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Review

Chemical composition and value-adding applications of coffee industry by-products: A review

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ABSTRACT

Processing urban waste is becoming a major challenge, with the current state and forecasted increase in urbanisation. Finding novel approaches to reduce and recycle this waste, using value-adding applications, is paramount if we are to meet the needs of a growing population. Organic waste is of particular concern, as much of this can be treated and recycled for horticulture practices, but most find their final sink in landfill. With coffee now the second largest commodity worldwide, recycling these nutrient-rich by-products could reduce the amount of organic waste sent to landfill, whilst producing value adding products. Some chemical compounds present in these by-products, such as caffeine, tannins and chlorogenic acid are of ecotoxicological concern and can limit their value-adding applications. The aim of this literature review was to 1) characterise the waste obtained from the coffee industry; 2) outline the current value adding applications; 3) highlight limitations that prevent full utilization of coffee by-products and 4) discuss possible solutions that could maximize by-product utilization and ameliorating their negative environmental impacts. It was concluded that full utilization of these by-products is not always achieved, even though there is evidence to support their potential. This was mainly due to a lack of infrastructure and cross-chain networks between applications.

1. Introduction

The global population is predicted to rise up to 11 billion by the middle of the century, with around a third of all people concentrated in urban cities and towns (UNDESA, 2014). With this change in population dynamics, we are now faced with the pressing challenge of processing urban waste, requiring a move towards more sustainable practices (Hoornweg and Bhada-Tata, 2012). Organic waste is one of the highest contributors to municipal solid waste (MSW) in Australia, with a high potential for energy recovery from landfill biogas and advanced waste treatment of garden waste, paper and timber (Randell et al., 2014). Although a large proportion of organic waste is recycled, it is still the second highest material category for disposal rates at over 6.0 Mt, suggesting more innovative recovery methods are required to reduce this wastage (Randell et al., 2014).

Globally, coffee is the second largest commodity and produces an estimated 0.5 and 0.18 t of coffee pulp (CP) and husk (CH) respectively per tonne of fresh coffee (Roussos et al., 1995) and six million tonnes of spent coffee grounds (SCG) per year (Mussatto et al., 2011b). According to the International Coffee Organisation (ICO, 2017), annual coffee production increased from 140 to 152 million 60 kg bags since 2010, thus minimizing coffee by-products presents a serious challenge (Fig. 1). Utilizing these by-products as a base or substrate for value adding applications is an effective way to minimize their wastage as landfill.

Current value adding applications include biofuel (Woldesenbet et al., 2016), mushroom (Thielke, 1989), and fertiliser (Hachicha et al., 2012) production, along with enzyme (Battestin and Macedo, 2007), dietary fibre (Ballesteros et al., 2014), and bioactive compound extraction (Murthy and Naidu, 2012a). The feasibility of by-products for particular applications can be limited due to their composition. The presence of phenolic compounds such as caffeine and tannins limits their use in animal feeds due to their anti-nutritional properties (Low et al., 2015). Similarly, the presence of chlorogenic acid limits their application as a plant fertiliser as it is phytotoxic (Franklin and Dias, 2011). Furthermore, there is mounting evidence that these bioactive compounds are of ecotoxicological concern. Developmental, behavioral and morphological abnormalities have been observed in a variety of aquatic organisms due to exposure to caffeine and tannins, including algae, sea urchin and fish (Meriç et al., 2005; Rodriguez et al., 2014; Zarrelli et al., 2014). Chlorogenic acid has negative effects on seed germination and plant growth (Al-Charchafchi and Al-Quadan, 2010).

Bioremediation using solid-state fermentation (SSF) and submerged fermentation are potential methods for detoxifying coffee by-products

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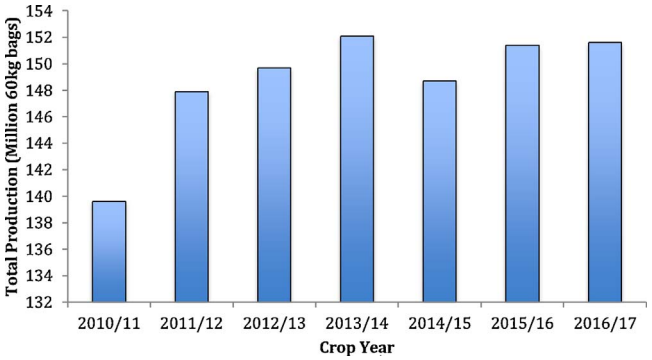

Fig. 1. Global coffee production between 2010 and 2017 obtained from the International Coffee Organisation.

while producing value added products such as enzymes (Mussatto and Teixeira, 2010). However, these methods can be costly, require technical expertise and infrastructure for operation. Composting and vermicomposting offer a simple and low-cost solution for detoxifying by-products that maximize their utilization. A study comparing bioaugmented and control mixtures of SCG showed that compost inoculated with a fungal strain (*Tinea versicolor*) displayed a reduction in volatiles, along with an increase in C and N (Hachicha et al., 2012). Similarly, Brand et al. (2000) showed that a strain of *Aspergillus* sp. had high efficiency in caffeine degradation in culture, demonstrating the high potential of microbes in the detoxification process.

There is an urgent need for applications that obtain maximum utilization of coffee by-products, and given the chemical composition of these by-products, this is highly feasible. The aims of this literature review are to 1) characterise the waste obtained from the coffee industry; 2) outline the current value adding applications and chemical composition of each component; 3) highlight limitations that prevent full utilization of coffee by-products and 4) determine the feasibility of by-product utilization and ameliorating their negative environmental impacts.

2. Coffee by-products

Coffee cherries are the fruit from coffee plants or shrubs, which belong to the family Rubiaceae. There are two commercially explored species of coffee plants, including *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta), which account for 75% and 25% respectively, of the world's coffee production (Mussatto et al., 2011b). The coffee process begins with removal of the external components of the coffee cherry, either through dry or wet methods, leaving only green coffee beans. The dry method is commonly used for Robusta and produces a husk, while the wet method is mainly used for Arabica and produces pulp as a by-product. The external components include the skin, pulp/husk and silver skin (Fig. 2), with silver skin being the main by-product of the roasting process.

2.1. Coffee pulp and husk (CP and CH)

Depending on the processing method, either wet or dry, coffee pulp and husk are the first by-products of the industrial process, and account for 29% and 12% of the overall coffee cherry (dry weight). The amount of coffee pulp and husk produced for a single tonne of fresh coffee is 0.5 and 0.18 t respectively (Roussos et al., 1995). Pulp and husk are rich in carbohydrates, mineral and proteins, however they also contain organic compounds such as tannins, chlorogenic acid and caffeine (Table 1) (Fan et al., 2003).

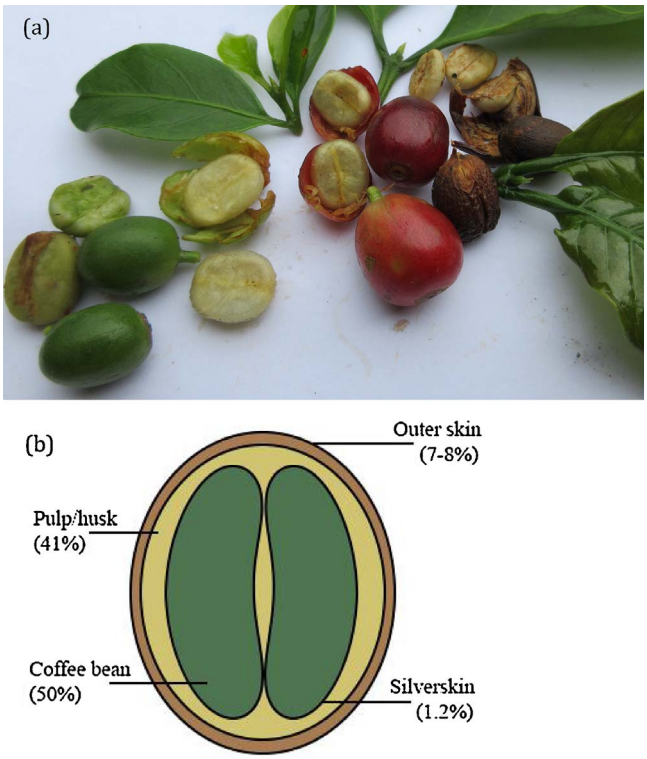

Fig. 2. Stages of coffee cherry development from immature fleshy green (left) to dried mature (right) fruits (a) and diagrammatic representation of dried mature fruits showing compositional percent (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2.2. Coffee silver skin (CSS)

The second by-product, coffee silver skin, is produced during the roasting process. The CSS is the integument of the coffee bean, and although it accounts for only a small fraction of the total coffee berry (1–2%), it is high in total dietary fibre, antioxidant activity and phenolic compounds (Murthy and Naidu, 2012a). Borrelli et al. (2004) used the gravimetric enzymatic method to determine total dietary fibre (TDF) of 62.4 per 100 g of product, with cellulose and hemicellulose the main constituents (Mussatto et al., 2011b). The composition of CSS indicates dietary fibre and antioxidant adjuncts for food industries as potential value adding applications.

2.3. Spent coffee grounds (SCG)

The coffee bean accounts for approximately 50% of the coffee cherry dry weight and produces spent coffee grounds as the final by-product of the coffee industry. SCG are generated during the production of solubilized instant coffee, whereby roasted, ground coffee beans are heat or steam treated to produce a coffee extract for consumption. The residue remaining after extracting is referred to as SCG. Annually, an estimated six million tonnes of SCG is produced worldwide (Mussatto et al., 2011a), with one tonne of green coffee producing 650 kg of SCG (Murthy and Naidu, 2012b). As urban SCG is often separated at the point of drink preparation from other wastes, it is feasible to prevent this from reaching landfill by developing coffee waste removal infrastructure.

3. Chemical composition and compounds of ecotoxicological concern

The chemical composition of coffee by-products changes substantially through dry and wet processing, roasting and brewing, with

Table 1
Chemical composition of raw and processed coffee by-products.

Component	Composition (wt%)			
	Raw fruits			Processed fruit
	Pulp	Husk	Silver Skin	Spent Coffee Grounds
Carbohydrates	44.0–50.0	57.8	44	82
Cellulose	63	43	17.9	8.6
Hemicellulose	2.3	7	13.1	36.7
Moisture	81.4	12	59.0–10.3	11.69
Lipids	2.5	1.5–2.0	2.2	6
Total fibre	18.0–21.0	31.9	62.4	60.5
Ash	8.9	6	4.7–7.0	1.6
Protein	10.0–12.0	9.2	16.2–18.6	13.6
Nitrogen	3.2	1.8	3	2.3
Caffeine	1.25–1.3	1.2	1.4	0.4
Tannins	1.8–8.6	4.5–9.3	0.02	0.02
Chlorogenic acid	10.7	12.59	15.82	11.45
References	Murthy and Naidu (2012b); Orozco et al. (1996); Pandey et al. (2000); Ulloa Rojas et al. (2003)	Brand et al. (2000); Murthy and Naidu, (2012b); Pandey et al. (2000); Shemekite et al. (2014)	Borrelli et al. (2004); Murthy and Naidu, (2012b); Mussatto et al. (2011b); Regazzoni et al. (2016)	Ballesteros et al. (2014); Hachicha et al. (2012); Kang et al. (2017); Murthy and Naidu, (2012b); Mussatto et al. (2011a); Mussatto et al. (2011b); Regazzoni et al. (2016)

major changes visible in fibre content, carbohydrates and caffeine (Table 1). The composition of CP and CH vary little in their constituents, with only small changes in composition percentages. Of particular interest for these two by-products is the tannin content, which has been reported in much higher amounts than CSS and SCG (Pandey et al., 2000). Research on tannin content is still widely debated, with many reporting inconsistent quantities for CH ranging from 4.5 to 9.3 g/100 g (Pandey et al. (2000) and Brand et al. (2000) respectively).

Variations in tannin content was due to the processing method used, with sun drying favouring superior tannin production (Brand et al., 2000). SCG contains the highest carbohydrate content at 82 g/100 g of dry material (Mussatto et al., 2011b) with the main constituents as hemicellulose (36.7 g/100 g) and mannose (21.2 g/100 g). The high carbohydrate content and high calorific power of SCG (5000 kcal/kg) suggests biofuel production as a potential value-adding process (Silva et al., 1998). However, the combustion of coffee waste results in high NOx and CO^2 emissions (Kang et al., 2017), which is known to affect global climates (Wild et al., 2001). Interestingly, all other by-products have higher cellulose compared to hemicellulose, which was reversed in SCG.

Dietary fibre had high quantities in CSS (62.4 g/100 g) and SCG (60.5 g/100 g) compared to CP (21 g/100 g) and CH (31.9 g/100 g), demonstrating their potential as fibre sources in the food industry (Toschi et al., 2014). The abundance of toxic compounds (tannins, caffeine and polyphenols) appears to decrease through the industrial processing of coffee cherries, however these compounds still present a risk to environmental pollution (Leifa et al., 2000) and pose hesitancy for unregulated usage.

3.1. Compounds of ecotoxicological concern

Many studies promote the beneficial properties of coffee beverages including antibacterial (Meckelburg et al., 2014), antioxidant (Murthy and Naidu, 2012a), anti-inflammatory and anti-obesity (Jia et al., 2014). However, the leaching of compounds such as caffeine, chlorogenic acid and tannins (Table 2) into the environment from coffee waste can have severe ecotoxicological effects (Fernandes et al., 2017). Although there are many benefits of caffeine consumption to human health, studies indicate that environmental leaching of caffeine has detrimental effects on other organisms. The toxicity of whole coffee leachate was variable and dependent on the test organism and its sensitivity to coffee compounds. Standardised toxicity tests on aquatic organisms found that the EC_{50} of coffee leachate was 6.02% v/v on *Vibrio fischeri*, lower for *Daphnia similis* at EC_{50} 1.5% (v/v) and less for *Ceriodaphnia dubia* with an EC_{50} of 0.12%. The reduced EC_{50} values visible between the bacteria and water fleas may be a result of increased exposure due to ingestion.

Although many studies have investigated caffeine concentrations in water ways (Moore et al., 2008), toxicity data is rather limited to lab simulations. There are ample studies on caffeine toxicity, but to our knowledge, no *in situ* toxicity testing has been performed on leachate from coffee producers. Furthermore, there are several points at which coffee can enter the environment such as processing/roasting or the retail consumption (spent coffee). This suggests there is a major gap in toxicity data for coffee industry waste products that requires urgent attention.

3.2. Caffeine

Caffeine is the major constituent of coffee that provides the mild stimulant effect of coffee beverages, allowing for maintained cognitive function (Toschi et al., 2014) and reduced central fatigue (Kalmar and Cafarelli, 2004). Due to caffeine's similar chemical structure to adenosine, it functions as an adenosine receptor antagonist (Fisone et al., 2004). When caffeine binds to the adenosine receptor it inhibits adenosine function, which is known to promote sleep (Basheer et al., 2004). The benefits of human consumption of caffeine include lowered risk of obesity and type two diabetes mellitus (Hino et al., 2007), a reduction in Parkinson's symptoms (Trevitt et al., 2009) and delayed onset of age-related cognitive decline and Alzheimer's disease (Carman et al., 2014).

Caffeine is toxic to aquatic organisms and mammalians and results in abnormal juvenile growth and reduced fecundity, which is a major environmental concern for higher trophic levels. At the juvenile stages, zebra fish (*Danio rerio*) have a developmental 10 h EC_{50} of 10 mM where permanent morphological abnormalities were observed (Rodriguez et al., 2014). Erratic movement and reduced touch sensitivity was also observed; interestingly effects were reversible if caffeine exposure was stopped before three hours. Similarly, chick embryos exposed to caffeine demonstrated teratogenicity effects on neurodevelopment with shortened neuron growth and disrupted proliferation (Ma et al., 2012). Caffeine also has negative effects on plant (Mohanpuria and Yadav, 2009), fungal (Miyashira et al., 2012) and bacterial growth (Sledz et al., 2015).

Table 2
Ecotoxicological data on chemical compounds of coffee waste and its toxicity on test organisms.

Compound	Test Organism[1]	Endpoint[2]	Concentration	Reference
Caffeine	*Artemia salina*[b]	LC_{50}	17800 µmol/L	Calleja et al. (1994)
	Brachionus calyciflorus[b]	EC_{50}, Population growth inhibition	104 mg/L	Zarrelli et al. (2014)
	Brachionus calyciflorus[b]	LC_{50}	24000 µmol/L	Calleja et al. (1994)
	Brachionus calyciflorus[b]	LC_{50}	1018 mg/L	Zarrelli et al. (2014)
	Ceriodaphnia dubia[b]	EC_{50}, Reproduction	44 mg/L	Moore et al. (2008)
	Ceriodaphnia dubia[b]	LC_{50}	60 mg/L	Moore et al. (2008)
	Chironomus dilutus[a]	LC_{50}	1230 mg/L	Moore et al. (2008)
	Danio rerio[b]	EC_{50}, Development	10 mM	Rodriguez et al. (2014)
	Daphnia magna[b]	EC_{50}, Mobility	822 µmol/L	Calleja et al. (1994)
	Mus musculus[a]	LC_{50} (Oral)	127 mg/kg	Lee and Wang (2015)
	Photobacterium phosphoreum[b]	EC_{50}, Luminescence inhibition	3460 µmol/L	Calleja et al. (1994)
	Pimephales promelas[b]	IC_{50}, Growth	71 mg/L	Moore et al. (2008)
	Pimephales promelas[b]	LC_{50}	100 mg/L	Moore et al. (2008)
	Streptocephalus proboscideus[b]	LC_{50}	2110 µmol/L	Calleja et al. (1994)
Chlorogenic Acid	*Arabidopsis thaliana*[a]	IC_{50}, Root growth	96.3 µM	Reigosa and Pazos-Malvido (2007)
	Artemisia herba alba[a]	EC_{50}, Shoot growth	0.15 mM	Al-Charchafchi and Al-Quadan (2010)
	Artemisia herba alba[a]	EC_{50}, Root growth	0.1 mM	Al-Charchafchi and Al-Quadan (2010)
	Artemisia herba alba[a]	EC_{50}, Germination	0.5 mM	Al-Charchafchi and Al-Quadan (2010)
	Fusarium culmorum[a]	EC_{50}, Growth inhibition	> 10 mM	Gauthier et al. (2016)
	Fusarium graminearum[a]	EC_{50}, Growth inhibition	> 10 mM	Gauthier et al. (2016)
	Hypericum perforatum[a]	EC_{50}, Shoot regeneration	50 mg/L	Franklin and Dias (2011)
Tannins	*Activated sludge*	EC_{50}, Microbial oxygen uptake rates	381 mg/L	Koyunluoglu et al. (2006)
	Danio rerio[b]	LC_{50}	> 100 mg/L	Koyunluoglu et al. (2006)
	Leuciscus idus[b]	LC_{50}	1–10 mg/L	Koyunluoglu et al. (2006)
	Phaeodactylum tricornutum[b]	IC_{50}, Growth rate	26.4 mg/L	Libralato et al. (2011)
	Phaeodactylum tricornutum[b]	IC_{50}, Growth inhibition	< 1% v/v	Babuna et al. (2007)
	Vibrio fischeri[b]	EC_{50}, Luminescence	40% v/v	Jochimsen and Jekel (1997)

[1] [a]terrestrial; [b]aquatic.
[2] EC_{50}; concentration at which a 50% decrease from the control is seen, IC_{50}; concentration at which 50% inhibition is seen compared to the control, LC_{50}; concentration at which 50% mortality is achieved.

3.3. Tannins

Tannins are traditionally associated with the leather tanning industry, and are prevalent in developing countries (De Nicola et al., 2007). These compounds are most commonly found in the bark of vascular plants, and to a lesser extent leaves, fruit, flowers and seeds (Osman, 2012). Tannins are widely accepted as an anti-nutritional compound, which limits their use in animal feed (Pandey et al., 2000). Tannins have properties beneficial to human health including antibacterial (Bors et al., 2000), antimicrobial (Cowan, 1999), anti-inflammatory (Santos-Buelga and Scalbert, 2000), anti-allergy (Bagchi et al., 2000) along with applications against cardiovascular diseases (Facinó et al., 1996). However, the beneficial properties of tannins may be affected by varying chemical structures and polymerization of tannin polymers to oligomers (Wei et al., 2012)

Tannins can be harmful, depending on the sensitivity of the organism and the concentration of exposure. Tannins affect sea urchin development (*Sphaerechinus granularis* and *Paracentrotus lividus*) and algae (*Dunaliella tertiolecta)* with increased fertilization success at low concentrations of 0.3 mg/mL but decreased when above 1.0 mg/L (De Nicola et al., 2007). Growth inhibition was seen in *D. tertiolecta* after exposure to tannins (0.1–30 mg/L) in a non-linear fashion. A similar result was found on another algal species, *Phaeodactylum tricornutum*, with an EC_{50} of 26.04 mg/L (Libralato et al., 2011). Tannins are also known for their low biodegradability (Koyunluoglu et al., 2006), thus remaining in the environment for extended periods and bioaccumulates along the food chain. Due to the health concerns of the tannery industry effluent, many studies are available on its toxicity ranging from aquaculture to aquatic ecosystems. Similar leaching occurs from the coffee industry by-products when they are released into the environment, however studies on tannins leached from the coffee industry is limited. Some industrial effluents have reported tannin concentrations above 100 mg/L (Koyunluoglu et al., 2006). This is substantially higher than many reported EC_{50} values, suggesting an urgent need for tannin removal before waste disposal.

3.4. Chlorogenic acid

Chlorogenic acid (CGA) is a soluble polyphenol formed by the esterification of caffeic acid with quinic acid (Gauthier et al., 2016), which has a plethora of properties beneficial to human health including hepatoprotective (Zhou et al., 2016), antioxidant (Sato et al., 2011), antiplatelet (Fuentes et al., 2014), anticancer (Barahuie et al., 2017) and neuronal cell death protection (Mikami and Yamazawa, 2015). However, CGA has reported synergism with plant growth regulators (PGR) such as auxins and cytokines (Franklin and Dias, 2011), along with many other plant functions. As such, CGA outside of standard concentrations results in phytotoxic effects. This has important environmental drawbacks and long-term implications if coffee is used as a fertiliser.

CGA has beneficial roles in many plant functions including cell wall synthesis (Aerts and Baumann, 1994), wound healing (Campos-Vargas and Saltveit, 2002) and root hair formation (Narukawa et al., 2009). However negative effects were observed based on CGA concentration, including reduced primary root, root hair length, the total number of root hairs (Narukawa et al., 2009) and root induction (Franklin and Dias, 2011) when CGA concentrations exceeded 50 mg/L, suggesting an optimal concentration is required for beneficial effects. Negative effects on germination occurred in *Arabidopsis thaliana* (Reigosa and Pazos-Malvido, 2007). There is also evidence suggesting that CGA has inhibitory effects on fungal growth, most likely due to its role in plant defence (Villarino et al., 2011).

4. Current value-adding processes

Utilization of coffee by-products for value addition is an essential consideration for the disposal of coffee waste and the reduction of environmental pollution. Traditional value adding applications were

Table 3
Coffee by-products, their application and efficacy.

Coffee by-product	Application	Product efficacy[1]	Reference
Coffee pulp	Amylase	2163 U/g	Murthy and Naidu (2011)
	Animal feed	NR	Nurfeta (2010)
	Caffeic acid	7.2%[b]	Torres-Mancera et al. (2011)
	Cellulase	2141 U/g	Murthy and Naidu (2011)
	Chlorogenic acid	54.4%[b]	Murthy and Naidu, (2012a)
	Compost	15C/N	Nogueira et al. (1999)
	Ferulic acid	19.8%[b]	Torres-Mancera et al. (2011)
	Mushrooms[a]	138%[a]	Velazquez-Cedeno et al. (2002)
	p-coumaric	2.3%[b]	Torres-Mancera et al. (2011)
	Pectinase	12,936 U/g	Murthy and Naidu (2011)
	Polyphenols	NR	Sera (2010)
	Xylanase	1,4765 U/g	Murthy and Naidu (2012a,b,c)
Coffee husk	Chlorogenic acid	17.5%[b]	Murthy and Naidu, (2012a)
	Citric acid	0.15 g/g	Shankaranand and Lonsane (1994)
	Ethanol	0.085 g/g	Gouvea et al. (2009)
	Gibberellic acid	0.49 mg/g	Machado et al. (2002)
	Mushrooms	85.8%[a]	Velazquez-Cedeno et al. (2002)
	Tannase	1.3–1.5 U/mL	Battestin and Macedo (2007)
	Vermicompost	NR	Sathianarayanan and Khan (2008)
	Xylanase	9475 U/g	Murthy and Naidu, (2012a)
Silver skin	Antioxidants	2.12 mmol/trolox gram dry weight	Murthy and Naidu, (2012a)
	Chlorogenic acid	25%[b]	Murthy and Naidu, (2012a)
	Dietary fibre	0.8 g/g	Murthy and Naidu, (2012a)
	fructooligosaccharides	0.7 g/g	Mussatto and Teixeira (2010)
	β-fructofuranosidase	71.3 U/mL	Mussatto and Teixeira (2010)
Spent Coffee Grounds	Antioxidants	2.04 mmol/trolox gram dry weight	Murthy and Naidu, (2012a)
	Biodiesel	NR	Kondamudi et al. (2008)
	Cellulase	2.67 U/g	Buntić et al. (2016)
	Chlorogenic acid	19.3%[b]	Murthy and Naidu, (2012a)
	Coffee oil	9.80%	Burton et al. (2010)
	Compost	14C/N	Hachicha et al. (2012)
	Dietary fibre	0.61 g/g	Ballesteros et al. (2014)
	Ethanol	6.12 g/L	Asrat et al. (2013)
	Mushrooms	88.6%[a]	Murthy and Manonmani (2008)
	Vermicompost	7.4C/N	Adi and Noor (2009)

[1] [a]Bioconversion efficacy; [b] Yield from total content; NR Not reported; C/N Carbon/nitrogen ratio.

inefficient or technically poor and included processes such as animal feed, composting and fertilisers. However, our understanding of coffee waste has developed and as such, we are beginning to optimize these applications for specific coffee by-products. The chemical composition determines the spectrum of applications that are suited to each by-product. These have focused on bioprocessing, detoxification and vermicomposting. Current applications include the production of mushroom, enzymes, organic acids, biofuels, and fertilisers (Table 3).

4.1. Mushrooms

Coffee by-products have been of interest as substrates for mushroom cultivation for nearly three decades. The initial by-product of interest for the cultivation of *Flammulina velutipes* was SCG (Song et al., 1993; Thielke, 1989). Later research expanded to the use of other by-products, such as coffee husk and pulp, which is also rich in organic content (Leifa et al., 2001), with some studies reporting biological efficacy between 125 and 138% (Velazquez-Cedeno et al., 2002). A study by Murthy and Manonmani (2008) found that a mixture of SCG, coffee cherry waste and coffee leaves had a bioconversion efficacy of 152%. Furthermore, the protein content of CH and SCG increased after the cultivation *F. velutipes*, as did the fibre content of CH (Leifa et al., 2001). Caffeine and tannin content is also reduced without any evidence of their presence in the fruiting body of the fungi, suggesting it is degraded in the cultivation process. Detoxification of coffee husk has important implications as these compounds limit its application in livestock feed and bioprocesses. Approximately 73% of the substrate will be utilised during mushroom cultivation, the remaining substrate can be further used as compost to produce a fertiliser for soils (Martínez-Carrera et al., 2000).

4.2. Enzymes

Two methods, solid-state fermentation (SSF) and submerged fermentation (SmF), dominate industrial enzyme production. The solid supports found in SSF can be inert materials such as industrial residues like coffee by-products. SSF is advantageous in the cultivation of fungi as the residues used can act as a carbon source for the production of enzymes (Torres-Mancera et al., 2011). A recent study explored the feasibility of SCG as a substrate for cellulase production by *Paenibacillus chitinolyticus* and achieved 71% yield under optimal conditions using a batch-adsorption system (Buntić et al., 2016). Similar studies have investigated feasibility and extraction optimisation on enzymes such as tannase (Battestin and Macedo, 2007), xylanase (Murthy and Naidu, 2012a), pectinase (Ngo and Phan, 2016), and β-fructofuranosidase (Mussatto and Teixeira, 2010).

4.3. Biofuels

Coffee by-products have excellent potential for ethanol production. Machado (2009) treated SCG with acid hydrolysis and fermented the hydrolysate with *Saccharomyces cerevisiae* and achieved a 50% yield. Gouvea et al. (2009) performed a similar experiment on CH but with a yield of only 8.5% (dry basis), possibly due the higher concentrations of caffeine and tannins. The potential of CP was further improved using an acid hydrolysis method, followed by fermentation with *Pichia anomala* achieved 78% yields of ethanol (Woldesenbet et al., 2016).

The concentration of ethanol produced from CP (6.12 g/L) was

more successful than poultry manure (5 g/L), but not as efficient as banana peels (9.8 g/L) or sugarcane (10.2 g/L). These high yields suggest coffee by-products are viable substrates for ethanol production. Similar studies on the feasibility of coffee waste for biodiesel and biogas production have yielded promising results. Oil has been extracted from SCG and converted to biodiesel with a 10–15% yield, where 100% of this oil was converted to biodiesel (Kondamudi et al., 2008). More recent studies have returned similar findings of biodiesel yields up to 16% using SCG and suggested an estimated 700,000 t of biodiesel could be produced from the 5,817,500 t of SCG waste annually (Park et al., 2016).

4.4. Organic acids

Organic acids such as citric and gibberellic acid (plant hormone) have been produced using coffee by-products as a substrate. Shankaranand and Lonsane (1994) used SSF with *Aspergillus niger* to produce an 82% yield of 1.5 g citric acid/10 g dry CH. SSF was also used in the production of gibberellic acid from *Gibberella fujikuroi*. Machado et al. (2002) determined that a mixture of CH and cassava bagasse obtained optimal results with 492.5 mg/kg of dry CH. Few studies are available for comparison of results, possibly due to their limited applications.

4.5. Bioactive compounds

There are many human health benefits associated with bioactive compounds, such as the phenolics previously described (chlorogenic acid and caffeine) including antibiotic, anti-inflammatory, hepatoprotective, antioxidant and cognitive improvement. These compounds occur in small quantities in foods and plant material, however agro-industrial by-products such as coffee waste are an excellent source of phenolics. Typically, bioactive compounds are obtained using solid-liquid extraction. Martins et al. (2011) also described the potential of SSF for bioactive recovery, which provided high quality bioactive extracts while avoiding any toxicity associated with organic solvents used in other methods. A recent study by Al-Dhabi et al. (2017) assessed for the first time the feasibility of phenolic extraction from SCG using ultrasound-assisted solid-liquid extraction (USLE). Using optimal conditions, they were able to obtain a total phenolics yield of 3.6%. This is nearly a six-fold increase in extraction compared to a SSF extraction performed by Machado et al. (2012), who obtained 7 mg of phenolic compounds per gram of SCG using *Penicillium purpurogenum*. The removal of these phenolics from SCG, which are of ecotoxicological concern, opens new possibilities for their use as fertilisers. Due to the organic nature of phenolic extraction substrates, this is an industrial and economically feasible solution as a single collection method could turn waste into a viable product. However, the composting process could be time consuming and require adequate space, thus warranting further research.

4.6. Dietary fibre

Dietary fibre (DF) promotes gastrointestinal health, reduces the risk of cardiovascular disease and obesity, with the recommended fraction ratio of 1:2 soluble/insoluble dietary fibre (Figuerola et al., 2005). DF includes a variety of non-starch polysaccharides such as cellulose, hemicellulose and lignin. SCG and CSS both have high proportions of DF (60.46 and 54.11% w/w), consisting of nearly five-fold more insoluble DF (IDF) than soluble DF (SDF) (Ballesteros et al., 2014). Coffee fibres have antioxidant activity (obtained by using a standard solution of trolox), with CSS slightly higher than SCG at 2.12 and 2.04 mmol of trolox equivalent/100 g of dry weight respectively (Murthy and Naidu, 2012a). The extraction efficacy of DF from coffee wastes is unknown. High DF content is also associated with high water holding capacity (WHC), which could be beneficial in its application as a fertiliser.

4.7. Composting and vermicomposting

Composting and vermicomposting provide a low-cost solution to agro-industrial waste, which create nutrient-rich fertilisers for increased plant productivity. Currently, CP is considered the most time efficient using conventional turning methods and will compost in three weeks (Murthy and Naidu, 2012b). Other materials, such as SCG have decomposition times of ninety days or more possibly as a result of the roasting process. Adi and Noor (2009) vermicomposted SCG following a twenty one day pre-treatment of composting. In all treatments amended with SCG, there was an increase in nutrient elements such as nitrogen and potassium, demonstrating their potential as a high-quality fertiliser.

Microorganism inoculation is a novel approach to increase the speed and quality of SCG composting. Hachicha et al. (2012) inoculated the compost with the white-rot fungus, *Trametes versicolor,* resulting in a mature final compost with reduced phenolic compounds that produced a germination index of 120% for barley in less than 20 weeks. The germination index was obtained using Eq. (1) (Hachicha et al., 2012).

$$\%GI = \frac{\%G \cdot \%L}{100} \quad (1)$$

Where %G: germination in treated relative to control compost; %L: root length in treated relative to control compost. Jiménez and Garcia (1989) suggested a germination index of greater than 80% for a mature compost, free of phytotoxic chemicals. Composting and vermicomposting appear to have great potential in converting whole by-products into value added materials in the form of a nutrient-rich fertiliser. If a waste infrastructure at an industrial level was designed specifically for commercial coffee waste (SCG) collection, it could produce a lucrative product from a low cost substrate, while reducing the negative environmental impacts of the coffee industry.

5. Overview and future directions

The chemical composition of coffee by-products varies only slightly, however these small differences can have great limitations to their value adding applications. The high phenolic content of CH and CP make them the most effective for phenolic extraction, while it limits their use as substrates for bioprocesses and compost/vermicompost. The high fibre content of SCG and CSS has great potential for dietary fibre supplements. More over, the antioxidant activity of these fibres could be utilized as antioxidant adjuncts for food processing. Their reduction in phenolics, compared to CH and CP, make them a more suitable substrate for bioprocesses such as enzyme production.

However, there appears to be a major gap in waste utilization at the commercial end of the coffee industries. There is strong evidence to suggest SCG and CSS has great potential as a horticultural fertiliser. Furthermore, SCG and CSS accounts for over 50% of the total waste produced by the coffee industry, thus is a large supply. Given that 100% of this waste could be converted to a nutrient rich fertiliser, it is concerning that there is currently no infrastructure in place to deal with this large supply. By-product utilization requires urgent attention if we are to ameliorate the ecotoxicological and environmental impacts of coffee waste.

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