

Review

# Why Should We Be Concerned with the Use of Spent Coffee Grounds as an Organic Amendment of Soils? A Narrative Review

Sergio Pérez-Burillo <sup>1</sup>, Ana Cervera-Mata <sup>2</sup>, Alejandro Fernández-Arteaga <sup>3</sup>, Silvia Pastoriza <sup>1</sup>, José Ángel Rufián-Henares <sup>1,4,\*</sup> and Gabriel Delgado <sup>2</sup>

- <sup>1</sup> Departamento de Nutrición y Bromatología, Instituto de Nutrición y Ciencias de los Alimentos José Mataix, Centro de Investigación Biomédica, Universidad de Granada, 18071 Granada, Spain
- <sup>2</sup> Departamento de Edafología y Química Agrícola, Facultad de Farmacia, Campus de Cartuja, Universidad de Granada, 18071 Granada, Spain
- <sup>3</sup> Departamento de Ingeniería Química, Facultad de Ciencias, Universidad de Granada, 18071 Granada, Spain
- <sup>4</sup> Instituto de Investigación Biosanitaria ibs.Granada, Universidad de Granada, 18071 Granada, Spain
- \* Correspondence: jarufian@ugr.es; Tel.: +34-958-242841

**Abstract:** Spent coffee grounds (SCG) are produced in massive amounts throughout the world as a bio-residue from coffee brewing. However, SCG are rich in carbohydrates, proteins, lipids, bioactive compounds and melanoidins, which are macromolecules with chelating properties. Additionally, SCG have showed potential applications in several fields such as biotechnology (bioethanol, volatile aromatic compounds, carotenoids, fungi and enzymes), energy production (combustion, pyrolysis, torrefaction, gasification, hydrothermal carbonization) and environmental sciences (composting). This review will focus on the last of these applications. SCG improve soil quality by increasing their chemical, physicochemical, physical properties and biological fertility. However, SCG inhibit plant growth at very low concentrations (1%) due to i. the stimulation of microbial growth and consequent competition for soil nitrogen between soil microorganisms and plant roots; ii. the presence of phytotoxic compounds in SCG, such as polyphenols. The SCG transformations that have proven to eliminate these compounds are vermicomposting and pyrolysis at 400 °C. However, it has been pointed out by some studies that these compounds are responsible for the chelating properties of SCG, which makes their elimination not recommended. The use of SCG as biochelates has also been studied, generating a residue–micronutrient mixture for the biofortification of edible plants.

**Keywords:** residue; coffee; re-utilization; organic amendment; biofortification; soil quality



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## 1. Introduction

Coffee is one of the most popular beverages in the world. It is the second most valuable product behind petroleum; for some developing countries, coffee exports account for more than 80% of their income [1]. Today, 125 million people depend on coffee production for their livelihood, and coffee is consumed in all parts of the world [2].

Coffee production includes a first postharvest processing that helps to separate the seed from the remaining parts of the fruit to ensure the final product quality [3]. Coffee husk is the main residue obtained during drying. For every ton of coffee harvested, 0.18 tons of coffee husk are produced [4]. These by-products pose an environmental threat to coffee-producing countries, as they pollute the soil and surrounding water due to their high caffeine and tannin content [3]. However, due to their composition, numerous applications have also been suggested. Both coffee husk and pulp have been used as organic soil amendments by the Kasongo group [5]. These authors added pulp and coffee husk to an Arenosol from Congo to improve its physicochemical characteristics. The addition of these by-products improved the soil's cation exchange capacity and increased its organic carbon

and nitrogen and water retention capacity. In a second work, Kasongo et al. [6] studied the effect of pulp and husk on the growth and mineral nutrition of ryegrass. These by-products stimulated the uptake of Ca, Mg, K, N and P and increased crop yield after three consecutive crop cycles. They have also been used for composting or vermicomposting [7].

The second processing step is coffee roasting, which is very important not only for the formation of specific compounds [4,8,9] responsible for the organoleptic properties of coffee beverage [10] but also because some of these compounds have a deep effect on the use of spent coffee grounds as a soil amendment [11,12]. Finally, coffee can be brewed following different techniques such as decoction, infusion or pressure [13]. Spent coffee grounds (SCG) are the main by-product obtained during coffee brewing. They are mainly produced in coffee shops, restaurants, households and during the industrial production of instant coffee. Instant coffee-derived residues usually present a poorer concentration of chemicals due to a more extensive extraction process [3]. Worldwide, approximately 15 million tons of SCG are produced each year [14].

The SCG composition is dependent on a number of factors: how coffee was brewed, crop conditions or type of coffee. Still, despite all of this, most SCG present a similar composition [15]. SCG include around 15% of lipids [10] such as linoleic, palmitic, stearic and oleic acids [16]. Carbohydrates are the most important constituents of SCG, up to 62% of dry weight [10]; in this sense, cellulose and hemicellulose are the main polysaccharides, up to 50% of SCG dry mass [15]. SCG also have a high protein content (13.6%) [10]. Associated with carbohydrates and proteins, different phenolic compounds have been reported in significant quantities in SCG [11]. According to Kovalcik et al. [17], the concentration of phenolic compounds in SCG ranges between 4.6 and 9.9 mg/g of SCG or between 16 and 173.3 equivalents of gallic acid/g of SCG. These compounds are important since they play a role in the phyto-toxicity of SCG, as will be discussed in this review. CG are also rich in melanoidins, high-molecular-weight compounds (estimated between 3 and 28 kDa) [18] of brown color generated during the last steps of the Maillard reaction [19,20]. Although melanoidins are beneficial for human health due to their antioxidant, antimicrobial, prebiotic, antihypertensive and anti-inflammatory properties [21,22], they have also showed a chelating capacity [23–26] that can be used to remove the toxic contaminant acrylamide from coffee [24] or to carry mineral elements [27]. Finally, SCG are rich in different mineral elements that can be incorporated into the soil as an organic amendment [5]. In general, SCG include K as the major macroelement, with 11,700 mg/kg, followed by Mg (1900 mg/kg), P (1800 mg/kg), S (1600 mg/kg) and Ca (1200 mg/kg). Regarding the microelements, SCGs are rich in Fe (52 mg/kg), Mn (29 mg/kg), Cu (19 mg/kg), Co (15 mg/kg) and Zn (8 mg/kg).

## 2. Potential Applications of Spent Coffee Grounds

SCG can be recycled in different ways to produce several types of biofuels, such as biohydrogen, biobutanol, biodiesel, fuel pellets, bio-oil, bioethanol, biogas and hydrocarbon fuels. They can also be reused to generate added-value products such as bioactive compounds and compounds for the food industry and the pharmaceutical, agricultural or cosmetic industry, among others [28]. Here, we will focus on the re-use of SCG as an organic amendment, directly or modified through composting, co-composting and vermicomposting. In this regard, Table 1 shows how the addition of SCG and other organic amendments improves the physical, chemical and physicochemical properties of soil.

**Table 1.** Applications of SCG and other agro-wastes as organic an amendment.

Property	Effect	Organic Amendment	Reference
SOC	+	Biowaste compost	[11]
C stabilization	+		

Table 1. Cont.

Property	Effect	Organic Amendment	Reference
N-NO <sub>3</sub> release	-		
Microbial biomass C	+	Sorghum stubble, sugarcane bagasse, sugarcane mill mud	[29]
SOC	+		
Soil aggregation	+		
BD	+	Biochar	[30]
Microbial biomass C	+		
Soil available N	+	Compost and vermicompost	[31]
BD	+	Agro-wastes	[32]
Porosity	+	Fermented plant juice	
CEC	+	Fermented plant juice with biochar	
C/N	+		
Exchangeable K and Ca	+		
Soil respiration	+		
Soil microorganisms count	+		
Fresh and dry weight	+	Bagasse, bio-slurry, kitchen waste compost	[33]
pH	+	Biochar + compost + NPK	[34]
TN	+		
P available	+		
CEC	+		
K and Ca	+		
Nutrient availability	+	Biochar from <i>Euterpe oleracea</i> seeds	[35]
Plant growth	-		
BD	+	Macadamia husk compost	[36]
W33	+		
TOC	-	Crop residues	[37]
Net nitrogen mineralization	-		
Soil structure	+	Biochar	[38]
Nutrient use efficiency	+		
Aeration	+		
Porosity	+		
W33	+		
Aggregate stability	+	Compost	[39]
BD	+		
W33	+		
Nutrients level	+		
Plant available water content	+	Organic waste	[40]
Organic matter quality	+		
Biologically available SOM	+	Organic farming	[41]
Soil microbe	+		

Composting is an alternative in the management of SCG to tackle their toxic nature. Liu and Price [42] evaluated two different systems: composting in containers and composting in an aerated static pile (for a period between 47 and 98 days). They concluded that SCG can be successfully composted using either of both systems to obtain an optimal carbon-to-nitrogen ratio (C/N) of about 25:1. Additionally, Santos et al. [43] studied the effect on gaseous emissions and quality of the final product of adding different amounts of SCG together with *Acacia dealbata* L. roots and wheat straw in the composting process. These authors reported that SCG can be co-composted regardless of the dose, though a 40% SCG addition showed the most favorable results, exhibiting low greenhouse gas

emissions and a better quality of the final product. Ronga et al. [44] evaluated the SCG compost as an alternative to commercial peat and other fertilizers commonly used in potted plants. According to these authors, the physicochemical characteristics of the SCG compost make it suitable to be used as a substrate for this type of application. On the other hand, Kopec et al. [45] showed that an SCG-enriched compost was less helpful for the germination capacity of seeds.

In addition, recent studies have demonstrated the viability of SCG as a substrate for vermicomposting. This is defined as a bio-oxidative process during which worms interact intensely with microorganisms and other fauna within the decomposer community, accelerating the stabilization of organic matter and greatly modifying its physical and biochemical properties [46]. Recently, González-Moreno et al. [47] studied SCG as a vermicompost substrate together with horse manure, using *Eisenia fetida*. These authors concluded that SCG were not toxic and that a 25% SCG dose was the best option to obtain a high-quality vermicompost. Sánchez-Hernández and Domínguez [48] studied the worm population (*Eisenia fetida*) as well as the chemical and biochemical properties of the vermicompost obtained from SCG. These authors showed that the addition of SCG increased worm density and biomass in a steady fashion between 14 and 28 days, resulting in approximately 14,000 individuals/m<sup>2</sup>. According to these authors, despite their high content in caffeine or bioactive compounds, SCG can be a viable alternative substrate for vermicompost. Because of the rapid mineralization of C during vermicomposting, there was an increase in micro- and macroelements. Conversely, Liu and Price [42] reported a low survival of worms when using SCG, though in this case, the worms studied were *Eisenia fetida*. These authors suggested the possibility of mixing SCG with other type of products to solve this issue.

### 3. Spent Coffee Grounds as a Soil Organic Amendment

#### 3.1. Soil Fertility

SCG have traditionally been used in agriculture due to their organic nature. However, it has not been until a few years ago that researchers began to study the effect that these residues have on the soil. Currently, one can find reports on different aspects related to SCG, soil and crops. We will discuss here some of them, including how SCG or derived/composted products can affect the soil physical, chemical and biological properties, their influence on the environment or their functionalization and use as biochelates for agronomic biofortification.

##### 3.1.1. Chemical Properties

The influence of SCG on soil's chemical and physicochemical fertility is summarized in Table 1. Yamane et al. [49] studied SCG addition to a sandy clay loam soil, finding an increase in C and N concentrations but a reduced C/N ratio. We studied the effect of SCG dosage (2.5 and 10%) on the chemical and physicochemical properties of soils from the Mediterranean area (Cambic Calcisol and Chromic Calcic Luvisol). We concluded that SCG addition increased the soils' chemical fertility, enriching them in the essential macronutrients N, P and K. In a different study, SCG managed to increase soil's organic matter, especially in those fractions that had a marked labile character [50]. SCG addition was showed to generate a high CO<sub>2</sub> emission (2103 µg/g), with a low level of residual C (86.8%), while also increasing soil extractable organic and microbial biomass C and N and causing N immobilization [51]. This study also showed that SCG lowered the soil pH, which is the opposite of what Hardgrove and Livesley [52] found in a field and greenhouse trial in three soils (sand, sandy clay loam and loam). These authors blamed it on low percolation, since it would produce an increase in exchangeable cations, which could lead to a decrease in H<sup>+</sup> ions and, thus, a higher pH. Kitou and Yoshida [53], however, found that SCG addition caused a decrease in pot soil pH.

The effect of SCG on cultivation substrates (peat) has also been studied. Cruz et al. [54] studied the effect of different SCG dosages (5, 10, 15, 20, 30%) on pH, electrical conductivity and OC. According to these authors, SCG decreased the pH and electrical conductivity

while increasing OC in the soil. Regarding the essential elements in the soil, SCG addition increased the K, Mg, Zn and Cu content [55]. The authors attributed this to the ability of SCG to trap and chelate such compounds within their structure [56]. In fact, in a recent study, it was shown that both fresh and SCG biochelates (SCG + Fe or Zn) significantly increased, up to 78%, the available reserve of Fe and Zn in the soil, in comparison to commercial chelates [57].

### 3.1.2. Physical Properties

SCG effects on soil physical fertility have been less studied. Table 1 summarizes the results of these studies. Our research group carried out a study in Vega soil and found that SCG improved all physical properties except plant-available water content, which decreased [58]. Therefore, SCG decreased the bulk density, increased the water retention at  $-33$  and  $-1500$  kPa and increased the structural stability of the aggregates. In addition, an increase in porosity was observed via SEM images and stereomicroscope images. Turek et al. [59] reported that the addition of 20% SCG increased humidity at field capacity by 23%, thus increasing plant-available water content in a sandy loam soil. On the negative side, SCG decreased soil drainage porosity by 93%. This increase in water holding capacity by SCG was also found by Hardgrove and Livesley [52]. Cervera-Mata et al. [58] showed that SCG increased the hydrophobicity of a soil from the Mediterranean area (Granada, Spain), probably due to the SCG hydrophobic nature.

### 3.1.3. Biological Properties

Only a single work was found regarding SCG and soil biological properties, in which the addition of SCG caused a disruption of soil microbial populations [60]. An increase in the abundance of phenolic acid-degrading bacteria and plant growth-promoting bacteria was observed following the application of SCG. SCG increased the complexity of microbial interaction networks, as well as bacterial diversity. The addition of 2.5% SCG increased the microbial diversity in two different soils from the Mediterranean area. The genus *Rubrobacter* was the most abundant observed in both soils. At the phylum level, it was found that *Proteobacteria* and *Actinobacteria* were the most abundant.

## 3.2. Effects of Spent Coffee Grounds on the Growth and Mineral Nutrition of Plants

Many studies have reported the effect of SCG on the growth, mineral content and bioactive compounds of several type of plants including edible plants (both for humans and for animals) such as beans, soybeans, broad beans, alfalfa, wheat, corn, clover, sorghum, sunflower, oats, rye, barley, buckwheat, lettuce, basil, ryegrass, tomato and *Brassica* [12,44,49,51–55,61–68], although inedible plants such as pine have also been studied [69]. In addition, SCG have been studied when fresh, that is, without any type of treatment [12,44,49,54,55,61,64–66], composted [44,62,65], combined with other types of waste [67,70], transformed into biochar or hydrochar [68,71–73] or supplemented with nitrogen fertilizers [51].

### 3.2.1. Effects on Plant Growth

The first reference on the effect of SCG on plant growth is in Kitou and Yoshida [53]. In a trial with pots, they studied the effect of this residue in a concentration of 1 and 2% on the growth of 12 edible plants. These authors found growth inhibition for most plants, attributing this effect to N immobilization, the multiplication of pathogenic fungi or the release of phytotoxins derived from fresh organic matter. Subsequently, many authors found the same detrimental effect of SCG on plant growth [12,49,52,55,61]. Hardgrove and Livesley [52] tested broccoli, leek, radish, sunflower and viola, Cervera-Mata et al. [51] and Cruz and Cordovil [66] tested lettuces, and Yamane et al. [49] tested alfalfa, guinea grass, crotalaria, sorghum, sunflower, oat, barley and rye. Yamane et al. [49] tried to corroborate the negative effect of SCG found in pots in a field trial. SCG displayed a negative effect on different plants, which was attributed to the presence of caffeine, tannins and polyphenols [74]. These authors suggested that SCG were better used for legume species



to counteract the possible immobilization of N due to the addition of an untransformed residue. Cruz and Cordovil [66] also found growth inhibition in carrot, spinach and lettuce. This group studied the bioavailability of N and P when SCG was added, concluding that SCG immobilized these elements and could be the cause of the lack of growth exhibited by the crops. In this same line of research, Hardgrove and Livesley [52] and Cervera-Mata et al. [51] added fresh isolated SCG and fresh SCG with a nitrogen fertilizer to confirm the hypothesis of N immobilization. These authors reported limited growth in both cases, with and without the addition of the nitrogen fertilizer. In fact, the combined addition of high amounts of both SCG and N limited plant growth to a greater extent. Therefore, both groups concluded that plant growth inhibition must have been due to either SCG phytotoxic compounds or to an insufficient N dosage to overcome microbial immobilization.

SCG also limited seed germination for the generation of seedlings [63], which was attributed to unsuitable substrate conditions (lack of porosity when SCG were added). On the other hand, SCG reduced the stomatal conductance of plants, which is related to a strategy to adapt to stressful conditions. Conversely, Cruz's group reported an increase in lettuce biomass using fresh SCG at concentrations of 2.5 and 10%, finding an inhibition with higher percentages [64]. In a later study [54], SCG were left fallow for 4 months before planting lettuces. In this case, as in the previous study, SCG increased lettuce biomass at a concentration of 10%, decreasing plant growth at amounts of 20 and 30%. In the next section, we will discuss how we can avoid SCG toxic effects by transforming them into other bioproducts such as vermicompost or biochar [62].

### 3.2.2. Effects on Mineral Content and Other Compounds

Different studies have recently been carried out on the reuse of SCG as an organic amendment to improve the mineral nutrition of edible plants (whether fresh, previously composted or directly composting on the ground) [12,54,55,57,61–63]. The addition of fresh SCG to cultivation substrates decreased the Mg, P, Ca, Na, Fe, Mn, Zn and Cu content in lettuce. This effect was attributed to mineral retention within the SCG matrix due to the presence of potential chelators or to the presence of caffeine [55]. Cervera-Mata et al. [61] found the opposite result: SCG increased the plant content of elements with nutritional importance, such as V, Fe, Co, Mn and Zn. They related it to the polyphenol, melanoidin or carbohydrate presence in SCG, which are molecules that have a chelating character and can mobilize these elements in the soil [62]. Other researchers also found an increase in some elements (Fe, Zn and Mn) in brown rice, after the application of SCG enriched with Fe and Zn [56]. Chrysargyris et al. [63] used fresh SCG as a cultivation substrate for seeds of the *Brassica* genus and observed that the levels of N, P and K increased, while those of Mg and Fe decreased. Caliskan et al. [69], who studied SCG and pine growth, reported that the addition of SCG increased the levels of N, K, Mg and P in a dose-dependent manner, whereas Ca and the C/N ratio decreased. Kasongo et al. [6] also investigated how the addition of different coffee residues (coffee husk and pulp) affected plant mineral nutrition. They found that these residues were able to favor Ca, Mg, K, N and P absorption, while decreasing the Cu, Zn, Mn and Fe concentration. However, most of the authors cited above did not use regular agricultural soils, but instead added SCG to very sandy, contaminated soils or to growing substrates, such as peat. This is an aspect that should be emphasized, since plants' nutritional characteristics depend on the soil's or growing medium's chemical, physical and physicochemical properties [75].

SCG have been used not only to improve the mineral nutrition of crops but also to improve (in the case of lettuce) their content of carotenoids [64] and active compounds, as well as to improve their antioxidant capacity [55]. In this regard, SCG addition increased lutein and  $\beta$ -carotene by 90 and 72%, respectively, whereas chlorophylls increased by up to 61%. This increase in bioactive compounds occurred with SCG concentrations up to 10% [64]. The antioxidant capacity of lettuces increased linearly with the fresh SCG concentration, although the same did not happen with lettuces grown with composted SCG [65].

### 3.3. Use of By-Products Derived from Spent Coffee Grounds in Agriculture

#### 3.3.1. Effects on Soil Fertility

Recently, Cervera-Mata et al. [73] studied the effect of biochar (270 and 400 °C), vermicompost and hydrochar (160 and 200 °C) on C and N soil dynamics. Both SCG and SCG vermicomposts, due to their high content of transformable molecules, are easily decomposed by microorganisms, releasing CO<sub>2</sub> into the atmosphere. The opposite was found for biochar at 400 °C and vermicompost. Biochar at 270 °C had an intermediate behavior. Despite being highly transformable bio-products, both SCG and hydrochars leave a large quantity of remaining C in the soil (87%); the percentage is much higher in the case of biochar (99%). In another study by our research group [71], SCG were transformed into hydrochar, and it was found that the effect of washed hydrochar was similar to that of SCG, regarding OC, total N, C/N ratio and available K and P contents.

#### 3.3.2. Effects on Plants

There has been much research aiming to reduce SCG phytotoxicity via different transformations such as composting, vermicomposting, pyrolysis, hydrothermal carbonization, washing with water and ethanol or defatting [54,62,68,71]. Vardon et al. [68] reported that defatted SCG had the same inhibitory effect as fresh SCG, although when a fertilizer was added, plant growth increased, but still not as much as observed for the control sample. Similarly, when both fresh and defatted SCG were transformed into biochar, they continued to limit the growth of sorghum, but when a nitrogen fertilizer was also added, the dry weight of the sorghum exceeded that of the control sample with the fertilizer. These same results were verified by Cervera-Mata et al. [62]. These authors also reported that the only treatment that eliminated phytotoxicity was vermicomposting followed by pyrolysis at 400 °C. These treatments cleared SCG of polyphenols, which are responsible for the phytotoxicity. However, it was observed that these compounds were also responsible for SCG chelating capacity, which increased the Cu, Fe and Zn content in lettuce. Cruz et al. [54] also studied the effect of composted SCG on the nutritional content of lettuce. The lettuce concentrations of Mg, Mn, K and Na increased, due to a better phyto-availability of these elements, as well as to caffeine degradation [65]. When these authors composted SCG directly in the soil for 4 months, lettuces grown with 20% and 30% SCG showed higher concentrations of total elements compared to lettuces grown with less SCG [54].

Other authors investigated the addition of ash together with the SCG, verifying that the combination of these two residues inhibited plant growth even more strongly [67]. The same results were found by the group of Ciesielczuk et al. [70] who supplemented SCG with ash, magnesium sulfate and blood meal.

Recently, Cervera-Mata et al. [57] created what they called “biochelates”, consisting of SCG combined with mineral salts to increase the bioavailability of Fe and Zn towards plants. These authors reported that SCG and melanoidins (chelate molecules present in coffee drinks) chelated Fe and Zn salts and had a lower biofortification capacity than commercial chelates; however, they generated a reserve of these microelements in soil far superior to that of commercial chelates.

### 3.4. Comparison with the Effect of Other Organic Amendments

Table 1 shows that the addition of other organic amendments has a very positive effects on the physical, chemical and physicochemical properties of the soil. Morra et al. [76] added biowaste compost, observing positive effects on SOC and the stabilization of C, coinciding with the effects of SCG. However, Hussain and Sarkar [77] observed that the addition of bagasse, bio-slurry or kitchen waste compost increased the fresh weight and dry weight of plants, contrary to the effect reported with SCG.

### 3.5. Therefore, Why Should We Be Concerned with the Use of Spent Coffee Grounds as an Organic Amendment of Soils?

Taking into account all the information reported in the previous sections, SCG can be considered as a biowaste with contradictory effects when used as an organic soil amendment. On one hand, SCG positively modify the chemical, physical and biological properties of the soil in relatively short time periods. On the other hand, SCG inhibit plant growth, even at very low concentrations (<1%). This inhibition is attributed mainly to their content of phytotoxic compounds and, to a lesser extent, to the stimulation of microbial growth (competing for nitrogen with plant roots). This contrasting effects of SCG are justified by their interesting chemical and biochemical composition: SCG are rich in proteins, sugars, lipids, mineral elements, etc., but also in compounds such as caffeine and polyphenols, which are toxic for plants. This particular composition is related to the fact that coffee beans are seeds, not a supporting part of the plant or a protective organ, such as most biomass derived from crops. SCG are, therefore, a peculiar biowaste whose management should be carefully investigated. It would even be necessary to review the paradigm of the use of all bio-residues in agronomy, which are mainly used in sufficient quantities to correct the carbon deficit in cultivated soils, and to improve their properties. However, in the case of SCG, given their high physicochemical activity, it would be interesting to explore other possibilities of use.

## 4. Conclusions

Spent coffee grounds can be used for different purposes such as for biotechnological applications (bioethanol, volatile aromatic compounds, carotenoids, fungi and enzymes), energy applications (combustion, pyrolysis, torrefaction, gasification, hydrothermal carbonization) and environmental applications (such as composting) among others. The high content of transformable molecules in SCG make them easy to decompose by microorganisms to release CO<sub>2</sub> into the atmosphere. However, the direct addition of SCG to soil allows a C retention of more than 85%. This is a promising environmental application of SCG related to climate change.

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