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A comprehensive review of composting from coffee waste: Revalorisation of coffee residue in Colombia

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REVIEW PAPER

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Abstract:

Purpose: Globally, Colombia is recognized as a coffee-growing country *par excellence*, which entails generating a large amount of coffee waste. This narrative study aims to review the possible use of such coffee waste to obtain nutrient-rich compost following key composting processes. The final is to investigate the importance and suitability of this compost type.
Method: The data collected for this study were from reviewing the scientific literature and research reports available in many reputable academic databases, i.e., Science Direct, Springer, PubMed, and Scopus. Reputable academic search engines like Google Scholar and ResearchGate were used to access relevant research and high-quality scientific documents.
Results: The result revealed that using combinations of agro-industrial coffee waste when composted can be applied in agriculture because it provides wide-ranging nutrients, which can fertilize soil, accelerate plant growth, and even improve the nutrient content of vegetables. The SCGs used in agriculture prevent improper waste disposal by decreasing the pollution caused by the degradation of SCGs' toxic components. Here we explore and review composting processes containing coffee waste.
Conclusion: Employing coffee waste for compost implies benefits compared to landfills. The conversion of this coffee biomass waste into compost, and using it as a soil amendment, can reduce the waste volume, improve soil physico-chemical properties, enhance the nutrient use efficiency of crops, and correct the typical soil acidity of Colombian soils used for coffee production.

Keywords: Spent coffee grounds; Coffee by-products; Agro-industrial coffee residues; Valorisation; Reutilisation

1. Introduction

Originally, coffee (*Coffea arabica*) was a rainforest species. It is one of the most popular drinks in the world, to the extent that it is considered the second most marketed product. Hoffman (2014) estimated that 125 million people depend on coffee production for their livelihood. Colombia (like other Central American countries, the Caribbean, and the rest of Latin America) has a long-standing coffee-growing history. Indeed, we can speak of Colombian coffee growing as a transcendent activity because it has been, and still is, a true vector of creating employment, foreign trade, and foreign exchange (Campuzano-Duque et al., 2021).
On a global scale, currently, growing coffee demand is detected, especially in recent decades, which has motivated extended coffee production (Soumare et al., 2003; Muhie, 2022). Thus, the coffee agro-industry has grown and gener-

ated large amounts of waste, practically in all the world's coffee-growing areas (Torga and Spers, 2020).

According to the Secretary of Agriculture of Meta and the National Agricultural Survey of 2006, the waste generated from the industrialization of coffee (particularly pulp and mucilage) can be used to produce edible mushrooms, silage, and vermiculture (Núñez, 2012). Along these same lines, the possibility of valorizing and reusing such waste by producing compost as a real possibility has been raised. Other possible avenues are the production of biofuels and even the manufacture of bricks. What is ultimately intended is to avoid impacts caused by inadequate disposal.

Waste from coffee "*sensu lato*" constitutes a potential low-cost and good-quality resource (Martínez-Saez et al., 2017). Given the organic waste combustion risk, the disposal of coffee grounds in landfills is not advisable because harmful methane and carbon dioxide can be generated Sousa et al. (2020) which, therefore, contributes to the greenhouse effect (Komilis and Ham, 2004).

Organic waste generation is a major environmental issue worldwide (Jeswani et al., 2021; Zhang et al., 2022). Global organic waste production is estimated at 2.01 billion metric tons per year (Raut et al., 2023). Biodegradable rubbish includes food scraps, garden waste, and other organic stuff (Mahapatra et al., 2022; Devendra et al., 2023). This rubbish can release greenhouse gases, particularly methane, when not properly managed, which contributes to climate change (Tian et al., 2016; Ntinyari and Gweyi-Onyango, 2021). Organic waste produces 30% of global methane (Adhikari et al., 2006), a greenhouse gas with a significantly higher warming potential than carbon dioxide (Ford et al., 2012; Saderne et al., 2023). The methane from organic waste decomposition contributes to global warming by causing rising sea levels, harsh weather, and ocean acidification (Sivaramanan, 2015; Roy, 2023). Many global measures have been implemented to solve this growing problem.

Composting is one effective solution. The process of composting involves converting organic waste into a fertilizer that is rich in nutrients, which may be used for gardening and agriculture (Islam et al., 2018). Reducing landfill methane release and promoting sustainable waste management are two benefits of composting organic waste (Tominac et al., 2020; Ayilara et al., 2020).

Compost is a rich source of nutrients with high organic matter content. Some scholars (Liu et al., 2019; Workineh et al., 2023) predict that compost improves soil properties (e.g., bulk density, porosity, water conductivity, water retention capacity, cation exchange capacity, organic carbon content, organic nitrogen content, biological functions, and mineralization). The same authors, plus others, indicate that plant growth and crop yield can ultimately increase (Carter et al., 2004; Diacono and Montemurro, 2010; Fischer and Glaser, 2012; Bass et al., 2016). A considerable amount of literature addresses how compost increases nitrogen (N) uptake, leaf N content, turf quality and growth of Kentucky bluegrass (Johnson et al., 2006), and crop yield (Diacono and Montemurro, 2010).

To the best of our knowledge, in Colombia, research to date has focused fundamentally on improving coffee productivity and has left the environmental repercussions that derive from its waste to one side. This article provides a brief review which intends to publicize the possibility of composting coffee waste and, in this way, to highlight the benefits that this can provide, especially from an agronomic and environmental point of view, with emphasis placed on Colombia. For this purpose, after analyzing coffee production both worldwide and in Colombia, emphasis is also placed on the production of the by-products that derive from the coffee agro-industry to discuss the composting of these by-products. In short, the purpose of this review is to provide a comprehensive and evaluative synthesis of the current scientific and technical literature pertaining to the management of organic refuse and its transformation into a new product: compost. The approach will not only provide a useful framework for informing policy and strategy development but will also lay the foundations for future research and progress in the domain of sustainable organic waste management and compost production.

2. Methodology

The data collected for this study were obtained from reviewing the scientific literature and research reports available in many reputable academic databases, i.e., Science Direct, Springer, PubMed, and Scopus, which house a diverse and extensive collection of academic works in a wide range of academic disciplines. In addition, reputable academic search engines, such as Google Scholar and ResearchGate, were used to access relevant research and high-quality scientific documents. This search strategy was implemented to ensure the inclusion of up-to-date peer-reviewed information, particularly in the composting field, to provide a solid foundation for the analysis and discussion presented in this academic work.

3. Some data on coffee production

Coffee (Coffea sp.) is a very popular beverage whose market is distributed on a global scale. Indeed, coffee is a product used worldwide and one of the most important agricultural exports, as is the case of Colombia (Blinová et al., 2017; Torga and Spers, 2020). Globally, the database for green coffee production is provided by the Food and Agriculture Organization of the United Nations. Its report indicates that in 2021, in production terms, Colombia is practically near the head.

According to Pohlan and Janssens (2010), the cultivated area of global coffee production is estimated to cover about 10 million hectares. World green coffee production has been estimated at 172.8 million 60-kilogram bags, of which South America participated with 77.5 million, and are distributed mainly between the Arabica (*Coffea arabica*) and Robusta (*Coffea canephora*) varieties. These coffee varieties represent around 60% and 35% of global production, respectively. The remaining percentage is made up of Coffea liberica species (ICO World Coffee Production). In Colombia, the best-grown varieties are *Bourbon, Typica, Caturra, and Maragogype* (Pohlan and Janssens, 2010; Fernandes et al., 2022).

Globally speaking, about 80 countries in Latin America, Asia, and Africa grow coffee. According to Grabs and Ponte (2019) and Bilen et al. (2023), the main coffee-producing countries appear in this descending order: Brazil > Vietnam > Colombia > Indonesia > Ethiopia. Other authors (Rojo, 2022; Aristizábal-Marulanda and Martín, 2022) consider that Colombia is the world's second coffee producer because coffee is the most relevant national crop from the country's agricultural sector. As of March 2021, and according to data from Campuzano-Duque et al. (2021), in Colombia, there are 844743 hectares of coffee, 83% of which are in the productive stage, with an average age of 6.89 years and density of 5261 trees per hectare.

Coffee cultivation in Colombia covers 600 municipalities in 22 departments (Campuzano-Duque et al., 2021). So, although the so-called Coffee Axis exists, made up of the departments of Tolima, Caldas, Quindío, and Risaralda, there are other departments in which coffee is grown, namely Nariño, Norte de Santander, Antioquia, Valle del Cauca, Cundinamarca, Huila and Cauca. Fig. 1 shows a map of Colombia, where coffee is grown, and its harvest times. Colombia is considered the world's leading mild coffee exporter. In 2008, an average of 12524 bags of coffee were estimated, each weighing 60 kg (Díaz et al., 2010). By 2020, Colombia produced 13.9 million bags of 60 kg of green coffee, with domestic coffee consumption of 2.3 million bags in the same year.

4. Production and subproducts related to the coffee agro-industry

Coffee plantations, which span more than 80 countries, produce approximately 8 million tons of coffee each year in the world (Döhlert et al., 2016) while generating abundant waste (Pohlan and Janssens, 2010; Fernández-Cortés et al., 2020).

In countries like Colombia, the waste generation from agricultural activities is a common and widespread fact throughout the country given the notable economic activity around this sector. So, processing products like coffee, oil palm, sugar cane, and panelera, corn, rice, and banana are of special relevance (Chávez and Rodríguez, 2016).

The waste that derives from the coffee production process, but also ground coffee, coffee skin, and returned coffee, form part of the coffee agro-industry. These by-products include those that derive from the post-harvest processing, roasting, and extraction of coffee, namely beans, husks (CH), skin and pulp (CP), parchment, silver skin (CS) and immature coffee grounds/defective (SCGs), some of which are toxic and pose serious environmental problems. It is estimated that only 9.5% of a kilogram of coffee cherry is transformed into drinkable part and the remaining 90.5% is waste. Fruit pulp represents 44% of the weight of the nut and lees, which is the product of coffee preparation from roasted and ground coffee, and represents, in turn, 10% of nut weight (Cury et al., 2017; Ruiz et al., 2018; Machado et al., 2023).

Several processes are involved in the coffee agro-industry (Fig. 2). To obtain coffee, the berry must be depulped, fermented, washed, dried, and roasted to produce residue: pulp and husk, mucilage, and parchment. Initially, the berries from the coffee plants are washed and peeled (depulping) by separating green beans from pulp or husk (Chong and Dumas, 2012). This work is generally done outside the plant. Pulp is one of the main by-products generated during the process (Chala et al., 2018).

In this context, several environmental impacts are recognized, of which it is worth high-lighting those that derive

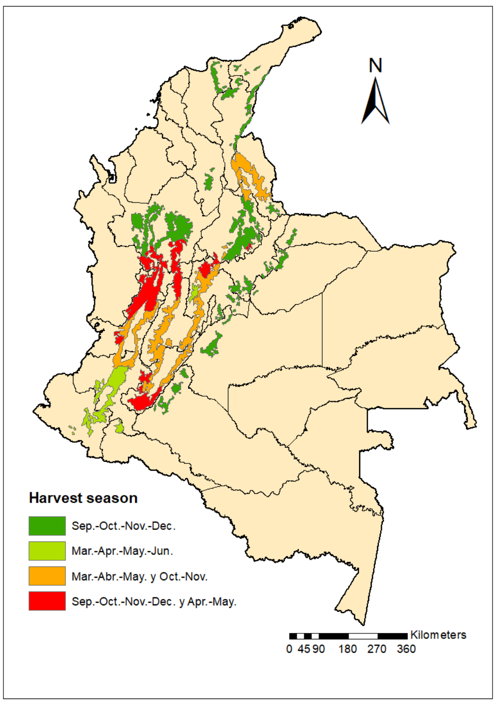

Figure 1. Main coffee harvest areas and times in Colombia.

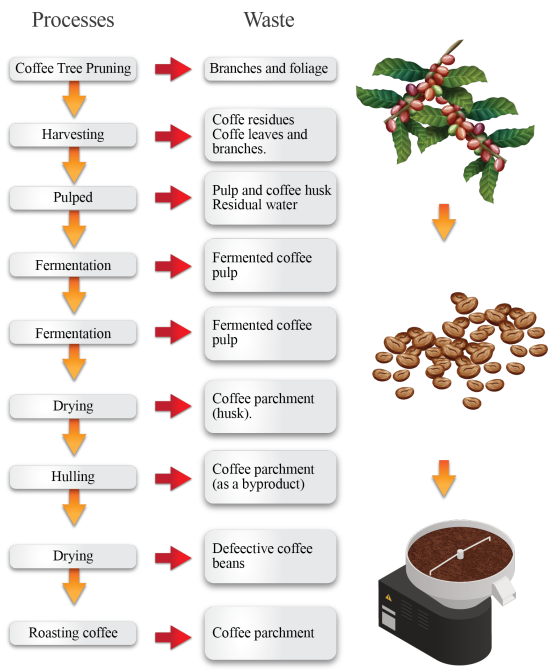

Figure 2. Stages of the production process-related by-products, including coffee bean manufac-turing processes.

from coffee production and processing because large quantities of solid and liquid waste are produced. In fact, globally, they are very relevant according to Hue et al. (2006). Echevería and Nuti (2017) estimate that more than 10 million tons of solid waste are generated annually from the world's coffee agro-industry, along with a large amount of wastewater and crop residue. Therefore, all these products that derive from production processes, and also consumption processes, have a certain environmental impact. Transforming coffee fruit into served coffee causes organic contamination processes that, in the case of water, lead to loss of quality because suspended matter and the resulting turbidity are observed, as well as unpleasant odours (Guardia, 2012).

5. Coffee waste production and uses: Spent coffee grounds

A considerable amount of the literature addresses the use of spent coffee grounds (SCGs) in composting for organic farming as a viable way to valorize such agro-industrial residue (i.e., (Santos et al., 2017)). This waste is generated in large quantities around the world, approximately 15 million tons annually (Kamil et al., 2019; Stylianou et al., 2018). Stylianou et al. (2018) reviewed the literature on the environmental benefits of reusing SCGs, including their employment as organic soil amendments. It is estimated that each ton of coffee beans produces 650 kg of waste after processing (Murthy and Naidu, 2012). In 2017, the global coffee industry generated 9.34 million tons of waste, which was incinerated, thrown into landfills, or composted (Zabaniotou and Kamaterou, 2019).

According to McNutt and He (2019), there are several possible uses for coffee residue (Fig. 3). In particular, Campos-Vega et al. (2015) points out that SCGs contain large amounts of organic compounds (i.e., fatty acids, amino acids, polyphenols, minerals, and polysaccharides), which justify their valorization. The possibility of formulating particulate composites made of biopolymers filled with coffee waste with acceptable physico-mechanical characteristics that will degrade has been proposed by (Ghazvini et al., 2022; Janissen and Huynh, 2018).

6. Composting process

Traditionally in many regions of the world, waste management consists of sending it to landfills (Seco et al., 2020). However, this option tends to be increasingly less used seeing that sustainable alternatives tend to be promoted. Thus, criteria have been issued for recovering waste and organic by-products. One such case is Waste Directive 2008/98/EC, known as the Waste Framework Directive and its subsequent modifications (e.g., EU Directive 2018/851 of the European Parliament and of Council of May 30, 2018, amending EC Directive 2008/98 on waste).

Many organic waste types employed on agricultural land can be processed by different methods to retain as many nutrients as possible (e.g., nitrogen, N, or phosphorus, P) and to, thus, increase their capacity for agricultural use while minimizing their impact on the environment. However, depending on the applied type of technology, the processing of organic waste can add agronomic, economic, and ecological values to the final product.

Much of the waste (a non-negligible percentage) that derives from the coffee industry (by-products of the harvesting, processing, roasting, and coffee processing stages) generally end up in landfills. The inherent toxicity of several components of coffee poses an environmental risk of contamination (Carter et al., 2004). So, currently, organic waste results in large quantities (in practically all world regions) and can cause significant pollution levels and environmental problems if rapid control is not carried out. Therefore, the composting process can be a satisfactory solution to this problem. Nonetheless, composting is not considered a new technology but a waste management strategy and this method is considered a suitable option for many waste management options due to its economic and environmental

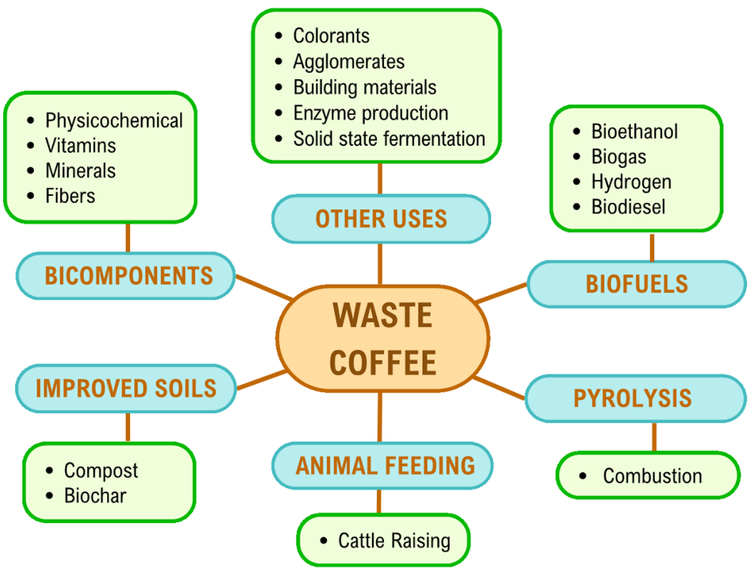

Figure 3. Possible coffee waste reuses (Modified from (McNutt and He, 2019)).

benefits (Bernal et al., 2009).
From all this, it follows that composting is a method that can be applied to reduce the amount of organic waste through recycling because, during the composting process, up to 30% of the waste volume can be reduced resulting in a product that can have beneficial effects on soil (Khater, 2015). Composting aims to, on the one hand, recycle waste and, on the other hand, to produce compost. Therefore, the processing of coffee waste to convert it into compost products is carried out more and more every day (Murthy and Naidu, 2012), and in such a way that composting currently constitutes an authentic promising technique for waste treatment because it converts organic matter and agricultural residue (i.e., from coffee) into compost ((Guideline, 2003; Shemekite et al., 2014).
It is also imperative to take into account the idea of Zohra et al. (2022): that the characteristic of compost is directly related to the material used for composting. Some studies have even argued that applying compost (e.g., from the coffee husk and pulp with source-separated municipal solid waste: SSMSW) can be served for unrestricted types of agricultural purposes (Dadi et al., 2019). Pellejero et al. (2021) concluded that the agricultural use of quality compost is an effective strategy to obtain high-quality products in an economically viable and environmentally sustainable way.
Generally, the composting process includes mostly three phases (Fig. 4): an initial mesophilic phase (degradation phase), in which the degradation of simple compounds like sugars, amino acids, etc., is carried out by mesophilic bacteria and fungi by rapidly raising the temperature up to 50°C (Albrecht et al., 2010). According to Gannes et al. (2013), *Pseudomonas, Acinetobacter, Steroidobacter, Bacillus*, and *Sphingobacterium* are the most abundant genera in rice straw, sugar cane bagasse and coffee hull composting processes with cow manure additions. In this phase, the composting process has to be controlled and frequently adjusted to ensure optimum conditions for microorganisms (mainly temperature and moisture). Solid material is biodegradable waste, the moisture inside and outside waste is the liquid part, and the air in the gaps between solid particles is the gaseous phase. All three constituents play a key role in the composting process (Albrecht et al., 2010).
The thermophilic phase (transformation phase), in which thermophilic microbes degrade organic matter (fats, cellulose, hemicelluloses, lignin), and the organic carbon content lowers in the feedstock ascribed to the metabolic activities of heat-tolerant microbes (Zhao et al., 2017). Temperatures of 40 - 60°C or the thermophilic stage lead to mesophiles being completely eliminated and microorganism thermophiles increasing their population. Given the presence and activity of the extreme thermophilic bacteria that act at temperatures between 60 - 80°C, they are the only ones that are active and are essential for the biodegradation and mineralization of biological waste, while species diversity lowers, but their concentration is high (100 to 1 billion cells per gram).
Pile also becomes populated with several invertebrates, such as mites, millipedes, beetles, earwigs, earthworms, slugs, and snails. As the material is a nutrient source to them, they continue the degradation process and cut down the coarse compost material into a crumbly soil-like substance. Although the material looks like compost, it is not yet stable. Hence, chemical substances (e.g., nitrite) may inhibit plant growth if applied directly to flora.
Cooling and maturation phase implies a slow process that takes about 150 days. It is also expensive due to the required labor, which means that looking for alternative formulas to manage this waste type is necessary.

7. Effects of coffee compost on soil

In technical terms, composting is understood as a process that culminates with the formation of an organic fertiliser, which results from the decomposition of the mixture of organic matter (of plant or animal origin). This decomposition is generated by a microbial activity that, at controlled pH levels and under favourable physical conditions, results in a very stable mixture of organic matters with components that are difficult to decompose. Compost is a valuable source of nutrients and organic matter, and can be used as a soil amendment in agriculture. Some important benefits of compost manure in agriculture include improved soil fertility, enhanced soil structure, reduced soil erosion, suppressed plant diseases, and no reliance on synthetic fertilizers (Fig. 5).

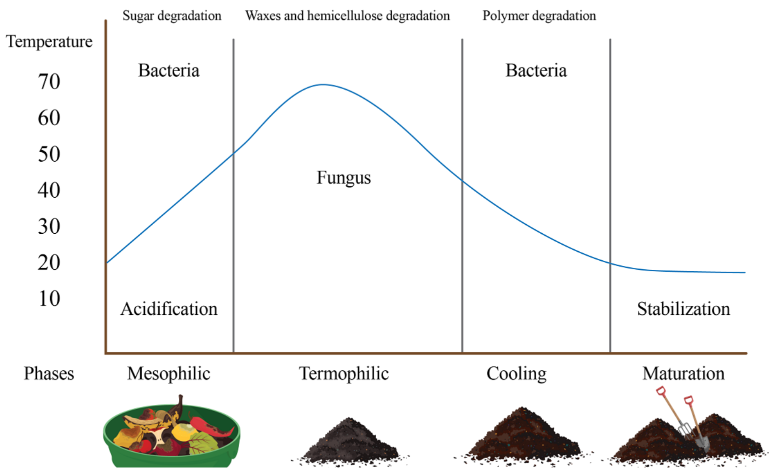

Figure 4. Changes during the composting process.

Composting is an ecological and economical alternative for organic waste treatment that turns management into a fertilizer/organic amendment (Huang et al., 2017). One of the best benefits of composting is its ability to improve soil quality. Compost that is rich in nutrients and organic matter improves the soil structure, increases its water retention capacity, and promotes beneficial microbial activity. In the US, for example, it is estimated that composting can increase soil water retention capacity by 25% (Morales-Maldonado and Casanova-Lugo, 2015). This is essential for agriculture because healthy soils and fertile lands lead to better crop yields and greater food security.

In fact, globally speaking, organic compost use in agriculture is a common and very advantageous practice because it avoids environmental pollution and is a source of organic matter in the soil (Durán-Lara et al., 2020).

Compost is applied to increase the quantity and to improve the quality of soil organic matter (SOM), and to improve soil carbon (C) sequestration by greater stability (Adani et al., 2007). Compost application supports soil microorganisms by providing nutrients, and also indirectly by changing soil physico-chemical properties. According to Sall et al. (2016), an increase in aggregate size is partially due to fungal activities. Soil colonization by fungal hyphae through compost addition is evident, which may be considered a cause of soil macroaggregate formation. Increased structural stability can be attributed to the development of roots, stimulated by the addition of organic amendments (Forge et al., 2016).

Adding compost to contaminated soil is known to have immobilizing effects on some metals because the humic acids that are present can bind to metals, such as Cd, Pb, Cu, and Cr (Park et al., 2011).

Composting is a preferred environmentally sound method whereby organic waste changes to organic fertilizer through biological processes. Coffee waste contains a high concentration of biodegradable organic compounds and minerals of plant origin, which can be used by composting with other organic matter (Durán-Lara et al., 2020). The major contribution of matured coffee husk and pulp compost samples is that they contribute elements such as Fe and K. They also contain other micronutrients that are essential for plant growth (and are required in much smaller amounts than macronutrients), such as Cu, Mn, Zn, Ni (Echeverría and Nuti, 2017).

Eisenia fetida earthworms, also known as red wigglers, are commonly used in coffee vermicomposts because of their capacity to induce significant physico-chemical changes in organic matter (Degefe et al., 2016; Trujillo-González et al., 2022a).

Several studies appear in the literature, some of which are recent, such as those by Franca and Oliveira (2009), Kassa et al. (2011), Shemekite et al. (2014), and Degefe et al. (2016), who have reported composting coffee husk with cow dung, fruit/vegetables, effective microorganisms and Khat (*Catha edulis*).

8. Compost use in agriculture. Spent coffee grounds

Apart from composting being an effective way to reuse organic waste (Lakhdar et al., 2011), it is considered an environmentally-friendly soil amendment for crops because it accumulates organic matter in soil compared to chemical fertilizers (Evanylo et al., 2008). Composting is a common practice for recycling bio-waste and is regarded as a simple efficient method to convert agro-industrial waste into stable, non-toxic, pathogen-free, and nutrient-rich products for soil conditioners and plant fertilizers (Poli et al., 2011).

One of the main coffee waste types is the so-called spent coffee grounds (SCGs), which are the solid waste obtained after preparing coffee drinks. According to Mussatto et al. (2011) and Cruz et al. (2012), SCGs are rich in N (about 1.2-2.3%), P (0.0-0.5%), and K (0.35%), which led Kondamudi et al. (2008) to study their possible use in agriculture as either a fertilizer or soil improver. The alternative of composting has also been suggested (Cruz and Santos Cordovil, 2015).

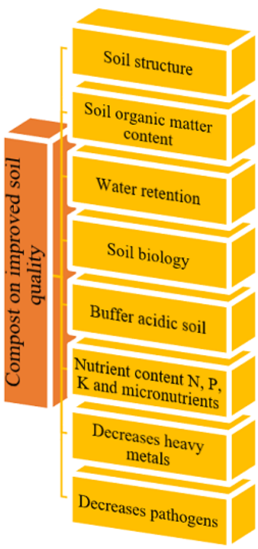

Figure 5. Selected soil quality criteria due to compost application.

In particular, SCGs are composed mainly of carbohydrates, dietary fibre, hemicellulose, lignin, lipids, and proteins, and are high in K and Mg, as well as bioactive compounds like chlorogenic acids, caffeine, and melanoidins. It is estimated that around 60 million kg are generated daily Forcina et al., 2023. Most SCGs are dumped in landfills or in-cinerated and they, consequently, generate greenhouse gas emissions (Klingel et al., 2020; Johnson et al., 2022). It is estimated that 15 million tons of SCGs are produced worldwide (Kamil et al., 2019).

Authors like Stylianou et al. (2018) indicate that SCGs can be used as an organic soil amendment because they can improve physico-chemical fertility, which can also affect the soil microbiota (Comino et al., 2020; Cervera-Mata et al., 2021; Cervera-Mata et al., 2022). SCGs have a nitrogen level of 1.0-2.5% and a C/N ratio of 20 to 25, which are much higher than typical horticultural soils and soil microbial communities (Pujol et al., 2013; Trujillo-González et al., 2022b). In fact, it has been found that the application of SCGs improves water retention, total porosity of N, P, and K concentrations, and improves the C cycle while lowering apparent soil density. Morikawa and Saigusa (2008) found that composted coffee grounds improve the growth of several horticultural crops in specified soils, while the results for non-composted SCGs are less apparent.

Compost quality can induce soil fertility benefits, such as physical, chemical, and biological, to prevent the immobilization of nutrients and the suppression of diseases in soil (Hachicha et al., 2012; Kutsanedzie et al., 2015). That is, employing combinations of agro-industrial waste when composted can be used in agriculture because they provide a wide range of nutrients that can fertilize the soil, accelerate plant growth, and can even improve the nutrient content of vegetables. In addition, employing SCGs in agriculture prevents the improper disposal of this waste, which decreases the contamination caused by the degradation of SCGs' toxic components.

Conducting research to fully understand and utilize coffee waste is crucial in order to discover new and creative solutions and take advantage of its various benefits. This research promotes the adoption of sustainable practices in the coffee business.

9. Conclusion

The coffee agro-industry generates large quantities of solid waste. Nowadays, despite the high political and social pressure to reduce pollution, there is still no overall social awareness, although there is certainly a trend towards waste reduction. Thus, any action that aims to dispose of coffee production by-products and to add value to them is extremely relevant. We conducted this research by focusing on coffee waste, which represents added value to the coffee agro-industry, and also to those who make a living from it. Utilizing coffee waste for compost implies benefits compared to landfills. The conversion of this coffee biomass waste into compost and using it as soil amendment can lower waste volumes, improve soil physico-chemical properties, enhance the nutrient use efficiency of crops, and correct the typical soil acidity of the Colombian soils employed for coffee production. Therefore, both communities and the coffee sector can benefit from this study to receive a positive environmental impact. In addition, a new door opens for farmers because they can sustainably apply compost in the future by returning soil amendments to their coffee plantations. We hope to contribute to clarifying the potential for using clean, high-value organic fertilizer compost made from local coffee waste. Finally, it is necessary to have a comprehensive policy framework that encourages sustainable waste management practices, such as composting coffee waste, through incentives, regulations, public awareness, and public-private partnerships is essential for fostering environmental stewardship and circular economy principles within the coffee industry. This framework should be implemented in order to ensure that the coffee industry adopts these principles.

Author contribution

Conceptualization and design of the work, RJB and JMTG; software, JMTG, FJGN, and RJB; investigation, RJB and JMTG; resources, FJGN; writing—original draft preparation, RJB and JMTG; writing—review and editing, RJB, JMTG and FJGN. All authors read and approved the final manuscript.

Conflict of interest statement

The authors declare that they are no conflict of interest associated with this study.

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