FUNCTIONAL FORMULATION OF COMPOSTING MIXTURES BASED ON SPENT COFFEE GROUNDS AND FOOD RESIDUES

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Abstract

Spent coffee grounds (SCG) represent an agro-food waste stream generated in substantial quantities and are characterized by a high content of organic matter, lignocellulosic compounds, lipids, proteins, bioactive compounds, and mineral elements. Although these characteristics support their potential for agronomic valorization, the direct application of SCG to soil may be limited by compositional variability, the presence of residual bioactive compounds, temporary nitrogen immobilization, and the physical properties of the material.This paper critically reviews the literature on SCG composting and proposes a conceptual framework for the functional design of co-composting mixtures, in which complementary feedstocks are selected according to their role in regulating the C/N ratio, pH, moisture content, porosity, and nutrient availability. Particular attention is given to banana peels, citrus residues, eggshells, and bulking materials.The available literature indicates that each of these waste streams may contribute differently to process optimization; however, their integration into a single system requires experimental validation. The paper identifies the need to develop standardized protocols for the formulation and characterization of composts based on spent coffee grounds.

Keywords: spent coffee grounds; composting; food waste; functional mixture design; compost maturity; circular economy; regenerative agriculture.

1. INTRODUCTION

High levels of coffee consumption worldwide are associated with the generation of considerable amounts of organic waste. Recent literature estimates global consumption at approximately 2.3 billion cups of coffee per day and the annual generation of approximately 6 million tonnes of spent coffee grounds. For every tonne of coffee beans used, approximately 650 kg of spent coffee grounds may be generated [1].Disposal through landfilling does not recover the organic and mineral resources contained in this material and may contribute to leachate formation and greenhouse gas emissions under anaerobic conditions.Among the available agricultural valorization pathways, composting is of particular interest because it enables the transformation of a relatively unstable organic material into a more stable matrix that is more suitable for incorporation into soil. De Bomfim et al. specifically investigated the characterization, composting, and reuse of SCG as a soil amendment [5], while Pérez-Burillo et al. highlighted both the potential and the risks associated with the direct application of SCG [6].At the same time, regenerative agriculture emphasizes soil health, nutrient recycling, the maintenance or increase of soil organic carbon, and the reduction of resource losses. Practices such as residue retention, reduced soil disturbance, and the incorporation of organic materials may contribute to these objectives, although their effects depend on pedoclimatic conditions and the agricultural production system [7,8].The objective of the present paper is to critically assess the potential of SCG as a composting feedstock and to propose a conceptual framework for its composting with complementary food residues within the context of the circular economy and regenerative agriculture.

The paper is designed as a narrative and conceptual review rather than an experimental study or a systematic review. Priority was given to articles relevant to four main areas: characterization and valorization of SCG; use of SCG in soil and composting; composting of banana residues, citrus residues, and eggshells; and compost maturity and regenerative agriculture.

Priority was given to studies published in journals such as *Bioresource Technology*, *Trends in Food Science & Technology*, *Science of the Total Environment*, *Agronomy*, *Sustainability*, and *Proceedings of the National Academy of Sciences*. Classical references on compost maturity were retained when they represented fundamental works that continue to be used in the current literature.

This approach aims to integrate existing findings into an applied framework and to identify combinations of feedstocks that warrant subsequent experimental evaluation. Although SCG composting and the composting of individual food residues have been investigated separately, the literature provides fewer conceptual frameworks for the functional selection of complementary feedstocks in SCG-based co-composting mixtures. The present paper proposes such an approach, based on compensating for the physical, chemical, and biological properties of the individual components.

2. COMPOSITION OF SPENT COFFEE GROUNDS AND RELEVANCE TO COMPOSTING

SCG is a complex lignocellulosic biomass. On a dry-matter basis, approximately 45–50% carbohydrates, 18–25% lipids, and 10–15% proteins have been reported [1]. Other data synthesized in recent literature indicate approximately 45–46% polysaccharides, significant fractions of cellulose ahemicellulose and a considerable lignin [1].The lignocellulosic structure is important for composting. Readily degradable components may be metabolized relatively rapidly, whereas the lignified fraction requires more complex microbial processes and may influence the time required for stabilization.SCG also contains phenolic compounds, caffeine, and other bioactive molecules. These characteristics make the material valuable for the extraction of value-added compounds but may represent a disadvantage in the case of direct and uncontrolled application to soil [4,6]

Component	Reported content	Main constituents
Carbohydrates	45–50%	Polysaccharides; cellulose 10–20%; hemicellulose 39–40%; galactomannans
Insoluble dietary fibre	≈35%	Structural fibre components
Soluble dietary fibre	≈8%	Structural fibre components
Lignin	22.2–33.6%	Coniferyl, p-coumaryl, and sinapyl alcohols
Lipids	18–25%	Linoleic acid 36–42%; palmitic ≈32%; oleic 10–12%; stearic 7–10%
Proteins	10–15%	Amino-acid-rich fraction
Phenolic compounds	16–173.3 mg GAE/g dry matter	Chlorogenic, caffeic, gallic, ferulic, and protocatechuic acids; flavonoids
Potassium	≈11,700 mg/kg	K

Phosphorus	≈1,800 mg/kg	P
Magnesium	≈1,900 mg/kg	Mg
Calcium	≈1,200 mg/kg	Ca
Sulfur	≈1,600 mg/kg	S
Iron	≈52 mg/kg	Fe
Manganese	≈29 mg/kg	Mn
Copper	≈19 mg/kg	Cu
Cobalt	≈15 mg/kg	Co
Zinc	≈8 mg/kg	Zn
Manganese	≈29 mg/kg	Mn
Copper	≈19 mg/kg	Cu

Table 1. Nutritional Composition of Spent Coffee Grounds

The values shown represent ranges and typical values compiled by the authors from the scientific literature rather than the analytical results of a single sample. From a mineral perspective, the data synthesized by Pilli et al. indicate approximately 11,700 mg/kg K, 1,900 mg/kg Mg, 1,800 mg/kg P, 1,600 mg/kg S, and 1,200 mg/kg Ca, together with Fe, Mn, Cu, Co, and Zn at lower concentrations [1]. However, these values should be interpreted as literature-derived values, rather than as a universal composition of SCG. Coffee variety, origin, degree of roasting, particle size, and brewing method influence the composition of the residual material [1]. A composition rich in organic matter and minerals does not automatically imply that SCG is suitable for direct application to soil.Pérez-Burillo et al. showed that the effects of SCG on soil and plants depend on application rate, material characteristics, and soil conditions, while the presence of caffeine, polyphenols, and other residual compounds must also be taken into consideration [5]. Furthermore, decomposition of fresh organic matter may result in temporary nitrogen immobilization by microorganisms.The review by Pilli et al. explicitly highlights limitations associated with the use of untreated SCG and identifies vermicomposting and other forms of processing as pathways for improving its agronomic valorization. Consequently, composting should not be regarded merely as a waste-reduction method, but as a biological stabilization stage prior to agricultural use.Composting is an aerobic process in which microbial communities transform organic matter into a more stable material. Process efficiency depends not only on the characteristics of each feedstock but also on how the different components are combined.SCG has a fine particle size and a high organic matter content. At high proportions, fine particles may promote compaction; therefore, combining SCG with bulking agents or residues with different physical properties may be advantageous.Composting makes it possible to simultaneously adjust the C/N ratio, moisture content, aeration, pH, and nutrient availability. Consequently, integrating SCG with other food residues should be regarded as a form of functional mixture formulation, rather than as the simple mixing of available waste materials.In this context, complementary materials may be added, including banana peels, citrus residues, and eggshells, each contributing to the development of a more balanced compost.Kalemelawa et al. investigated the aerobic and anaerobic composting of banana peels in different combinations and demonstrated the possibility of converting this residue into compost with agronomic value [9]. Their study monitored compositional changes over a period of 12 weeks and showed that combining banana peels with other organic materials may promote mineralization.The importance of banana peel in an SCG-based system is particularly associated with its compositional differences compared with coffee grounds and with its mineral contribution, including potassium. Within a conceptual co-composting framework, banana peel may therefore contribute to the diversification of the organic substrate and to modification of the mineral profile of the mixture.Citrus waste has specific characteristics, including an acidic nature and high water content. Van Heerden et al. studied the composting of citrus residues using a mixture adjusted to a C/N ratio of 24:1, pH 6.3, and moisture content of 60%. The material was regularly turned and re-moistened, and composting was completed in approximately three months [10].This finding is relevant to SCG–citrus mixtures because it demonstrates that the acidity and high moisture content of citrus residues can be managed through appropriate mixture formulation and control of composting conditions.Orange peel should therefore not be regarded exclusively as a nutrient source, but also as a component that influences moisture content, acidity, and the overall degradability of the mixture.Eggshell serves a different function from plant residues. It is predominantly mineral in nature and rich in calcium carbonate. Agronomic studies have demonstrated that the use of ground eggshells may increase the pH of acidic soils and improve calcium availability.Holmes et al. evaluated ground eggshells as a liming/amendment material in corn and soybean crops [11], while more recent studies have confirmed their potential for soil amendment and for influencing phosphorus availability [12].Of particular relevance to co-composting is the study by Wang et al., in which the addition of eggshell waste together with rice husks improved the composting of green waste by accelerating degradation and humification [13].These findings support the hypothesis that a controlled amount of eggshell may serve a dual role in a mixture containing SCG and fruit residues: supplying Ca and modifying the buffering capacity of the system. Bernal et al. demonstrated that compost maturity should be assessed using a combination of chemical and biological indicators. Under the conditions of their study, indicators such as a C/N ratio <12, a low NH_4/NO_3 ratio, and a germination index $>50\%$ were identified; however, the authors also emphasized that certain parameters depend on the nature of the feedstocks [15].Accordingly, brown coloration, texture, or the disappearance of unpleasant odours may provide useful observations but cannot, by themselves, confirm compost maturity.For SCG-based composts, evaluation of at least pH, electrical conductivity, organic carbon, total nitrogen, the C/N ratio, and the germination index is recommended.In the current literature, regenerative agriculture is associated with improved soil health, nutrient cycling, diversification of agricultural systems, and the enhancement or conservation of soil organic carbon. Khangura et al., however, emphasize that the effects of regenerative practices depend on region, soil type, climate, and agricultural system, and that long-term studies are required to validate their benefits [7]. A meta-analysis published in *Proceedings of the National Academy of Sciences* showed that certain practices associated with regenerative agriculture, such as reduced tillage and the intensification/diversification of cropping systems, may increase organic carbon in the upper soil layer, including particulate organic carbon and mineral-associated organic carbon fractions [8].In this context, composts produced from locally available residues may form part of regenerative systems by recycling organic matter and nutrients. Nevertheless, it is not justified to automatically claim that any SCG-based compost "regenerates the soil"; its effects must be demonstrated for the specific soil–plant system in which the product is applied.

3. CONCLUSIONS

Spent coffee grounds represent a complex biomass rich in organic matter and mineral elements, with potential for agricultural valorization. However, their variable composition and the presence of residual bioactive compounds justify avoiding uncontrolled direct application to soil.Composting represents a promising pathway for SCG stabilization. The literature confirms the feasibility of composting spent coffee grounds, banana peels, and citrus residues and demonstrates the usefulness of eggshells as a source of calcium and as a material with soil-amendment potential.The integration of these residues into a single composting system is conceptually justified by the complementarity of their properties. SCG may constitute the main organic substrate, plant residues may diversify the biodegradable organic matter, while eggshells may contribute to the mineral fraction and help regulate acidity.

From the perspective of the circular economy and regenerative agriculture, the valorization of SCG through composting offers the possibility of transforming a waste stream into a resource for soil improvement. The potential of this approach is significant, but its practical application should be supported by characterization, standardization, and agronomic validation.

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