generators must separate organics for composting or energy recovery; includes coffee grounds.
New York City	Mandatory for all	Yes	All buildings > 4 units	From 2025, mandatory source separation of food waste, including coffee grounds; fines for non-compliance.
San Francisco	Mandatory for all	Yes	All generators	All residents and businesses must separate organics for composting; includes coffee grounds.
Seattle	Mandatory for all	Yes	All generators	Mandatory collection of organic waste for all residents and businesses; includes coffee grounds.
Portland	Mandatory for all	Yes	Large generators (>250 lb/week)	Businesses generating over 250 lb/week of food waste must compost; includes coffee grounds.
Austin	Mandatory for all	Yes	All generators	All residents and businesses must separate food waste for composting, including coffee grounds; door-to-door collection in place.

Table. 4
USA main regulatory instruments

Case Study: New York and Colorado's SCGs Initiatives

New York City has integrated coffee residues into its broader organics collection system through the "Grounds for Change" program, coordinated by GrowNYC in partnership with the New York City Department of Sanitation (DSNY). The initiative involves a network of cafés, restaurants, and office buildings that separately collect spent coffee grounds for local reuse. SCGs are gathered in dedicated containers and delivered to urban composting sites and community gardens across the city's five boroughs, where they are used as nutrient-rich compost additives or soil conditioners. The project also aims to reduce contamination within the organics stream by promoting single-material collection (coffee grounds only) and public awareness campaigns on the potential of SCGs as a circular bioresource. The initiative complements the city's mandatory organics separation requirements, which will become fully enforceable for all residential buildings in 2025.

In Boulder, Colorado, a series of pilot projects and research collaborations have explored the potential of SCGs valorization beyond composting, focusing on high-value bio-based applications. Supported by the City of Boulder Circular Economy Grant Program and conducted in collaboration with the University of Colorado Boulder, local start-ups and university laboratories have tested the transformation of SCGs into biochar, biopolymers, and natural colorants. These efforts aim to develop low-emission alternatives to petrochemical materials by leveraging the lignocellulosic and lipid fractions of coffee waste. Early results demonstrate the feasibility of small-scale recovery networks that integrate cafés and research institutions, promoting local circularity and reducing the environmental footprint of coffee consumption.

Korea

The Republic of Korea has progressively established a comprehensive legal and operational framework to support the transition from waste management to resource circulation. The Wastes Control Act (WCA), enacted in 1986 and amended multiple times (notably in 2007), serves as the cornerstone of the national waste policy. It provides the definitions of "waste", sets responsibilities for collection and treatment, and regulates licensing requirements for waste-related activities.

A significant milestone came in 2005, when the landfilling of food waste was formally prohibited, thereby mandating separate collection and recycling of organic residues. This was followed in 2013 by the introduction of a volume-based "pay-as-you-throw" system, under which citizens are required to dispose of food waste using certified biodegradable bags, with costs linked to weight or volume. These measures have achieved one of the highest food-waste recycling rates globally, exceeding 95% in urban areas 25.

Within this framework, SCGs were officially recognized as circular resources on 15 March 2022, following the Ministry of Environment's Notice on the Designation of Circular Resources. This measure reclassified coffee residues from "household waste" to "circular resource" status, thus allowing their reuse without the need for conventional waste treatment permits, provided that established quality and handling standards are respected . A further revision of the Notice, notified in July 2025, expanded technical guidelines to define permissible applications and quality thresholds for SCGs-derived products.

This evolution demonstrates how Korea's national legal framework underpins the valorization of SCGs through an integrated approach to waste, resources, and circularity.

The table below summarizes the main National regulatory instruments currently in place in South Korea:

Level	Regulation / Programme	Scope	RY	Notes
National	Wastes Control Act (WCA)	Framework law defining waste, responsibilities, treatment permits.	1986 (rev. 2007)	Legal foundation for all waste management policies
National	Food -Waste Landfill Ban	Prohibition on landfilling food waste; it mandates recycling/composting	2005	Cornerstone for organic waste diversion
National	Pay-as-you-throw system	Requires certified biodegradable bags; fees by volume/weight	2013	Promotes separation, reduction, and behavioural responsibility
National	Circular Resource Recognition for SCGs	Coffee grounds re-classified as circular resource	2022	Enables reuse of SCGs without full waste-treatment permits
National	Revised Notice on Designation of Circular Resource)	Defines standards, product uses, quality criteria	2025	Establishes quality and application standards
Local – Seoul	Seoul Coffee Grounds Recycling System	City-wide mandatory collection and recycling system for SCGs	2021	Municipal scheme under SMG, targets SCGs stream and covers +25k cafès
Local – Seoul	District coffee Grounds Collection & composting project	District-level pilot collecting 157.5 tonnes annually	2025 (pilot)	Collaboration with social enterprises, replicable model

Table. 5 Main Korean regulatory instruments.

Case Study: Seoul Metropolitan SCGs recycling system

On 23 December 2021, The Seoul Metropolitan Government (SMG) launched the Seoul Coffee Grounds Recycling System, designed to promote the separate collection and recycling of coffee residues generated by the city's extensive café sector: Seoul, home to more than 25,000 coffee shops, generates approximately 145 tonnes of coffee grounds per day. Under the programme, cafés install dedicated containers for SCGs, which are then collected by district offices and transferred to authorized service providers for processing. The system is governed by contracts between the municipality (via district offices) and private-sector operators:

- Coffee shops are required to separate SCGs at the source, ensuring a clean and homogeneous stream for recovery.
- District offices oversee collection logistics, coordinating with certified private recycling companies.
- Collected SCGs are reprocessed into compost, biofuel pellets, construction materials, and feedstock, depending on quality and demand.
- Cafés participating in the programme may receive certification marks and economic incentives, such as reduced waste disposal costs and public recognition for environmental responsibility

The initiative also promotes social inclusion, as part of the collection and handling chain is operated by social enterprises employing vulnerable groups.

In terms of cost-sharing and incentives: cafés benefit from reduced waste disposal fees (since SCGs are diverted from standard volume-based pay-as-you-throw waste streams), while district offices may subsidize collection infrastructure (containers, promotional material) and logistics contracts. Private recycling companies gain access to a stable feedstock which can be processed into higher-value outputs, thereby creating an economically viable circular service.
Importantly, the system distinguishes between commercial generators (cafés/bars) and individual households. The main focus of Seoul's programme is on cafés and other commercial coffee-shops, where SCGs volumes are large and logistics more manageable.

SCGs collected under Seoul's programmes are processed into a variety of secondary products. Key transformations include:

- Compost for agricultural or landscaping use cafés SCGs that are turned into nutrient-rich compost, often distributed to farms or community gardens.
- Bio-energy / bio-fuel, high calorific value of SCGs is leveraged by firms such as Cheonil Energy to produce wood-chip substitutes or solid fuel.
- Up-cycled composite materials: SCGs have been processed into benches and interior materials (as in the city of Incheon) made of coffee-ground composites.
- Substrate for mushroom cultivation / other agronomic uses.
- Potential for advanced materials (bio-char, bioplastics, fillers) although less documented commercially in Seoul specifically, national research projects in Korea indicate SCGs are being valorized into bioplastics and high-value material streams.

Market Survey

This section presents the findings from a targeted survey designed to capture **how SCGs are currently managed** and to **identify emerging opportunities for circular innovation** within the coffee sector. The objective was to build a clearer picture of existing practices, perceived barriers, and the enabling conditions needed to scale sustainable uses of this material across the industry and into adjacent sectors.

The survey sought to answer three key questions:

- What approaches to SCGs management and reuse are working effectively today?
- What barriers are limiting broader adoption of circular solutions?
- What support, partnerships, or policies are needed to accelerate progress?

To ensure the survey was comprehensive and captured perspectives from relevant stakeholders, **two distinct survey** instruments were developed. The **first targeted stakeholders within the coffee industry** with the aim of understanding how SCGs are handled within their operations and supply chains. The **second was designed for circular economy innovators and entrepreneurs** who are developing new value pathways for SCGs, whether through energy generation, material recovery, or product innovation.

The surveys were distributed through multiple channels, including the C4CEC membership network, the International Trade Centre (ITC) Coffee Guide Network, and the C4CEC LinkedIn page. They were also shared with partner organizations including the International Women's Coffee Alliance (IWCA), the Specialty Coffee Association (SCA), the Swiss Coffee Trade Association (SCTA), and the African Fine Coffees Association (AFCA). In addition, members promoted the survey across several LinkedIn groups for coffee professionals, producers, roasters, retailers, and baristas.

Despite the low survey response rate, **25 responses were collected from respondents from 10 different countries, across Africa, the Americas, Asia and Europe**, including both coffee producing and consuming countries. Despite low survey response rate, the insights gathered remain valuable for the purpose of this paper, as **they reveal how SCGs are currently perceived and managed**, highlight emerging circular initiatives, and underscore the challenges and opportunities that must be addressed to unlock their full potential as a sustainable resource within the global coffee system.

The State of Circular Economy: Market Insights on Products from Spent Coffee Grounds

When asked about which stages of the coffee value chain dominate SCGs valorization, **respondents emphasized the mid-to-late stages of the chain dominating SCGs valorization**, with small enterprises playing a central role. Perceived barriers from respondents are multifaceted, spanning financial, technical, infrastructural, and regulatory dimensions, while support priorities emphasize partnerships, knowledge, and market access. Awareness and dissemination of best practices remain critical to promoting circular economy initiatives across the coffee sector.

In the **first survey**, **14 responses were received from respondents of 8 different countries**, from both Global North and South across Africa, the Americas, Asia and Europe, also representing a wide range of roles within the coffee sector. More than 50% of respondents correspond to small enterprises, operating with fewer than 50 employees. The **predominance of small businesses** in survey responses is reflected in half of respondents generating modest SCGs volumes, less than 10 kg/day.
Approximately a third of respondents reported being aware of at least one service provider or company offering SCGs valorization solutions. Some examples reported by respondents, including the use of SCGs in cosmetics or their integration into mushroom cultivation, were mainly discovered through professional networks like the ITC Coffee Guide Network Circular Economy Working Group and the C4CEC network .
In general, respondents reported a mix of barriers and enablers for SCGs valorization. About half of participants identified no major obstacles, while the remaining half highlighted multiple challenges. These results reflect that respondents have very different experiences and that, potentially, factors like funding, expertise, and infrastructure, are heterogeneous within the sector. To overcome these barriers, respondents mentioned specific types of support, among which the most cited were partnerships, funding, market access, and technical knowledge. These findings suggest that strong collaborations, resource availability, and supportive frameworks are critical for advancing circular economy practices in the coffee sector.

Insights from Circular Economy Actors: Valorizing Spent Coffee Grounds

Based on **11 responses from respondents of 10 different countries**, our **second survey** targeting more direct users of SCGs found that SCGs valorization is driven by small, innovative, and sustainability-focused actors. These actors span **a spectrum from low-tech composting to advanced industrial applications, supported by multichannel storytelling, educational initiatives, and intellectual property strategies**. Respondents underline clear economic, environmental, and social potential of using SCGs, highlighting this byproduct as a promising resource for circular economy models in the coffee industry.

90% of the responses received correspond to start-ups and small enterprises engaged with coffee industry businesses. The predominance of SME's is a reflection of the type of entities which have been more constantly engaging with the C4CEC. This underscores the role of agile, entrepreneurial actors in advancing circular economy practices for SCGs. Consequentally, more than 80% of respondents report daily valorization volumes below 50 kg. **Applications of SCGs** reported by respondents are diverse, ranging from **agriculture** (fertilizers, compost, vermicomposting, mineral-organic fertilizers) to **cosmetics**, **food/nutraceuticals**, **bioplasti-**

cs, and **industrial chemistry**. This demonstrates the adaptability of SCGs as a circular resource.

Storytelling and communication play a key role in highlighting SCGs value. Techniques include digital content, partnership case studies, on-site demonstrations, industrial narratives, cultural heritage storytelling, and consumer branding, connecting circularity to tangible outcomes, social impact, and everyday experiences. These strategies intentionally avoid terms like “waste” or “waste-based” to maintain credibility and emphasize upcycling and value creation. **Education and awareness efforts focus on environmental and economic benefits, using personalized interactions, in-store activations, social media, webinars, and events**. Narratives often link SCGs valorization to the evolution of coffee, circular economy principles, and consumer engagement.

Respondents perceived **a predominant market interest in SCGs-based products by sustainability-focused businesses, innovative consumers/companies and eco-conscious consumers** highlighting the alignment of circular products with environmentally responsible and forward-thinking stakeholders. Moreover, they also recognized the economic benefits of SCGs reuse. In addition, awareness and strategic use of intellectual property (IP) is notable among respondents, as it results in a channel for partnerships, licensing, fundraising, branding, and protecting proprietary processes. These economic incentives could be used as an avenue to engage more businesses and expand the market.

In spite of the low response rate, the responses received have been an insightful beginning to expanding the potential of SCGs. It presents an opportunity to relaunch a follow-up survey which could reach a broader sample of respondents. These findings have also been **a reminder of the need to exchange, share and echo the opportunities** that can be unlocked while adopting circular economy practices in the different stages of the coffee value chain. Survey findings reflect that **knowledge and best practices on SCGs are dispersed across stakeholders**, highlighting the necessity for a platform where innovators, entrepreneurs and companies can consult, exchange and learn from each other.

Financing SCGs Innovation

Evidence shows that the financial sector is only beginning to engage meaningfully with circular economy opportunities. According to the United Nations Environment Programme (UNEP) Finance Initiative (2020), most financial actors currently see the greatest potential for circularity finance in the **construction and building sectors**, while **more than 30% identify opportunities in food and agriculture** (Ellen MacArthur Foundation, 2020). This is a critical entry point for SCGs valorization, which lies at the intersection of both sectors: food waste recovery and the development of bio-based construction materials.

Yet, despite this alignment, **investment in circular ventures, particularly in African countries and other emerging markets**, faces the same constraints observed globally: a lack of standardized data, inadequate disclosure on performance, and insufficient transparency on both historical and forward-looking risks (Ellen MacArthur Foundation, 2020). High risk perception and limited familiarity with circular business models among financial institutions and fund managers further constrain the flow of capital toward start-ups and SMEs innovating in this space.

For startups working on SCGs valorization, intellectual property (IP) can be a decisive factor in whether an idea progresses beyond the lab. In capital-intensive technology development, particularly in impact-driven sectors like circular economy ventures, a strong IP position helps de-risk investor capital, signals market potential, and supports financing of further innovation and commercialization. **Patents**, in particular, can give startups **leverage to secure early-stage investment, capture market share, and build defensible business models**.

This matters for SCGs valorization not only because **new technologies can generate economic growth and jobs**, but also because they directly support environmental goals, diverting waste from landfills and creating higher-value uses for coffee by-products. However, identifying truly novel, patentable innovations in this space can be difficult. Coffee has a deep cultural history and a substantial body of existing prior art, which means that many incremental advances may not meet the threshold for patent protection.
Even when patentable solutions exist, another challenge emerges. **Developing and maintaining IP portfolios is costly and complex, often requiring specialized legal and technical expertise** that early-stage founders lack. Startups may need to raise capital simply to protect their ideas, before they can even commercialize them. This creates a contradiction: the very mechanism (IP protection) that enables financing is itself prohibitively expensive to secure.

There are, however, important efforts to close these gaps. Government subsidies, grants, or accessible IP education and advisory services can play a critical role in ensuring innovators are able to protect, finance, and scale their technologies. **The development of circular economy taxonomies**, such as the EU Taxonomy on sustainable finance, **is beginning to provide investors with clarity on what constitutes circular activity** (Ellen MacArthur Foundation, 2020). In parallel, tools like Circulytics and other measurement frameworks enable the integration of circular metrics into investment decision-making, allowing for the setting of ambitious KPIs and more rigorous impact evaluation. **Policy instruments** are also reinforcing these shifts: the European Union is directing unprecedented levels of support through Horizon Europe (€95.5 billion until 2027), LIFE, and advisory services provided by the European Investment Bank (European Circular Economy Stakeholder Platform, 2020), while consumer trends are leaning in favor of upcycled goods.

Consumer sentiment also provides a supportive backdrop. **Surveys indicate that European consumers associate upcycled food products with innovation, recycling, and environmental responsibility** (EIT, 2025). Such perceptions reduce market-entry risks for SCGs-derived products and help create a favorable environment for financing.

Taken together, these developments suggest that the landscape for financing SCGs valorization is slowly improving, though it still requires more deliberate strategies to de-risk investment and build confidence in circular SMEs and start-ups. **Blended finance models that combine public and private resources, coupled with transparent data and measurable outcomes, will be central to unlocking the market's full potential**. Yet, financing alone cannot guarantee the success of valorization initiatives. Beyond mobilizing capital, entrepreneurs and firms need to establish clear competitive advantages and build long-term resilience. This is where intellectual property (IP) becomes an effective strategy. By protecting the innovations, processes, and brands that emerge from SCGs valorization, **IP not only strengthens profitability but also increases investor confidence**, paving the way for more sustainable and scalable circular solutions.

Conclusion

Spent coffee grounds (SCGs) represent an enormous untapped resource in the global coffee sector. With 11 million tons generated annually, their current disposal practices contribute significantly to greenhouse gas emissions and squander valuable bioactive compounds. This white paper demonstrates that **SCGs are not waste, but a versatile feedstock prime for innovation across agriculture, food, cosmetics, energy, and materials industries**.

The evidence is clear: **valorizing SCGs can reduce emissions by up to 76% compared to landfill disposal, conserve resources, and create new socio-economic opportunities, particularly for women and youth**. Yet, realizing this potential requires overcoming persistent barriers: fragmented collection systems, complexity to safeguard valuable properties, and regulatory ambiguity that slows or inhibits valorization.

To unlock the full promise of SCGs, **stakeholders across the coffee value chain must act decisively**. **Policy alignment is essential** to harmonize waste classifications and establish end-of-waste criteria. Investment and financing mechanisms must be scaled to support circular business models and de-risk innovation. Collaboration between producers, innovators, and policymakers will accelerate the development of localized processing hubs and integrated biorefineries, ensuring environmental and economic benefits are maximized.

Embedding circularity in the coffee sector is a critical step toward an innovative green economy, aligning industry growth with environmental stewardship and social equity. Every ton of SCGs diverted from landfill is a step toward climate resilience, resource efficiency, and inclusive growth. The time to act is now: join forces to transform coffee waste into a cornerstone of the global circular bioeconomy.

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