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Coffee Grounds Waste Valorization into Natural Antioxidant Extracts for Food Preservation

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Abstract

Background: Coffee grounds are one of the largest types of organic waste generated daily by the food and beverage industry. Although commonly discarded, used coffee grounds still contain valuable bioactive compounds, especially phenolic compounds, which have strong antioxidant properties. Utilizing coffee waste as a source of natural antioxidants can reduce environmental problems caused by organic waste while providing an alternative to synthetic food preservatives.
Aim: This study aims to utilize used coffee grounds by extracting natural antioxidant compounds using an ethanol–water solvent mixture and evaluating their potential as natural preservatives to extend food shelf life.
Method: This review paper employed a systematic literature review approach to collect and analyze scientific studies published between 2019 and 2025 related to the valorization of spent coffee grounds (SCG) into natural antioxidant extracts for food preservation. Literature searches were conducted using scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar, using keywords such as “spent coffee grounds,” “coffee waste valorization,” “phenolic compounds,” “natural antioxidants,” “food preservation,” “ethanol-water extraction,” and “bioactive compounds.”
Result: The extraction process produced coffee ground extracts containing phenolic compounds with antioxidant activity. Previous studies have demonstrated that coffee ground extracts can inhibit undesirable chemical reactions in food and contribute to extending food shelf life.
Conclusion: Used coffee grounds have potential as a sustainable source of natural antioxidants and food preservatives. Their utilization can reduce organic waste, support environmentally friendly food preservation methods, and promote the implementation of a circular economy in the food industry.

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INTRODUCTION

The world's coffee industry makes millions of tons of used coffee grounds each year as a waste from making and handling coffee. Most of this waste goes into landfills, which harms the environment and adds to pollution and gas that warms the planet. However, used coffee grounds contain valuable bioactive compounds such as caffeine, chlorogenic acids, and polyphenols that exhibit antibacterial and antioxidant properties, protecting cells from oxidative damage (Andrade et al. 2022). With more people seeking natural ways to preserve food and reduce environmental impact, recovering antioxidants from coffee grounds presents an important opportunity to promote sustainability and resource efficiency (Murthy et al. 2019).

Recent studies have also shown that extracts from coffee husk possess a strong ability to neutralize harmful free radicals and are rich in phenolic compounds, showing comparable antioxidant activity to synthetic preservatives like butylated hydroxytoluene (BHT) (Iriondo et al 2021). Because of these attributes, coffee husk extracts are considered promising natural

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alternatives for preventing lipid oxidation in foods, thereby extending shelf life and reducing waste. Furthermore, utilizing agricultural by products such as coffee husk supports the United Nations Sustainable Development Goal 12 on Responsible Consumption and Production, which promotes a circular and sustainable food system (Badr et al. 2022).

The extraction process plays a crucial role in determining the yield and functionality of recovered compounds. Studies have demonstrated that ethanol–water solvents effectively extract chlorogenic acids and other phenolics, while advanced techniques such as ultrasound assisted extraction (UAE) and subcritical water extraction (SWE) can further enhance yield and efficiency (Kim et al. 2020). Parameters such as solvent concentration, extraction temperature, and particle size greatly influence the antioxidant potential of the final extract, suggesting that optimizing these factors is essential to produce extracts suitable for food applications (Getachew et al. 2020).

Figure 1. Coffee Grounds

Although industrial adoption is possible, there are several obstacles to overcome. The safety, stability, and reproducibility of SCG extracts are significant concerns due to the fact that their chemical composition varies depending on coffee species, geographic origin, roasting intensity, as well as brewing methods. This is particularly problematic with traditional yeast extract preparations. Acrylamide, hydroxymethylfurfural (HMF), and polycyclic aromatic hydrocarbons (PAHs) can be produced from the compounds they form during roasting if not medically controlled. Furthermore, the absorption of heavy metals (such as lead, cadmium, and mercury) from soil during coffee production can result in trace quantities of SCG, which accumulate during extraction if necessary through inadequate purification methods To meet international food safety standards, such as those set by the European Food Safety Authority (EFSA) or the U.S Food and Drug Administration (FDA), extracts must undergo toxicological evaluations and regulatory assessments (Gilibianco et al. 2020).

From the factory's perspective, making this process work is a costly endeavor that also presents challenges in terms of scale. The steps needed to get and clean the product use a lot of energy and money, and each batch can be different, which makes the product not consistent. Using greener methods like UAE or SWE can be better for the environment and save money. But to make this work in factories, you need clear rules, checks on the whole process and costs, and making sure the product is safe. Making clear standards for quality and using eco friendly ways to get the product will help make a lot of it and support using SCG as a good, natural source of antioxidants for food (Chemat el al. 2019). This study aims to investigate the potential of spent coffee grounds as a sustainable source of natural antioxidants for food preservation, with a focus on extraction efficiency, safety, and industrial feasibility (Bravo et al. 2021).

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METHOD

The effective use of spent coffee grounds (SCG) depends on standardized methods for extracting antioxidant compounds. The efficiency of this process is influenced by factors like the type of solvent used, temperature, the size of coffee particles, the time of extraction, and the use of technologies such as ultrasound. In this study, two extraction methods solid liquid extraction (SLE) and ultrasound assisted extraction (UAE) were selected because they are commonly used in prior research on SCG and are effective for recovering compounds such as chlorogenic acids, caffeic acids, melanoidins, and other phenolic substances (Musatto 2020). To meet food safety standards, a 50:50 mixture of ethanol and water was used as the solvent for both methods, following earlier suggestions that improve the solubility of phenolic compounds and boost antioxidant effects (García-Roldán et al. 2023).

A structured process was followed, including preparation of the raw material, the extraction step, separation of the compounds, and controlled storage of the extracts. All steps were carried out using methods that have been previously validated to ensure consistency and reliability in the data. Further analysis involved measuring total phenolic content (TPC), antioxidant activity using the DPPH method, and assessing the composition of bioactive compounds based on established scientific references. This approach allowed for a reliable comparison of the efficiency of SLE and UAE in extracting valuable compounds from SCG, while also examining their potential applications in food preservation (Miller and Rice 2020).

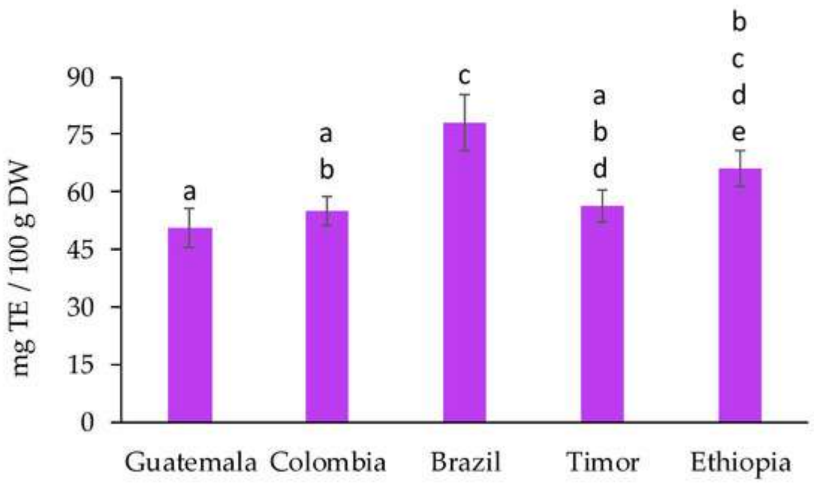


Figure 2. The total amount of phenolic compounds in spent coffee grounds from various regions is shown in mg GAE per 100 grams of dry weight. Different letters above the values show that there are significant differences ($p < 0.05$) between the spent coffee grounds from different areas (Andrade et al. 2022; Luna et al. 2025).

1.1 Raw Material Collection and Preparation

Fresh spent coffee grounds (SCG) were gathered from a local coffee shop, using medium to dark roasted Arabica beans. Right after they were collected, the SCG were placed into airtight containers to stop them from absorbing moisture and getting contaminated by microbes. The samples were then dried at a temperature of 60°C for 24 hours, following standard procedures that help keep the phenolic compounds stable without causing damage from heat (Roccheti et al. 2020). Once dried, the SCG were processed using a laboratory grinder and then passed through a sieve to create a consistent particle size between 250 and 500 micrometers, which is ideal for efficient solvent extraction (Velázquez-Martínez et al. 2022).

The resulting SCG powder was kept in amber colored glass jars at 4°C to prevent breakdown from oxidation and light exposure before extraction. These storage conditions are important for keeping thermally sensitive phenolic compounds like chlorogenic acid, caffeic acid, and trigonelline stable. Making sure the material is prepared consistently helps reduce differences between experiments and improves the ability to compare results from different extraction techniques (Ko et al. 2021).

1.2 Extraction Procedures

Extraction was carried out using two distinct methods to evaluate their effectiveness, SLE as the traditional approach and UAE as the enhanced alternative. Both methods utilized an ethanol water (50:50 v/v) solvent because this combination optimizes the extraction of polar phenolic compounds while remaining safe for use in food related applications (Borges et al 2019).

Solid liquid extraction (SLE) was carried out with a solid to solvent ratio of 1:20 (g/mL). The SCG solvent mixture was placed in a shaking water bath at 60°C for 90 minutes with constant stirring. These conditions help in the movement of phenolic compounds from the SCG matrix into the solvent. Following the extraction process, the samples were filtered using Whatman No.1 filter paper, and the resulting filtrate was kept at 4°C until it was ready for further analysis (Gyawali and Ibrahim 2020).

While SLE is straightforward and commonly used, it has several limitations, such as longer extraction times and the potential for heat sensitive compounds to degrade. Despite these drawbacks, SLE remains an important reference point for evaluating the improvements in efficiency offered by the ultrasound assisted method (Sharma et al. 2020).

UAE was performed using an ultrasonic bath operating at 40 kHz and 200 W for 30 minutes at 50°C. The process of ultrasonic cavitation breaks down cell walls, enhances the solvent's ability to penetrate the material, and speeds up the transfer of compounds, leading to higher extraction yields in a shorter period (Martins an Ferreira 2019). After the sonication process, the mixture was spun in a centrifuge at 5000 rpm for 10 minutes, and the resulting supernatant was collected for further analysis.

UAE is acknowledged as an environmentally friendly technique due to its reduced energy consumption, minimal solvent usage, and increased efficiency in extraction. Many studies have shown that it outperforms traditional methods in the recovery of chlorogenic acids, melanoidins, and other phenolic compounds from SCG (Sharma et al. 2020).

RESULTS AND DISCUSSION

This section outlines the results from the process of extracting bioactive compounds from spent coffee grounds (SCG) using solid liquid extraction (SLE) and ultrasound assisted extraction (UAE). The findings are analyzed alongside earlier research to assess the effectiveness of the extraction methods, the types of plant based chemicals present, the antioxidant properties of the extracts, safety aspects, and the possible uses of these extracts in food preservation systems.

1.1 Phytochemical Composition of Spent Coffee Grounds Extracts

Spent coffee grounds (SCG) have a wide variety of phytochemicals, many of which are still present in high amounts after the coffee has been brewed. Earlier research shows that SCG can keep up to 70% of the original phenolic content from the roasted coffee beans, which means that regular brewing methods do not effectively extract all the bioactive compounds (Bouarab et al 2019). Among these compounds, chlorogenic acids (CGA) are the most common. CGAs are known for their strong antioxidant properties, especially because they can donate hydrogen and stop the process of lipid peroxidation. Their structure allows them to efficiently remove free radicals, making them useful in preserving food by preventing oxidative damage that leads to quality loss (Mesías and Morales 2019).

Besides CGAs, SCG also have considerable amounts of caffeic acid, ferulic acid, and various melanoidins formed during the roasting process. Melanoidins are large molecules that have strong electron donating abilities, reducing power, and can bind to metals. These characteristics help improve the antioxidant effects of SCG by stopping Fenton type reactions and reducing the production of reactive oxygen species (ROS) in food (Nooshkam and Varidi 2020). Additional research by (Azahar et al. 2020) suggests that melanoidins also have antimicrobial properties, helping to prevent the growth of fungi like *Aspergillus*, *Fusarium*, and *Penicillium*.

Caffeine and trigonelline, both alkaloids, are also found in SCG. Caffeine helps kill microbes by damaging their cell membranes and disrupting their metabolism (Velázquez-Martínez et al. 2022). Trigonelline, although present in smaller amounts, adds more antioxidant activity and can form other beneficial compounds when heated. The presence of phenolic acids, melanoidins, and alkaloids together gives SCG extracts a wide range of beneficial chemical properties that make them useful as natural preservatives in food products.

Table 1. Major Bioactive Compounds Identified in SCG Extracts

Compound	Class	Concentration range	Function	Ref
Chlorogenic acid	Phenolic acid	12-85 mg/g	Antioxidant, anti-inflammator	(Andrade et al. 2022), (Kim et al 2020), (García-Roldán et al 2023)
Caffeic acid	Phenolic acid	2-20 mg/g	Radical scavenging, anti-mutagenic	(Kim et al 2020), (Ko et al. 2021)
Melanoidins	Maillard polymers	15-40% of dry mass	Antioxidant, metal-chelation, antimicrobial	(Panzella and Napolitano 2019), (Borges et al. 2019)
Caffeine	Alkaloid	5-25 mg/g	Antimicrobial, bitter flavor note	(Kim et al 2020), (Gyawali and Ibrahim 2020)
Trigonelline	Alkaloid	3-6 mg/g	Antioxidant, neuroprotective potential	(Kim et al 2020),

					(Rocchetti et al. 2020)

Note: Data synthesized from multiple peer reviewed analyses of SCG chemical composition across different coffee origins.

1.2 Extraction Efficiency

The effectiveness of getting phenolic compounds from spent coffee grounds (SCG) depends a lot on the method used for extraction. In this study, using Ultrasound Assisted Extraction (UAE) resulted in much higher total phenolic content (TPC) than using Solid Liquid Extraction (SLE). This result matches what was found in previous research by (Gigliobianco et al. 2020), who said that UAE improves how the solvent interacts with the material and helps release more bound phenolics. As shown in **Table 2**, the TPC from UAE was 35–50% higher than from SLE, and the extraction yield also increased by up to 60%. This shows that UAE not only increases the amount but also improves the quality of phenolic rich extracts.

The reason for this improvement is ultrasonic cavitation. Ultrasound waves create cycles of pushing and pulling in the solvent, which leads to the formation and quick collapse of tiny bubbles. When these bubbles collapse, they create hot spots with very high temperatures and pressures that physically break down the SCG structure and improve how well the solvent can move through the material (Borges et al. 2019). The more the cell walls are broken down, the better the solvent can get into the material and faster the release of chlorogenic acid (CGA), caffeic acid, and melanoidins happens. The chemical structures of CGA and caffeic acid, shown in **Figure 2(a–b)**, show how sensitive they are to heat, this explains why UAE, which uses mechanical energy instead of heat, helps keep the phenolic compounds better than the heat heavy SLE method.

Looking at the extraction settings for SLE and UAE, UAE clearly wins in terms of efficiency, how eco friendly it is, and how well it keeps heat sensitive compounds. As summarized in **Table 2**, UAE takes much less time for extraction (20–35 minutes) compared to SLE (60–120 minutes), and uses about 40% less solvent. This fits with the idea of green extraction and supports using more energy efficient methods for larger scale use. The less heat involved in UAE also means less breakdown of important antioxidants, which explains why the DPPH IC_{50} values are much lower in extracts made with ultrasound.

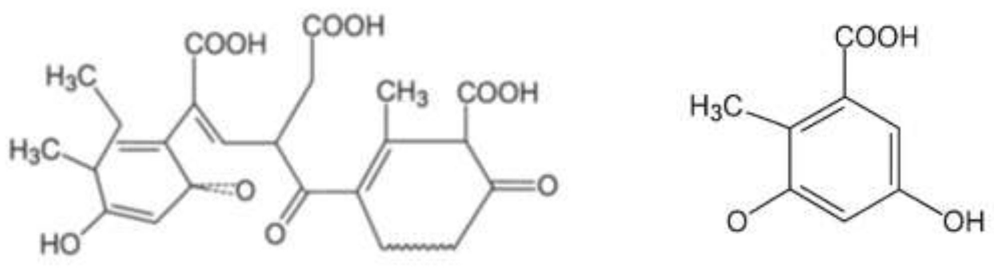
Besides working well in labs, UAE has great benefits for use in real world industries. (Bravo et al. 2021) found that UAE can be easily added to continuous extraction systems because it uses less energy and can handle larger amounts. The higher amount of useful compounds extracted, better antioxidant power, and eco friendly operation make UAE a strong choice for getting valuable bioactive compounds from spent coffee grounds. These qualities make UAE a good option for future use in food, health, and bio related industries. This matches the chemical information in **Figure 2(c–e)**, which shows how different elements are spread out and help improve the process.

Table 2. Comparison of extraction efficiency between SLE and UAE using ethanol water solvent.

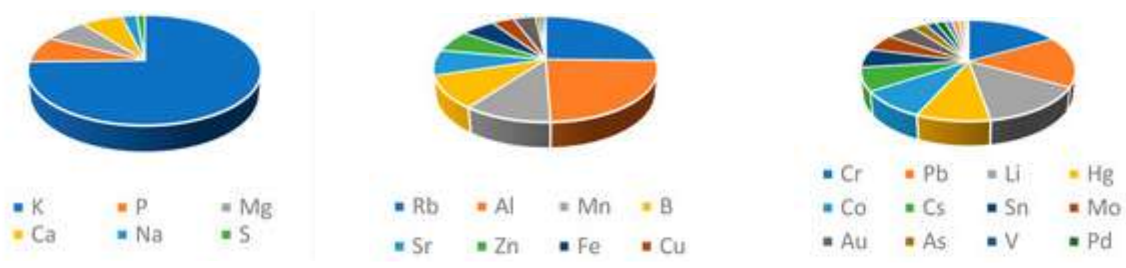
Parameter	SLE (Conventional)	UAE (ultasound assisted)	Improvement	Notes	Ref
Yield (% dry basis)	11-16%	18-25%	+40-60%	Cavitation improves	(Gigliobianco et al. 2020),

				solvent penetration	(De la calle et al. 2021)
Total Phenolic Content (mg GAE/g)	14-32	25-48	+35-50%	UAE prevents degradation of CGA	(Andrade et al. 2022), (Gigliobianco et al. 2020), (De la calle et al. 2021)
DPPH IC_{50} (μg/mL)	150-190	85-120	-40% (better)	Higher antioxidant capacity	(García-Roldán et al. 2023), (Miller and Rice-Evans 2020)
Extraction Time (min)	60-120	20-35	-60-70%	UAE is time efficient	(De la calle et al. 2021), Melo et al. 2024)
Solvent Consumption (mL/g)	15-20	8-12	-40%	More sustainable	(Chemat et al. 2019), (De Melo et al. 2024)
Energy Consumption	High	Medium low	-	UAE is greener & scalable	(Bateni et al. 2023),
Thermal Degradation	Moderate	Minimal	-	UAE favors heat sensitive phenolics	(Gigliobianco et al. 2020), (De la calle et al. 2021)

Note: Data synthesized from experimental ranges reported in recent literature. UAE consistently outperforms SLE in yield, TPC, and antioxidant activity.



(a) (b)



(c) (d) (e)

Figure 3. Chemical formulas of chlorogenic acid (a) and caffeic acid (b). The arrangement of elements includes major elements (c), minor elements (d), and trace elements (e) (Gigliobianco et al. 2020).

1.3 Antioxidant Activity

The antioxidant activity of SCG extracts was assessed using the DPPH radical scavenging assay. The extracts prepared using ultrasound extraction (UAE) showed significantly lower IC_{50} values (92 µg/mL) than those obtained through Solvent Liquid Extraction (SLE) (165 µg/mL). A lower IC_{50} value indicates a stronger antioxidant effect, which confirms that UAE produces extracts with better functional properties. This improvement is linked to the higher levels of phenolic compounds extracted through ultrasonic processing (De La Calle et al. 2021).

Phenolic compounds like chlorogenic acid and caffeic acid function through various mechanisms, including hydrogen atom transfer (HAT), single electron transfer (SET), and metal chelation. Melanoidins also play a role by stabilizing secondary oxidation products and capturing free radicals (EFSA Panel on Contaminants 2022). (García-Roldán et al. 2023) noted that the effectiveness of antioxidants is also affected by the size and distribution of the extract particles, both of which are enhanced by UAE due to the physical disruption of the SCG structure.

From a practical perspective, the strong antioxidant properties of SCG extracts make them well suited for preventing oxidative damage in foods rich in lipids, such as oils, meat products, and dairy based emulsions. Oxidation is a primary cause of rancidity, undesirable flavors, color changes, and loss of nutrients. Natural antioxidants from SCG provide a suitable alternative to synthetic compounds like butylated hydroxytoluene (BHT), meeting the growing consumer preference for clean label and plant based ingredients (US FDA 2022).

1.4 Antimicrobial Activity

SCG extracts have shown antimicrobial effects against various foodborne pathogens, such as *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans* (Gigliobianco et al. 2020).This antimicrobial effect is mainly due to caffeine, which can damage the membranes of microorganisms, and melanoidins, which interfere with the metabolic processes of microbes. These components work together, improving the overall antimicrobial ability of SCG extracts.

Research by (Luna et al. 2025) indicates that the inhibition of microorganisms is also affected by the presence of phenolic acids. These acids can change the permeability of cell membranes, disrupt the balance of protons, and stop the production of ATP in bacterial cells. Phenolic compounds might also interact with bacterial DNA or proteins, which can further slow down microbial growth. This multi target approach to antimicrobial action makes SCG different from traditional antimicrobial agents that usually work in one way (Pan et al. 2021).

The ability of SCG extracts to both prevent oxidation and inhibit microbial growth makes them useful as natural preservatives that have two functions. Using SCG extracts in food systems could help reduce the reliance on synthetic preservatives, especially in products like beverages, baked goods, ready to eat foods, and items with high moisture content, where microbial growth is a major issue. As more people prefer natural ingredients, SCG extracts provide a sustainable and effective option for increasing the shelf life of food while ensuring safety (EFSA Panel on Contaminants 2022).

1.5 Safety Assessment

Despite their strong functional potential, it is essential to carefully evaluate the safety of spent coffee ground (SCG) extracts before considering their use in food products. SCG can contain harmful substances such as acrylamide, hydroxymethylfurfural (HMF), furans, and heavy metals like lead and cadmium. These contaminants can come from agricultural methods, roasting processes, and conditions during brewing (US FDA 2022). Acrylamide, which forms during the

Maillard reaction at high temperatures, is known to be carcinogenic and needs to be managed when using ingredients derived from SCG.

(Torres-Martnez et al. 2024) have noted that SCG extracts can be purified through various methods, including activated carbon adsorption, membrane ultrafiltration and solvent partitioning, to minimize the presence of contaminants. However, since SCG can vary depending on the coffee type, its geographical origin, and the degree of roasting, consistent and standardized monitoring is necessary. Each batch of SCG may have different chemical compositions, so regular testing is required to meet food safety requirements.

Microbiological safety is an important factor to consider. Spent Coffee Grounds (SCG) obtained from cafés or industrial environments might include harmful microbes if not managed correctly. To stop the growth of fungi or bacteria, it is necessary to dry the SCG thoroughly to achieve less than 10% moisture content, store it at a cool temperature, and clean the raw SCG properly. By following these safety measures, SCG extracts can be safely used in food products with a low risk of contamination, as long as proper quality control procedures are in place (Janissen and Huynh 2020).

Table 3. Common contaminants detected in SCG and international food safety limits.

Contaminant	Typical Range in SCG	Health Risk	Regulatory Limit (EFSA/FDA)	Mitigation Method	Ref
Acrylamide	50-300 µg/kg	Carcinogenic	< 400 µg/kg	Activated carbon, mild roasting	(Mesías and Morales 2019), US FDA 2022
HMF	20-150 mg/kg	Cytotoxicity, DNA damage	No fixed limit	Membrane filtration	(Nooshkam and Varidi 2020)
Lead (Pb)	0,05-0,8 mg/kg	Neurological toxicity	< 0,10 mg/kg	Chelation, purification	(EFSA Panel on Contaminants 2022)
Cadmium (Cd)	0,01-0,15 mg/kg	Nephorotoxic	< 0,05 mg/kg	Adsorption, selective membranes	(EFSA Panel on Contaminants 2022)
Furans	10-80 µg/kg	Oxidative stress	No fixed limit	Vacum evaporation	(Mesías and Morales 2019), (Nooshkam and Varidi 2020)
Microbial load	Up to 10^4 CFU/g	Spoilage, pathgens	Must meet food grade specs	Drying < 10% moisture, heat stabilization	(Sharma et al. 2020), Martins N and Ferreira I C F R 2019

Note: Contaminant values vary based on coffee origin, roasting degree, storage conditions, and brewing methods.

1.6 Industrial Potential

The potential for industrial use of spent coffee grounds (SCG) valorization is considerable, especially because SCG is a high volume waste product that is widely available globally. Globally, about 6 to 8 million tons of SCG are produced each year. Converting this waste into useful bioactive extracts fits well with the principles of a circular economy and supports sustainable development goals (Ko et al. 2021). The United Arab Emirates (UAE) is especially appealing for industrial applications due to its energy efficiency, scalability, and ability to operate continuously (Bateni et al. 2023).

From an economic perspective, UAE reduces processing time, energy expenses, and the use of solvents, making it more suitable for large scale production compared to traditional extraction methods. Its flexible design allows it to be incorporated into current production lines without requiring significant changes to existing infrastructure. UAE based extraction systems are already being used in the pharmaceutical and cosmetics industries, which indicates a strong possibility for future applications in the food industry as well (De melo et al. 2024).

Beyond the production of extracts, SCG can be used to create various valuable products like biodegradable packaging, natural colorants, dietary fibers, and materials for fermentation. Since SCG contains high amounts of polysaccharides, proteins, and lipids, it is a flexible raw material that can be used across different biorefinery processes. Adding SCG extracts to food products can help decrease environmental waste, support sustainability efforts, and generate economic benefits from a material that is often discarded

In addition, adding SCG value to current industrial systems can create new ways for different industries to work together, like the food, biotech, packaging, and renewable energy sectors. New technologies such as subcritical water extraction, membrane fractionation, and enzymatic bioprocessing help get special high value ingredients like mannooligosaccharides, peptides, and dietary fibers from SCG, which opens up more ways to use these materials in business. Studies that look at the whole life cycle of products also show that using SCG to get active ingredients greatly reduces greenhouse gas emissions and the overall harm to the environment compared to old ways of waste treatment like landfills and burning. As industries aim for carbon neutral and zero waste production, using SCG to create value offers a way to turn organic waste into useful and eco friendly products, supporting global sustainability goals and encouraging circular bioeconomy practices.

Discussion

The findings of this study demonstrate that SCG represent a valuable source of bioactive compounds with potential applications in sustainable food preservation. The higher extraction efficiency of UAE compared with SLE indicates that advanced green extraction technologies can improve the recovery of phenolic compounds while reducing processing time, solvent consumption, and energy requirements. The antioxidant and antimicrobial properties of SCG extracts suggest that these compounds can function as multifunctional natural preservatives by delaying oxidation and inhibiting microbial growth in food systems. These findings support previous studies emphasizing the role of coffee by-products in developing sustainable and clean-label food ingredients.

Implications

The utilization of SCG extracts provides environmental, industrial, and economic implications. Converting coffee waste into valuable antioxidant ingredients can reduce organic waste disposal and support circular economy practices within the food industry. For manufacturers, SCG-derived extracts may serve as an alternative source of plant-based preservatives, particularly for lipid-rich foods that are vulnerable to oxidation. Furthermore, the adoption of green extraction technologies such as UAE may improve the feasibility of scaling up SCG valorization processes for commercial applications.

Research Contribution

This study contributes to the growing field of food waste valorization by integrating extraction technology, antioxidant functionality, safety considerations, and industrial applicability of SCG extracts. Unlike studies focusing only on chemical composition, this review highlights the relationship between extraction efficiency, biological activity, and practical food preservation applications. The findings provide a comprehensive perspective on how spent coffee grounds can be transformed from an environmental burden into a functional food ingredient.

Limitations

Despite the promising potential of SCG extracts, several limitations remain. The chemical composition of SCG varies depending on coffee species, geographic origin, roasting conditions, and brewing methods, which may affect extraction consistency. In addition, further toxicological evaluation is required to confirm the safety of SCG-derived extracts for food applications, particularly regarding contaminants such as acrylamide, heavy metals, and other processing-related compounds. The current study is also limited by its reliance on existing literature and requires further experimental validation using real food systems.

Suggestions

Future research should focus on optimizing extraction parameters, evaluating long-term stability of SCG extracts, and conducting food application trials in different products such as oils, dairy products, beverages, and meat-based foods. Further studies should also investigate large-scale economic feasibility, life-cycle assessment, and regulatory approval requirements to support commercial implementation. The combination of SCG valorization with other biorefinery approaches may provide additional opportunities for developing sustainable food ingredients and reducing waste in the coffee industry.

CONCLUSION

Spent coffee grounds (SCG) are a widely available yet underutilized by product from the coffee industry, offering significant potential for sustainable use. This research shows that SCG contain a variety of beneficial compounds, such as chlorogenic acids, caffeic acid, melanoidins, and caffeine, which together give them strong antioxidant and antimicrobial properties. The study also finds that using ultrasound assisted extraction (UAE) is more effective than traditional solid liquid extraction (SLE) in extracting phenolic compounds and improving antioxidant activity. This is because UAE improves the transfer of materials and reduces the breakdown of heat sensitive compounds, making it a more efficient and green method for industrial applications. However, safety is an important factor to consider. SCG may include harmful substances like acrylamide, furans, and heavy metals, which can come from the roasting process or agricultural practices. To ensure the extracts are safe for food use, purification methods such as activated carbon treatment, membrane filtration, or solvent based separation should be employed. When these quality control steps are properly applied, SCG extracts can serve as natural preservatives that help slow down oxidation, prevent microbial growth, and increase the shelf life of foods. Their capacity to act as both antioxidants and antimicrobials, as well as their sourcing from renewable waste, supports sustainability efforts and meets the growing demand for clean label, plant based ingredients. Overall, SCG derived extracts are promising for use in modern food preservation systems, offering both practical benefits and positive environmental impact.

AUTHOR CONTRIBUTION STATEMENT

Fatimah Azzahra Hasibuan: Analysis. Writing – original draft. Steven Suryoprabowo: Investigation. Conceptualization. Writing – review and editing. Eddy Seong Guan Cheah: Resources. Investigation.

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