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Bio-recycling of spent coffee grounds: Recent advances and potential applications

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Coffee (*Coffea*) is one of the largest-selling beverages in the world, creating a large amount of waste. The spent coffee grounds (SCG) contain numerous organic compounds (fatty acids, amino acids, polysaccharides and polyphenols) and minerals with extremely high economic value for recycling and thus have the potential to be used in the pharmaceutical and cosmetic industries. Several studies have indicated various products that can be valorised from SCG, including biofuel, biopolymers, food components (such as bioactives, i.e. antioxidants), food additives, animal feed and construction materials. This review briefly summarises the composition of SCG, mainly focusing on bio-reusing products and standard recycling methods available today, with trends for future applications and potential directions.

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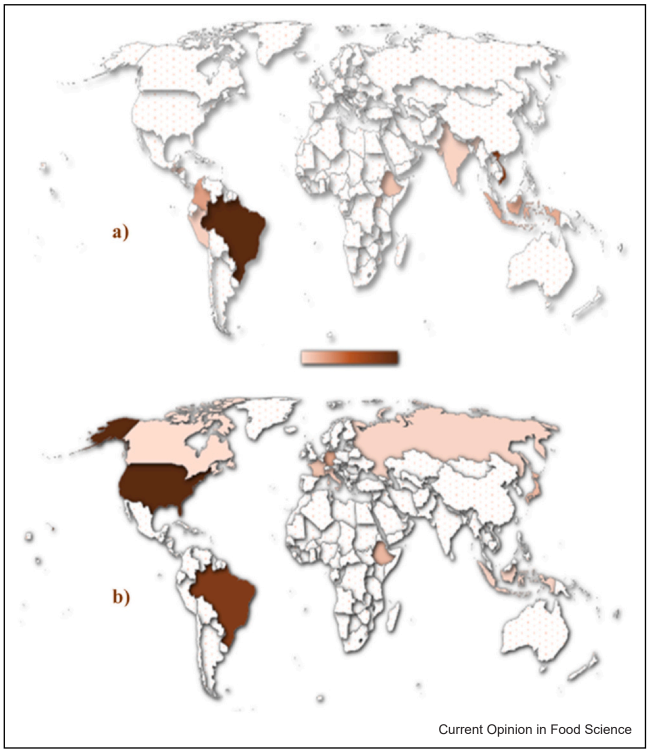
Introduction

Coffee is one of the most consumed beverages in the world, produced in more than 50 countries, with Brazil as the leading coffee producer [1,2]. According to the International Coffee Organisation, world coffee bean production was almost 10 million tons in 2021/2022, with a similar amount consumed annually worldwide [3–5]. Globally, coffee consumption is expected to reach 12 million tons by 2030 [6]. The daily coffee consumption worldwide is over 3 billion cups [2]. About 33% of global coffee consumption takes place in Europe, following Asia and Oceania with a 22% market share, then North America (19%), South America (16%), Africa (7%) and Central America and Mexico (3%) [4]. Worldwide, the production (a) and consumption (b) rate of spent coffee grounds (SCG) are shown in Figure 1.

Depending on worldwide coffee production, at least 6–8 million tons of waste is generated every year. These wastes comprise by-products such as SCG, silverskin, cascara and mucilage. SCG are solid residues obtained after the preparation of coffee as a beverage [7]. Approximately 650 kg of SCG is obtained from 1 ton of coffee beans [8]. SCG are a large amount of solid waste released by coffee consumption causing storage and disposal problems [6].

SCG possess significant potential as a versatile and sustainable resource to be used in various fields such as food additives (preservative, fibre), animal feed, nutraceuticals (i.e. antioxidant, fibre), compost, biodiesel, bioplastic and fertiliser contributing to the circular economy and sustainability efforts [7]. SCG has a positive effect on human health, such as anti-diabetic and antioxidant activities, prevention of cardiovascular diseases and reduction of brain damage, according to its rich content of organic compounds (such as oil, cellulose, hemicellulose and lignin) [9]. Additionally, SCG contains bioactive compounds such as catechins, tannins, alkaloids, chlorogenic acid, quinic acid and caffeic acid, and compounds such as caffeoylquinic, ellagic, trans-ferulic, feruloylquinic, gallic, *p*-hydroxybenzoic and *p*-coumaric [10–13]. However, further research and technological advancements are required to fully unlock the economic and environmental benefits of their utilisation in agriculture, bioenergy, cosmetics and sustainable materials. The main issues to be solved to address wider adoption of these applications and provide more benefits include the problems regarding large-scale collection and processing methods, variability in chemical composition and cost-effective utilisation. Future research

Figure 1



World coffee production **(a)** and consumption **(b)** rate. The highest ratio is shown in the darkest colour [4].

should focus on optimising extraction methods and conducting life cycle assessments to understand the environmental impacts of utilising SCG entirely. This review aims to highlight the importance of SCG bio-recycling and the diversity of bio-recycling products and also guides future research.

Macro- and micronutrient compositions of spent coffee grounds

The elemental analysis results of SCG present 45–60% of carbon (C), 32–47% of oxygen (O), 6.00–7.57% of hydrogen (H) and 1.18–4.00% of nitrogen (N) [14]. SCG are an attractive raw material rich in macronutrient [15,16]. Recent studies have shown that the most abundant components in SCG are carbohydrates, that is, polysaccharides such as hemicellulose and cellulose (45%), proteins (13.5–19.5%) and lignin and oil (10–15% each); in minor amounts, minerals (< 1%), caffeine (1–2%) and phenolic compounds (1.0–1.5%) [10,17,18]. SCG has been used as a carbon source for producing bioethanol and biochemicals by microbial fermentation to produce glucose, galactose, mannose and arabinose [15]. Also, proteins with various ratios of essential branched-chain/aromatic amino acids were found in SCG. In a study, the extraction and isolation of proteins in SCG were investigated, and their amino acid profile and protein nutritional quality were determined [10]. The highest detected level was observed for leucine (1.04%), and the lowest was for tryptophan (0.08%) in essential amino acids, whereas for non-essential amino acids, the highest was glutamine (1.82%) and the lowest was cysteine (0.02%) in SCG [7]. On the other hand, SCG are accepted as a potential raw material due to their high calorific value, cellulosic content and lipids. Using GC–MS, the fatty acid composition of the SCG oil was determined as linoleic acid and palmitic acid with values of 36.92% and 34.05%, respectively [9]. The micronutrients of SCG include folic acid and vitamins E and B. Hechmi et al. (2023) have reported the presence of calcium (Ca) and magnesium (Mg) in SCG at 5%, and smaller amounts (less than 5%) of iron (Fe), sodium (Na), nickel (Ni), zinc (Zn), copper (Cu), potassium (K) and cobalt (Co) [16].

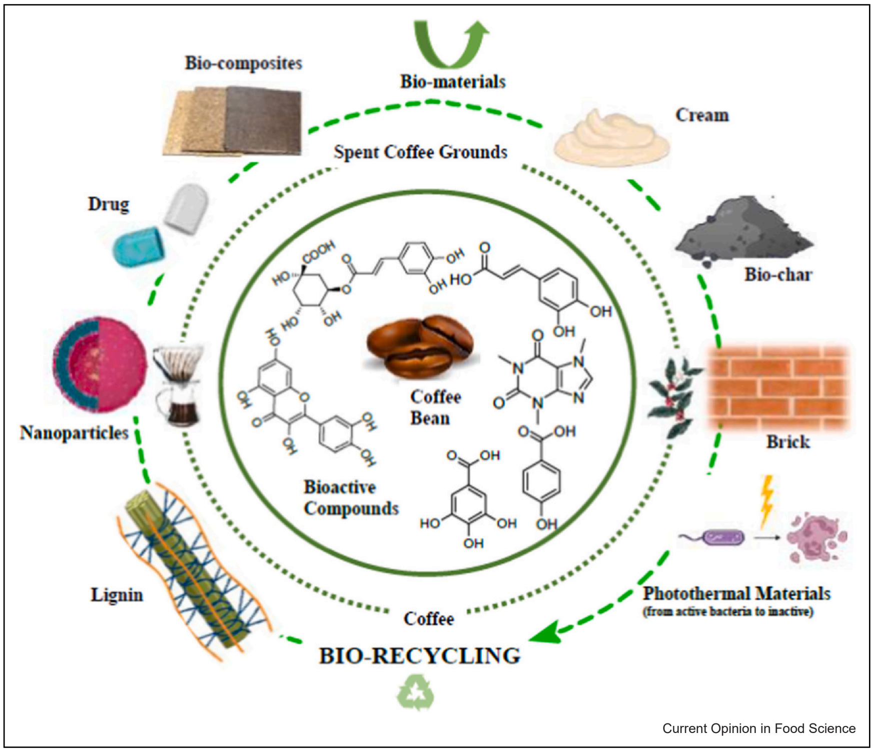
The composition of SCG help to increase the renewable energy sources, with SCG-derived biopolymers, carbohydrates, lipids and proteins considered potential candidates for bio-recycling.

Despite the nutritional value of SCG, it is unlikely that it may become a significant source of nutrients in our diet. But they still have the potential to be valorised and applied in different forms, which could contribute to human health, environment and society. However, it should be noted that the difficulties in collecting and handling the samples, considering the sustainability and safety issues together with the economic impact of the whole process, would be the main challenges to be resolved. In addition, the nutritional content of SCG can vary depending on factors such as the type of coffee beans used, the brewing method and whether any additives or flavourings were included in coffee, which could result in raw materials with variable characteristics and thus lead to difficulties in processing and valorisation.

Bioactive compounds in spent coffee grounds

SCG are rich in various organic compounds, such as fat, cellulose, hemicellulose and lignin, that can be used for different purposes, that is, food additive, animal feed, nutraceutical, compost, biodiesel, bioplastic and so on. According to the Organization for Economic Co-operation and Development test guidelines, the presence of polyphenols in food has been proposed as required for a healthy human body [9]. These compounds have various biological roles relevant to human health, such as antioxidant activity, anti-diabetic activity, cardiovascular protection and reduction of brain damage [11,12]. Coffee beans and SCG are rich sources of bioactive compounds such as catechins, tannins, chlorogenic, quinic, caffeic, caffeoylquinic, ellagic, trans-ferulic, feruloylquinic, gallic, *p*-hydroxybenzoic, *p*-coumaric, *p*-coumaroylquinic, protocatechuic and ferulic acids, rutin, quercetin and alkaloids

Figure 2



Selected bioactive compounds and bio-recycling of SCG.

(i.e. caffeine, trigonelline) presenting potent biological properties that can be recovered by reusing SCG [10–13]. The extraction of phenolic compounds from waste coffee grounds could be done using a hydrothermal delignification method followed by ultrasonic-assisted extraction [12]. In Table S1 different extraction methods from 2017 to 2023 are listed. Extracted SCG polyphenols and antioxidants will have wide applications in food and medicine in the future [9]. For this purpose, phenolic and antioxidant compounds from SCG are encapsulated by spray-drying (the most commonly used and efficient method), coacervation, fluidised bed coating and freeze-drying.

Current advances in spent coffee grounds bio-recycling

SCGs are available worldwide as a by-product of coffee preparation, therefore, they are considered a new generation of non-food raw materials sustainable for bio-based applications [7,19,20]. Recent studies on alternative uses of SCG have evaluated the application areas as wide and range from cosmetics to environmental protection materials. Some suggestions for alternative uses of SCG or their extracts are already provided, such as cosmetics, surfactants, foaming agents, biopolymers and other materials with electromagnetic properties [21].

SCGs are proposed as an energy storage material to carbonise and convert them into battery electrodes. In a study by Hsieh and others (2021), SCGs are used to produce high-performance capacitors by initially making mesoporous-activated carbon after carbonisation and carbon dioxide activation [22]. Another advantage of SCGs in bio-recycling is their use as a flame retardant and heat insulation material. In another study, a highly effective flame retardant was developed by mixing SCG and epoxy resin, which presents evidence of more attention paid to environmental protection and the utilisation of biomaterials [22]. SCGs are proposed as environmental materials, with their use as photothermal agents and catalysts [23,24]. Another area of application is agricultural iron biofortification using activated hydrochars from activated SCG [25]. Bio-recycling of SCG's schematic representation is given in Figure 2.

The real values of SCG are environmental sustainability, helping in bio-economic growth, and bio-utilisation resources, rather than the nutritional additives. In terms of environmental remediation, they eliminate some heavy metals from contaminated soil. The current studies about SCG highlighted the importance of circular economy initiatives, especially considering that worldwide it has focused on the conservation and reuse of discarded products. Mainly, they can be used for generating energy, which helps to reduce the carbon footprint in the world. Moreover, SCGs are part of sustainable textiles and materials, biodegradable packaging materials (e.g. coffee mugs). These are future insights into this valuable product. Except for pharmaceuticals and food components, cosmetic companies are considering SCG as cleaning and washing ingredients for some skincare items.

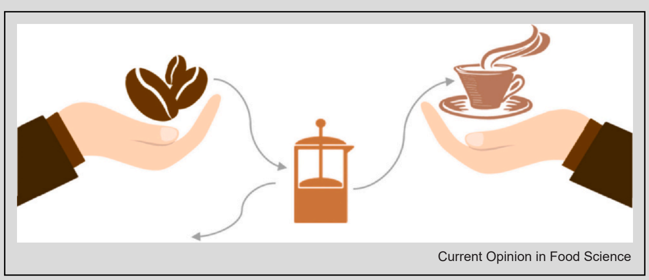
Bioactive compounds and fatty acids obtained from SCG are considered for various applications in pharmaceutical industry sectors [9]. The high-protein content of SCG may provide a source of potential drug-related components improving the prevention treatment of skin cancer types, burns and liver failure, while the fatty acids in SCG oil have excellent emollient and moisturising properties, helpful in improving skin health conditions [9,10]. Moreover, due to their high calorific value, cellulose and lipid contents, they are potential raw materials for producing solid fuel or biodiesel. Lipids from SCG could be extracted and recovered by adopting various techniques (conventional, soxhlet and supercritical extraction) before conversion to biodiesel via *trans*-esterification. SCG oil is rich in long-chain fatty acids, so the extracted oil can be used as biodiesel feedstock [9,19,20,26].

The SCG can generally be processed into pellets that provide a high low heat value (LHV = 18 000 kJ/kg total solid), and these pellets are also suitable for biogas production [27]. In addition, solid fuel briquettes can be obtained from SCG with a high-pressure hydraulic briquette press [28].

It has been reported that the extracts obtained from SCG are a rich source of antioxidants. Therefore, SCG can be used instead of synthetic antioxidants in many food-related applications. In addition, several studies show that SCG can produce fermented alcoholic beverages [21]. Another study investigated the use of SCG in bakery products due to its rich fibre source. For this purpose, SCG was added directly to the formulation in biscuit production without affecting the final nutritional or sensory quality of the product and was as a natural source of fibre and essential amino acids [29]. SCGs were added to cake formulation to achieve higher weight and volume [21]. Further investigations are needed to explore the full potential of SCG in various applications, from food additives, bakery, cosmetics and pharmaceutics to bioenergy sources. Text Box 1 and Figure 3 present several cutting-edge technologies and applications of SCG.

SCG can be converted into different food ingredients by solvent extraction, enzyme hydrolysis, fermentation and innovative technologies such as encapsulation. Fermented food products have become very popular, especially in recent years, due to their health benefits. Food ingredients can be produced by fermentation and

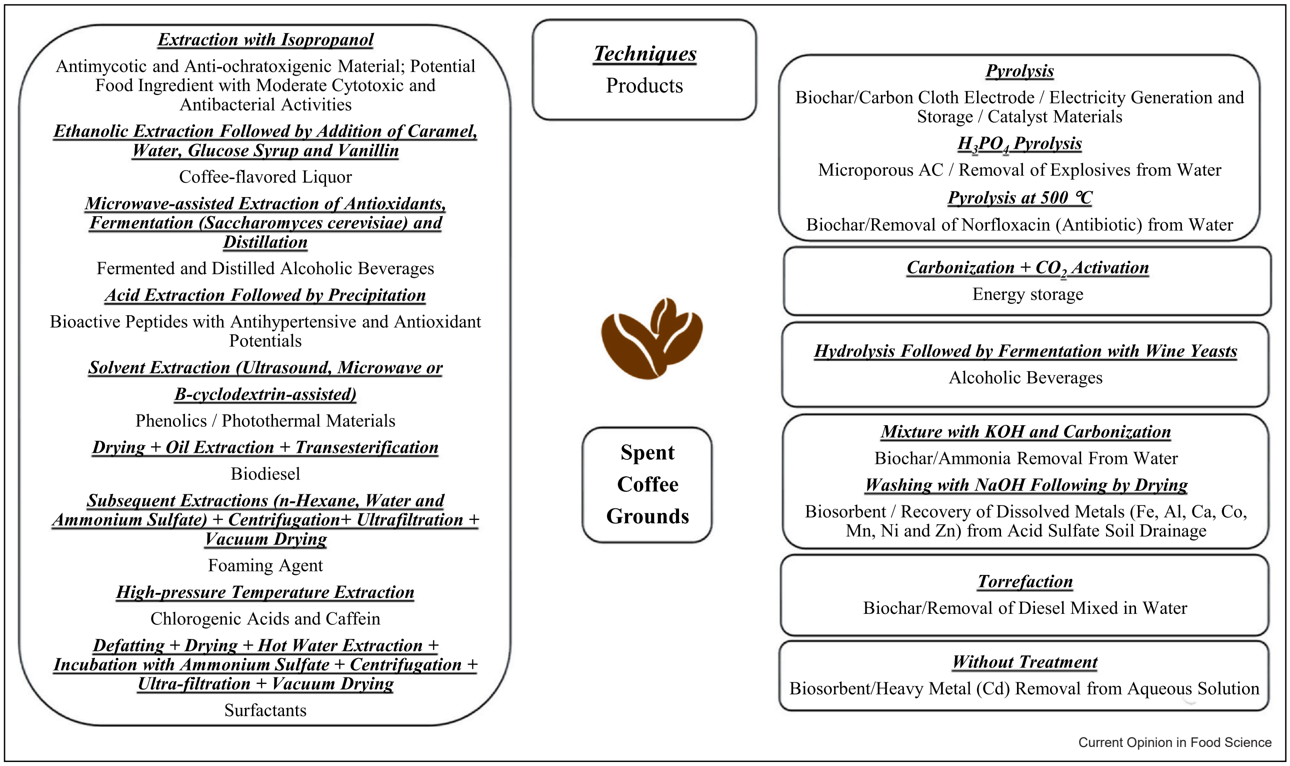
Box 1 Potential utilisation of SCG.



Text Box-1 Potential utilisation of SCG.

- A rich source of natural colorant (potential of producing astaxanthin) [30,31]
- Animal feed, brick production and bioactive compounds [11]
- Bio-battery and biodiesel applications [32]
- Bio-char [33]
- Biocomposite materials [34]
- Biopolymer precursors, composite production [35]
- Biopolymers [18]
- Environmental materials (photothermal and catalyst materials) [23,24]
- Food ingredients, food products [21]
- Glutathione (obtained by adding *Millerozyma farinosa*) [30]
- Medicine, pharmaceutical and skin health (fatty acids) [15]
- Polylactic acid composite for 3D-printing [36]
- Using electrochemical-activated adsorbent [37]

Figure 3



Products obtained from SCG using different techniques.
Data sourced from Refs. [22–24,38–43].

microbial-assisted enzyme hydrolysis of SCG, which is very difficult to digest. However, limited research has been conducted on the microbial fermentation of SCG, and some studies have proven that SCG can be used as a source of prebiotic fibre to support intestinal health [44,45]. More research on this subject is recommended to confirm the safety and health benefits of such food innovation. Besides this, considerably more work is required to determine the anti-diabetic and anti-cancer effects of SCGs in terms of cytotoxicity, health and food science-related studies, including their effects on glycaemic index and blood glucose. Additionally, randomised and epidemiologically controlled trials could provide more reliable evidence of benefits for medicinal treatments.

SCG have significant potential as a versatile and sustainable resource such as sustainable agriculture, bioenergy production, food ingredient and waste reduction. Further investigations are required to fully open up the economic and environmental benefits of their utilisation in agriculture, bioenergy, cosmetics and sustainable materials, with more wet-lab and cell culture studies to be included.

Conclusions, knowledge gap and future perspective

Nowadays, with the rise of the bio-residue recycling economy, SCGs are recognised as a potential source of bioactive molecules of high economic value and have gradually got greater worldwide attention. This perspective review presented the main components of SCG and their potential utilisation with various extraction methods and technological strategies incorporated. Sustainable development of the coffee industry can contribute to various industry sectors, from food to energy, applications, including food components, animal feeds, cosmetics, compost and biopesticides, fertilisers, bioenergy, biofuels, catalysts and composites. As the methods used for SCG extraction can be environmentally friendly, renewable and inexpensive, these recycling activities can help reduce environmental pollution, and greenhouse gas emissions increase the removal of pollutants in aqueous solutions, which as a consequence can diminish some chronic disease development. One of the greatest achievements done in SCG utilisation is the extraction of polyphenols for repurposing them as food, antioxidant and antibacterial substances. There are still limitations of the current technology and in the re-utilisation of SCG, for instance, the processing and recycling of SCG have not been industrialised. The currently available systems cannot recycle the coffee grounds produced in daily coffee shops. Therefore, coffee producers are setting up a recycling line of SCG to work on it individually. The industrial upgrading to large coffee enterprises and realise the onsite reuse of SCG is the most important challenge for the moment. From the pharmaceutical industry point, 2,3-butanediol co-products obtained from SCG are potential nature-derived bioactive components with the ability to reduce therapeutic doses used in drug treatments, instead of the synthetic counterparts used before. In particular, it could be effective in well-known metabolic disorders, including diabetes and cardiovascular diseases. The current research related to SCG is focused on developing several independent single-product lines, which could be improved by applying multipurpose technology to extract as many as possible bioactive compounds from crude SCG. A few studies have proposed a possible scenario of the bio-refinery concept for coffee by-products since SCGs have a high recycling value as a bio-residue with a wide variety of sustainable products and high economic benefits. In summary, a more holistic approach should be followed to better valorise SCG and find its potential and value-added applications in multi-sector industries. Still, more studies are required to investigate the efficient extraction and processing of valuable components in SCG, assessing the safety issues and consumer acceptance, protecting and improving the nutritional value and bioactive components of SCG and considering life cycle assessment and best economic aspects.

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CRediT authorship contribution statement

Büşra Yusufoğlu: Conceptualization, Data collection, Writing – review & editing, Visualization. **Gizem Kezer**: Conceptualization, Data collection, Writing – review & editing, Visualization. **Yifan Wang**: Conceptualization, Data collection, Writing. **Zyta M. Ziora**: Conceptualization, Data collection, Supervision, Writing – review & editing, Project administration. **Tuba Esatbeyoglu**: Conceptualization, Data collection, Supervision, Writing – review & editing, Project administration.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cofs.2023.101111.

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- • of special interest
- •• of outstanding interest.

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