Potential environmental applications of spent coffee grounds

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Abstract

Coffee is considered the most popular beverage in the world. However, this results to the production of million tons of relevant wastes, i.e. plastic cups, aluminium capsules (Nespresso) and spent coffee grounds (SCG), all thrown untreated in landfills. It is estimated that 1 kg of instant coffee generates around 2 kg of wet SCG; a relatively unique organic waste stream, with little to no contamination, that is collected separately to other waste in containers next to the espresso machines. The produced nutrient waste has the potential to be used as a value-added product in multiple different processes. SCG are considered a valuable, rich source of bioactive compounds (e.g. phenolics, flavonoids, carotenoids, chlorogenic and protocatechuic acid, melanoidins, diterpenes, xanthines, vitamin precursors, etc) and a useful resource material for a variety of other applications (e.g. soil improver and compost, heavy metals remover, biochar, biodiesel, pellets, health care, food and deodorization product). This paper aims to provide an holistic approach for the SCG waste management, highlighting a series of steps for applications in environmental solutions, food industry and agricultural sector. The latest developments and approaches of SCG waste management are presented and discussed.

Keywords: Spent coffee grounds, Solid waste, Bioactive compounds, Food waste, Landfills

1. Introduction

Coffee is considered the second largest traded commodity after petroleum and has been growing steadily in commercial importance, not surprising considering that it is the most popular beverage in the world [1]. According to the International Coffee Organization (ICO) [2], coffee production (by all exporting countries worldwide) is estimated up to 148 million bags, with world consumption estimated at slightly lower to 151.3 million bags, which gives a global deficit of 3.3 million bags [2].

Statistics regarding Coffee in Cyprus given by the ICO for year 2015, shows a total consumption of 86,000 (60kg bags) [2]. Per capita consumption is increasing the last 10 years, from 4.53(Kg) for 2012 [3] to 6.1 (kg) for 2015 [2], placing Cyprus among the highest consumption countries. Coffee imports in Cyprus for 2015 (60kg bags) were 17,312 for green coffee, 10,450 for roasted coffee and 61,339 for soluble coffee [2]. Furthermore, data from the Statistical Service of Cyprus (on 2015) reports that there are 615 cafeterias and 515 coffee shops, which account more than 1100 establishments that produce SCG.

A great amount of waste is produced from this famous commercial product, mainly of spent coffee grounds (SCG), which refers to coffee grounds after they have been used. These are the primary coffee waste by product (45%) generated in coffee beverage preparation and instant coffee manufacturing, e.g. by the espresso coffee extraction process [4].

Within these processes, raw coffee powder is contacted with hot water or steam, under conditions which favour the release of aroma compounds and other coffee-bean constituents into the liquid [5]. Due to these processes, SCG has a high humidity content (80% to 85%), fine particle size, organic load and acidity [6]. Its' chemical composition (Table 1), reveals a product rich in sugars, proteins, oil, lignin and polyphenols [6] components, which are valuable if they are obtained from SCG and used in other applications, such as in biofuels, compost, animal feed, biosorbents and enzymes, in bioenergy and in other food and health applications [7]. Possible methods of the exploitation and use of this waste have been investigated in recent years, emanating from the need of waste reduction and environmental protection. Until recently SCG had been discarded as solid waste and were considered not to have any commercial value [5].

Table 1. Composition of SCG[1], [4], [6]

Chemical composition / Parameter	Content (wt%)	Chemical composition / Parameter	Content (wt%)
Cellulose	8.6-13.3	Arabinose	1.7
Hemicellulose	30-40	Galactose	13.8
Proteins	6.7-13.6	Mannose	21.2
Oil	10-20	Ashes	1.6
Lignin	25-33	Organic matter	90.5
Polyphenols	2.5	Nitrogen	2.3
Caffeine	0.02	Carbon/nitrogen (C/N ratio)	22/1

2. SCG environmental applications

Companies no longer consider residues as waste, but as raw materials for other processes. Targeting the field of agriculture and food industry, SCG attracted the attention of many researchers as a promising substrate for various processes enabling the conversion of SCG into value-added products; where they can fit into the waste hierarchy either as a product to be reused for feeding people or livestock, or for recovering valuable compounds so as to produce energy or other products such as fuels, materials, chemicals and energy. The number of published scientific research dealing with SCG after 2010 has been increased, showing that the valorization of SCG has recently become an important research topic [8]. An overview of the potential usages of SCG is presented in Figure 1 and are developed in the following sections.

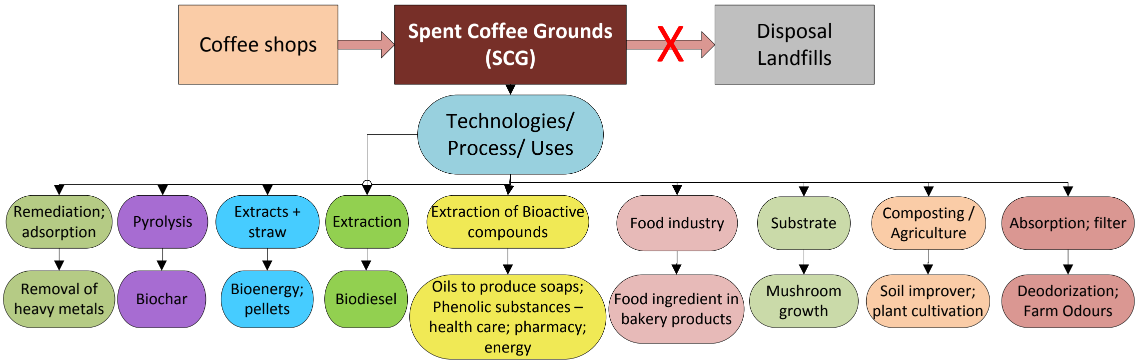

Figure 1. Overview of potential usages of SCG

SCG has been studied for its use as a fuel in industrial boilers due to their high calorific power but this use showed that special attention must be paid to the generation of particulate matter which can pollute the atmosphere. The possibility to use SCG as animal feed was also tested, but the high lignin content was considered a limiting factor [6]. However, there are other technologies which might offer a better strategy for the SCG valorization, yielding in high value products including biodiesel, ethanol or substances for pharmaceutical and cosmetic purposes, which are presented in the next paragraphs [1].

2.1. Source of natural antioxidants

The use of SCG as a valuable source of natural antioxidants was also studied and more particularly for recovering the phenolic compounds, which can be further used as nutritional supplements, foods, for health care and for pharmacy applications [5], [9], [10].

Phenolic compounds have received considerable attention due to their beneficial effects on human health, such as a protective action against chronic degenerative diseases (cataracts, macular degeneration, neurodegenerative diseases, and diabetes mellitus), cancer and cardiovascular diseases all these are ascribed to their antioxidant activity. In a recent study, extracts produced from SCG exhibited anti-tumor and anti-allergic activities, which were related to the presence of phenolic compounds such as chlorogenic acid in their composition. Extracting antioxidant phenolic compounds from SCG can be thus considered an interesting alternative to obtain these important industrial ingredients from a such low cost raw material [9].

Panusa et al. (2013), reported that the phenolic compounds are mainly responsible for the antioxidant activity of SCG. After extraction of SCG, the total phenolic content expressed as gallic acid equivalents (GAE) ranged from about 17 to 35 mg GAE g^{-1} dry waste. These values are higher than those found in other agroindustrial wastes such as grape pomace, carrot peels, and apple peels, which were below 15 mg GAE g^{-1} dry matter. This supports the suitability of SCG as a source of phenolic antioxidants [11].

Various extraction methods are reported for the extraction of Phenolic compounds. Monente et al. (2015), tested three treatments (alkaline, acid, saline) to spent coffee extracts. Alkaline hydrolysis and saline treatment were suitable to estimate the total bound and ionically bound phenolic acids, respectively, whereas acid hydrolysis is an inadequate method to quantitate coffee phenolic acids [12].

2.2. Energy

Extraction of oil from SCG has also gained much attention due to the increased interest in biodiesel as an environmentally-friendly fuel. Studies showed that crude lipids extracted from the SCG were converted into fatty acid methyl ester (FAME) and fatty acid ethyl ester (FAEE) via the non-catalytic biodiesel transesterification reaction. However, the direct conversion of bioethanol from SCG was not found to be a desirable option, because of the relatively slow enzymatic saccharification behavior in the presence of triglycerides and the free fatty acids (FFAs) found to exist in the raw materials [13], [14].

Limousy et al. (2015) investigated the production of compressed logs for energy production from SCG. The use of an industrial press compressed various blends of SCG and wood chips and its chemical properties and calorific value was analyzed. The results showed that SCG leads to better combustion but CO and particle emissions increased leading to lower CO_2 concentrations, which indicated that the combustion of compressed logs is not suitable under the specific stove design and may lead to uncomfortable heating [15].

2.3. Agronomic potential of SCG and its impact on soil biology and fertility

2.3.1. Additive for plant growth and in the composting process

The excessive use of chemical fertilizers is an issue of global concern due to the environmental negative impacts. Particularly for Cyprus, gross nitrogen surplus is among the highest in EU, meaning that the input of N in agricultural ecosystems is higher from the output (Eurostat, 2010). It is therefore important to find efficient alternatives to chemical fertilizers. The use of SCG could be a promising nutrient source, since its structure could improve soil structure, aeration as well as fertility. However, the use of SCG in agriculture as a nutrient supplement requires scientific evidence while environmental safety issues that should also be assessed. The presence of SCG amount in soil may increase plant productivity in a dose-responsive way.

High concentrations of nutrients and carbon/nitrogen ratio makes SCG as a valuable material for the composting process. Different composting systems were evaluated for the management of SCG by Liu and Price (2011) [16]. Their study showed that SCG reduced earthworm growth and survival which was faced by adding cardboard. Hardgrove and Livesley (2016) showed that applying SCG directly to urban agriculture soils greatly reduces plant growth [17]. Low et al (2015) reported that composted SCG should be applied to soil instead of fresh, in order to achieve greater soil mineralisation, as well as, to increase the uptake of mineral nutrients by the cultivated plants [18]. Cruz et al (2014) showed that the addition of SCG through composting for cultivating lettuce, were a valuable source of bioactive compounds, proving to potentiate the antioxidant pool and quality of the vegetables produced [19].

2.3.2. Evaluate the impact of SCG on soil biology and fertility

Despite the fact that SCG is a promising alternative source of nutrients for plants, its environmental safety has been overlooked. So far, there are no available data regarding the impact of SCG on soil functional microbial communities, as well as, soil functioning. It is well known that SCG contains several compounds with antimicrobial properties thereby incorporation of SCG in soil could reduce soil microbial activity or even change the community structure plant growth promoting bacteria. Studies towards this direction should be conducted in order to to assess the impact of SCG soil incorporation in bacterial community structure of the soil as well as the total microbial activity. We hypothesize that SCG will change the bacterial community structure of the soil and will increase the microbial activity of the soil.

2.4. Dietary fiber

Lopez-Barrera et al (2016), investigated the anti-inflammatory effects of SCG. Their results showed that SCG had higher total fiber and resistant starch content compared to coffee beans. SCG exerts anti-inflammatory activity, by reducing the release of inflammatory mediators, providing the basis for SCG use in the control/regulation of inflammatory disorders, and furthermore, support the use of SGC in the food industry as dietary fiber source with health benefits [20]. Martinez-Saez et al (2017) evaluated the use of SCG as a food ingredient and its application in bakery products. They showed that SCG are a natural source of antioxidant insoluble fibre, essential amino acids, low glycaemic sugars, resistant to thermal food processing and digestion process, and totally safe [7].

2.5. Low-cost adsorbent

The use of SCG as a low-cost adsorbent for the biosorption of heavy metals from aqueous solutions has also been investigated, showing very good results for the removal of Cd [21], Cr(II) and Cr(IV) [22], Cu [23] Pb [24]. Also, the generation of biochar (pyrolysis) from SCG and its use for heavy metal removal was investigated giving promising results for Zn [25], Cd, Cu and Zn [26]. Kemp et al (2015) proposed a mechanism for the formation of activated carbon from SCG. SCG activation at 900 °C showed to be an effective and stable medium for methane storage and also exhibits an impressive hydrogen storage capacity [27].

2.6. Biogas production from coffee waste through anaerobic digestion

According to Battista *et al.* 2016, not many researchers have been focused on the anaerobic digestion (AD) of coffee wastes [28]. Shofie et al. (2015) working under mesophilic conditions failed in their attempt to degrade coffee grounds by means of AD because of the recalcitrant lignocellulosic composition of the substrates [29]. Lane (1983) reported a gradual decrease in biogas production in a mesophilic reactor after 80 days, due to unknown inhibitory compounds [30]. The inhibitory effects produced by bioactive compounds contained in coffee grounds e.g. aromatic compounds, polyphenols, and alkaloids could be minimized by mixing different substrates [31]. A common practice to increase biogas production and to alleviate phenolic inhibition is through anaerobic digestion at thermophilic temperatures and/or co-digestion with other waste. Co-digestion is advantageous over mono-digestion for efficient and stable performance, while the mono-digestion of SCG is prone to failure even when alkalinity and micronutrients were supplied. A co-digestion strategy can be beneficial to enhance the process feasibility and stability by balancing the C/N ratio of the feedstock, remedying the trace element deficiency, improving the buffering capacity, and diluting the inhibitory compounds. In addition, Kim et al. 2017 found that SCG can be co-digested without a significant loss in *biochemical methane potential* (BMP) with the following co-substrates food waste, Ulva and whey. However, co-digestion of spent coffee waste with waste activated sludge resulted in decrease of biogas production [32]. Another important factor about the anaerobic digestion of SCG is the application of the thermophilic temperature. In view of this, thermophilic digestion is advantageous with a higher metabolic rates, sufficient solubilization and high degradation of lipids (fats and oils). More specifically, Shofie et al. (2015) found that the organic solid waste with a high carbon content like SCG (C/N ratio: 24–25) is therefore suitable for being treated with other substrates possessing high nitrogen and micronutrient content such as milk waste (C/N ratio: 6–12) and sludge (C/N ratio: 5.8) to obtain a nutrient balance [29]. Dinsdale et al. (1996), reported the failure of maintaining a stable biogas production in a thermophilic reactor treating coffee waste water due to the volatile fatty acids (VFA) accumulation [33]. Recent studies by Qiao et al. (2013a,b) on thermophilic co-digestion of coffee grounds and sludge using anaerobic membrane reactor found a process instability during the first 115 days due to the lack of alkalinity, decreased pH, and deficiency of microelements, while a high concentration of propionic acid of 1–3 g/L and H_2 of 100–200 ppm was observed throughout the reactor operation time [34]; [35]. Mixing coffee grounds with sludge (85:15) has been reported to result in a more stable digestion process compared to digestion of sole coffee grounds, while 15% sludge (dry basis) in the feedstock was sufficient to provide a reactor with micro elements [35]. Up to date no study has examined the biogas production from SCG after phenolic extraction. The phenolic extraction is expected to remove part of inhibition of anaerobic biomass; therefore it is possible the digestion to take place under mesophilic conditions.

3. Conclusions

Food waste is an increasing waste stream that needs to be managed with great concern since it attracted an increasing attention due to its environmental, social and economic impacts. Global production of coffee is increasing because of higher consumption, leading to high generation of million tons of plastics, aluminium capsules (*Nespresso* latest trend) and SCG worldwide. It is estimated that thousands of ton/year are produced and sent to landfills; this results to soil, water and air pollution. According to the literature, SCG is a valuable source of bioactive compounds (e.g. phenolics, flavonoids, carotenoids, chlorogenic acid, protocatechuic acid, melanoidins, diterpenes, xanthines, vitamin precursors, *etc*) and a useful resource material for other applications (e.g. soil improver and compost, heavy metals remover, biochar, biodiesel, pellets, health care, food and deodorization products).

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