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Study Review

Coffee phytochemicals and post-harvest handling—A complex and delicate balance

Leah M. Munyendo, Daniel M. Njoroge *, Eddy E. Owaga, Beatrice Mugendi

Institute of Food Bio-resources Technology, Dedan Kimathi University of Technology, Private Bag, 10143, Dedan Kimathi, Nyeri, Kenya

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ABSTRACT

The balance between coffee phytochemicals and post-harvest handling is complex and delicate since these compounds are affected either negatively or positively. Studies have shown positive health effects arising from regular consumption of coffee, which are linked to phytochemicals present in the coffee bean. However, phytochemicals must be available in considerable amounts at the time of consumption in order for them to confer the beneficial health effects. This review aims at summarizing the available literature on the impact of coffee processing steps on the content as well as sensory and functional characteristics of phytochemicals. The phytochemicals in coffee include, majorly: Chlorogenic acids, caffeine, diterpenes and trigonelline. Literature reveals that variation in coffee post-harvest handling techniques such as degree of roast, processing method, brew preparation method and parameters results into brew with varied sensory and functional properties. This could be majorly attributed to the variation in the phytochemicals content in the cup. Further research on how coffee phytochemicals are affected during post-harvest handling practices would unlock the health benefits of this popular beverage and immensely benefit the consumer.

1. Introduction

Coffee species are evergreen shrubs belonging to *Rubiacea* family, the largest plant family worldwide consisting of 450 genera and 6500 species (Wiart, 2006). According to the Food and Agriculture Organization, coffee is the fourth most valuable agricultural traded commodity and the most consumed beverage globally (Pendergrast, 2009). A report by International Coffee Organization (ICO) shows that production of coffee globally in 2016 was approximately 151 million bags with an export value of twenty billion dollars (ICO, 2016). Stimulant effects of caffeine and desirable sensory properties have been emphasized as factors that contribute to the coffee beverage popularity worldwide (Camargo et al., 1999). Many previous studies have reported positive effects associated with regular coffee consumption, which has been attributed to the presence of bioactive phytochemicals in the coffee bean. Phytochemicals are described as substances with biological activity mainly produced by plants (Mendoza and Silva, 2018). Some of the reported positive effects are on neurological conditions (Parkinson's and Alzheimer disease), psychoactive responses (learning capacity, alertness, and mood change), and metabolic disorders for instance diabetes and reduced risk of gallstone disease development (Larsson and Wolk, 2007; Ranheim and Halvorsen, 2005; Salazar-Martinez et al., 2004).

The positive effects of phytochemicals present in the coffee bean are linked to their biological activities such as radical scavenging and antioxidant activities, anti-carcinogenic and hepatoprotective properties (Moura-Nunes et al., 2009; Lee et al., 2007; Cavin et al., 2002). Examples of phytochemicals in coffee include chlorogenic acids, caffeine, ferulic, caffeic, p-coumaric acid, diterpenes, trigonelline and proanthocyanidins (Moeenfard et al., 2016; Narita and Inouye, 2015; Belitz et al., 2009; Richelle et al., 2001). In addition to the functional properties, phytochemicals have been highlighted as quality precursors implying that they play a significant role in cupping characteristics of the coffee beverage (Ribeiro et al., 2016; Farah et al., 2005b). For example, the roasting process results in the degradation of trigonelline into pyrroles and pyrazines that impacts the aroma and flavor, positively (Fassio et al., 2016; Ky et al., 2001). Chlorogenic acids, on the other hand, are degraded into compounds with low-molecular-weight such as cathecols and phenols which are later incorporated into melanoidins thus contributing to the development of color and flavor in the roasted bean (Farah et al., 2006).

* Corresponding author.
E-mail addresses: leahmunyendo@gmail.com (L.M. Munyendo), daniel.njoroge@dkut.ac.ke (D.M. Njoroge), eddy.owaga@dkut.ac.ke (E.E. Owaga), bmugendi@ymail.com (B. Mugendi).

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The balance between post-harvest handling of coffee and equivalent phytochemicals may be described as complex and delicate. These compounds are affected differently at different stages of processing from farm to cup. For instance, wet-processed coffees, which undergo a fermentation process, have a different chemical composition from dry-processed coffees. One of the hypotheses for these differences is the metabolic processes, which are specific to each type of post-harvest treatment (Selmar et al., 2006). During coffee roasting, a percentage of some phytochemicals are degraded to other compounds to produce coffee with desirable sensory properties (Ribeiro et al., 2016; Farah et al., 2005b). However, it should be noted that phytochemicals must be available in considerable amounts at the time of consumption in order for them to confer beneficial health effects. Another important factor that determines the levels of phytochemicals consumed is the preparation methods and parameters of the brew (Moeenfard et al., 2014a, 2014b; Niseteo et al., 2012; Ludwig et al., 2012). Therefore, this review aims at demonstrating the complex and delicate balance between post-harvest handling processes of coffee and phytochemicals by giving a summary of current studies that highlight the impact of different practices on the corresponding phytochemicals.

2. Phytochemicals in coffee

Coffee has been reported as a major source of phytochemicals including phenolic compounds, alkaloids as well as terpenoids (Song et al., 2018; Kitzberger et al., 2016; Ribeiro et al., 2016; Vignoli et al., 2014). The following section describes some of the important phytochemicals in coffee.

2.1. Chlorogenic acids

Chlorogenic acids (CGAs) make up the chief phenolic compounds present in coffee beans. The acids are an ester derived from esterification between *trans*-cinnamic acids such as ferulic, *p*-coumaric and caffeic with (-)-quinic acid (Narita and Inouye, 2013). Feruloylquinic, dicaffeoylquinic, *p*-coumaroylquinic, caffeoylquinic and caffeoylferuloyl quinic acids are among the sub-classes of chlorogenic acids that have been reported in coffees (Clifford et al., 2003). Three major sub-classes of CGA includes; 3-di-caffeoylquinic acid (3-diCQA), caffeoylquinic acids (CQA) and feruloylquinic acid (FQA), representing approximately 80 %, 15 % and 5 % of total CGAs in Arabica coffee and 67 %, 20 % and 13 % in Robusta coffee respectively (Farah et al., 2008; Ky et al., 2001). Generally, the total content of CGA in beans varies depending on the coffee variety, degree of maturation and geographic location where coffee is grown (Narita and Inouye, 2015). Based on the variety, a lot of literature has highlighted Robusta coffee as having a higher chlorogenic acid content compared to Arabica coffee. Song et al. (2018) reported the chlorogenic acid content of Robusta coffee bean to be 19.42 %, which was higher than one recorded for Arabica coffee (15.72 %). Similarly, Ribeiro et al. (2016) reported similar findings with the isomer 5-caffeoylquinic acid (5-CQA) recording the highest amounts compared to other chlorogenic acids that were identified.

Considering the degree of maturity, the main isomers of CGAs, i.e. 5-CQA and 3-diCQA, change in their content in relation to maturity. Isomer 5-CQA mainly accumulates in immature coffee cherries and radically decreases upon maturity. A decrease of diCQA (chiefly di3,5-CQA) from 8.4 % in unripe coffee cherries to 2.3 % in ripe cherries was observed; on the contrary, minor components, for instance, 4-caffeoylquinic acid (4-CQA) as well as 3-caffeoylquinic acid (3-CQA), accumulated gradually throughout the maturation of the bean (Joet et al., 2010; Lepelley et al., 2007). Other studies have been carried out to compare the total phenolic content of different parts (seed and pericarp) of coffee species with an aim of finding novel natural antioxidants sources for nutraceuticals. The immature pericarp of Liberian and Bengal coffee species reported the highest phenolic content of 0.148 % and 0.142 %, respectively, which was directly linked to the content of CGA (Patay et al., 2016).

2.2. Diterpenes

Diterpenes are described as pentacyclic alcohols owing to the fusion of isoprene units to form a skeleton of twenty kauren carbons. Kahweol ($C_{20}H_{26}O_3$) and cafestol ($C_{20}H_{28}O_3$) are the two main diterpenes that have been isolated from green and roasted coffee beans, brews and oils (Kitzberger et al., 2013; Moeenfard et al., 2016). Kahweol differs from cafestol due to the presence of unsaturation points between carbon number one and two resulting in a spectrum with maximum peak absorption at a different wavelength (Speer and Kölling-Speer, 2006). The diterpenes content in coffee beans is chiefly species dependent with *Coffea arabica* having more cafestol than *Coffea canephora* (Speer and Kölling-Speer, 2006). Generally, the composition of coffee diterpenes is approximately 0.2–1.5 % and 1.3–1.9 % (w/w) of green beans of Robusta and Arabica coffee, respectively (Araujo and Sandi, 2006). Kahweol is specific to Arabica coffee species or detected only in traces in Robusta coffee (Dias et al., 2010). Thus, its concentration has been reported as a likely factor of discrimination between coffee species in Arabica coffee and Robusta coffee blends (Dias et al., 2010).

The differences in diterpenes content could also be attributed to cultivation and geographic conditions (Sridevi et al., 2010). Other than the variations of the diterpenes content between *Coffea* species, other studies have highlighted the variations among cultivars of the same species. Kitzberger et al. (2013) conducted a study on four different *Coffea arabica* cultivars and the cafestol content ranged from 221 to 604 mg/100 g. Moreover, kahweol showed higher variations with a range between 371 and 986 mg/100 g. Among the cultivars analyzed, cultivar IPR 106 and IPR 100 contained higher kahweol content as compared to other cultivars. Similar findings were also observed for *Coffea robusta* species where three cultivars studied (Diamante, Jequitibá and Centenária) showed variations in the kahweol levels ranging from absent (below quantification limits of 3.2 mg/100 g) to 5.3 mg/100 g while that of cafestol ranged from 200 to 264 mg/100 g (Mori et al., 2016).

2.3. Caffeine

Caffeine (1,3,7-trimethylxanthine) is a bitter-tasting purine alkaloid synthesized in some groups of higher plants, for instance, tea (*Camellia sinensis*) and coffee. This alkaloid accounts for less than 10 % of the perceived coffee beverage bitterness (Smith, 2005). Its biosynthesis in coffee plants occurs in the pericarp and the upper leaves followed by accumulation in the mature leaves. Upon the start of seed formation, the accumulated caffeine is trans-located through the membranes into the endosperm (Ashihara and Crozier, 2001). Caffeine accumulation is highly dependent on the genotype as well as the environment in which coffee is grown. Among the commonly cultivated *Coffea* species, that is, Arabica and Robusta, the content of caffeine in the Robusta beans is approximately double that found in Arabica (Belitz et al., 2009). Other than the genotype, the environment also significantly influence the caffeine accumulation and its final concentration in the bean.

Some researchers have reported an increase in the content of caffeine with an increment of the shade levels from 0 to 45 % in Arabica coffee cv K7 beans. Similar findings were observed during the second year of study (Vaast et al., 2006). An increase in shade of 30, 50, 70 and 80 %, showed a constant caffeine content improvement in Arabica coffee cv Costa Rica 95 beans as compared to the treatment that was fully under the sun (Odeny et al., 2016). Caffeine content has also been studied in leaves where the leaves of *Coffea eugenioides, Coffea salvatrix* and *Coffea bengalensis* showed 3–7 times less caffeine content than those from *Coffea arabica* (Ashihara and Crozier, 1999).

2.4. Trigonelline

Trigonelline is the second most abundant alkaloid after caffeine in

raw coffee beans. It is biologically derived from enzymatic methylation of the nitrogen atom of nicotinic acid thus the name N-methyl nicotinic acid (Allred et al., 2009). Being a derivative of pyridine, trigonelline is a precursor of aroma contributing to the desired flavor compounds produced during roasting of coffee, for instance, furans, pyrazine, pyrroles and alkyl-pyridines (Clifford, 1985; De Maria et al., 1996). The content of trigonelline majorly depends on the variety of coffee, but also on the implemented extraction and dosage methods during analysis. Robusta coffee has less trigonelline than Arabica coffee with 0.7–1.24 % and 0.80–1.82 %, respectively (Bicho et al., 2013; Fassio et al., 2016).

In addition to the commonly cultivated coffee species which has been highly investigated, a study of trigonelline content on fourteen wild coffee species reported a trigonelline content that ranged from 0.39 to 1.77%. Differences were highly significant between species, which represented 82 % of the total variance (Campa et al., 2004). The content of trigonelline is also dependent on the environmental conditions of the region where coffee is grown. Lower trigonelline levels were observed in coffee beans grown under the shade (Vaast et al., 2006). Nevertheless, the decrease in content in relation to the increase in shade levels was non-linear. Odeny et al. (2016) reported a decline in trigonelline content with an increment of shade levels of 0–30 %, 50 % and 70 %, which was then followed by a reduction at 80 % shade.

3. Correlation between phytochemicals and sensory characteristics

Coffee beverage quality is dependent on the flavor acquired during the roasting process where chemical compounds present in unroasted coffee beans are involved in chemical and physical reactions. Some of these compounds have been described in the literature as potential sensory quality descriptors of coffee as evidenced in Table 1 (Ribeiro et al., 2016; Farah et al., 2005b). Chlorogenic acids undergo numerous transformations during the process of roasting including lactonization, epimerization, isomerization resulting in their degradation to low-molecular-weight compounds such cathecols and phenols. These compounds are later incorporated into melanoidins, which contributes to the development of color and flavor in the roasted bean. Chlorogenic acids have been reported to confer bitterness, astringency, as well as acidity to the coffee brew. However, Farah et al. (2006) noted that high amounts of some sub-classes of chlorogenic acids (caffeoylquinic and feruloylquinic acids) in green coffee bean might lead to the production of objectionable flavor, probably owing to degradation as well as oxidation products formed prior to roasting. During roasting, chlorogenic acids are also degraded into chlorogenic acid lactones because of the water molecule loss from quinic acid moiety. These lactones significantly contribute to the coffee beverage bitterness, which is a significant aspect of quality (Farah et al., 2005a).

Coffee oils mainly kahweol and cafestol occur in esterified form with fatty acids, such as, linoleic acid, which contributes to the bitterness of the coffee beverage. Fatty acids composition in specialty coffee is significant in bringing about mouthfeel characteristics such as texture and body and vital aroma as well as flavor compounds to the beverage (Fassio et al., 2017). Caffeine accounts for less than ten per cent of the perceived coffee beverage bitterness, which has been noted to be important for the flavor of coffee (Stoll et al., 1967). Farah et al. (2005b) conducted a study on the correlation between chemical components in green beans and the cup quality. The levels of 3,4-dicaffeoylquinic acid and trigonelline in unroasted and roasted coffee showed a strong correlation with high cup quality. The caffeine levels were linked to good cup quality but to a lesser extent. Gimase et al. (2014) reported a significant ($p \leq 0.05$) association between sugar levels and flavor, fragrance, aftertaste and overall quality of the cup while trigonelline showed a significant ($p \leq 0.05$) negative association with the cup's body. Other studies have also reported trigonelline to be having a positive association with qualities related to sensory characteristics such as flavor, acidity and sweetness (Fassio et al., 2017). Trigonelline plays a key role in the brew's bitterness and it is a precursor for the development of various classes of volatile compounds during coffee roasting for instance pyridines and pyrroles, some of which as stated by Stoll et al. (1967) might confer unpleasant flavor. In addition, the component has also been highlighted to indirectly contribute to the development of desired aromas during the process of roasting since it is degraded to pyrazines and pyrroles which have positive flavor and aroma qualities (Fassio et al., 2016; Ky et al., 2001).

4. Phytochemicals determinant of functional characteristics

There has been increased coffee consumption globally owing to its desirable sensory properties (taste and aroma), stimulant effects of caffeine and functional characteristics. Several reports on coffee show that it can exert beneficial effects against cancer, diabetes, cardiovascular disease and obesity (Cavin et al., 2002; Larsson and Wolk, 2007; Salazar-Martinez et al., 2004). These effects are linked to the biological activities of the phytochemicals present in coffee bean including antioxidant activity, anti-carcinogenic properties and hepatoprotective properties (Cavin et al., 2002; Lee et al., 2007; Moura-Nunes et al.,

Table 1
Summary of studies in literature highlighting the role of phytochemicals on sensory and functional characteristics of coffee.

Phytochemicals	Functional characteristics		Sensory characteristics	Reference
	Biological activities	Target disease & health effect		
Chlorogenic acids	Anti-oxidant and anti-inflammatory activity	prevent DNA and tissue damage, liver disease, obesity	Contributes to color, flavor, bitterness, astringency and acidity of the beverage.	Liang and Kitts (2016); Shin et al. (2015); De Magalhaes et al. (2012); Yang et al. (2017); Tan et al. (2016); Ma et al. (2015); Farah et al. (2005a).
	Anti-mutagenic and anti-carcinogenic effect	cancer; prevent tissue damage		Valko et al. (2007); Ramos (2008); Hoelzl et al. (2010).
	Anti-diabetic effect	type-2 diabetes mellitus disease		Huxley et al. (2009); Battram et al., 2006; Karthikesan et al. (2010); Kempf et al. (2010).
	Anti-microbial effect			Almeida et al. (2006); Antonio et al. (2010).
Diterpenes	Antioxidant activity	Prevent DNA damage	Significant to the bitterness, body, aroma and flavor of the beverage.	Lee and Jeong (2007); Huber et al. (2003); Fassio et al. (2017).
	Anti-inflammatory effect	Prevent tissue damage		Cárdenas et al., 2011; Kim et al. (2012).
Caffeine	Hepatoprotective and anti-oxidant effect	Prevent cell damage	Contributes to bitterness and flavor of the beverage.	Machado et al. (2014); Ruhl and Everhart (2005); Lee (2000); Stoll et al. (1967).
	Antimicrobial effect			Almeida et al. 2006; 2012).
Trigonelline	Anti-diabetic effect	type 2 diabetes	Important to the flavor, bitterness, acidity and sweetness of the beverage.	Lin et al. (2011); Zhang et al. (2009); Zhou et al. (2013); Fassio et al. (2017).
	Anti-carcinogenic effect	colon and pancreatic cancer		Hirakawa et al. (2005); Arlt et al. (2013).

2009). Farah (2017) noted that the contributions of coffee to reduced risk of some diseases are mostly because of synergistic effects of the different compounds present in coffee. A summary of the functional properties of major phytochemicals present in coffee is presented in Table 1.

Studies on the ability of CGAs to scavenge free radicals (antioxidant activity) using cell-based assays, animal models as well as chemical-based assays have been reported in the literature (Liang and Kitts, 2016). Among important free radicals endogenously generated because of mitochondrial respiration includes reactive nitrogen species and reactive oxygen species (Davis et al., 2010). These compounds have the ability to oxidise important biomolecules in our body (Halliwell and Gutteridge, 2007). The CGAs are important dietary anti-oxidants capable of serving as non-enzymatic anti-oxidants thus conferring health benefits. These health benefits have been reported to emanate from the ability of CGAs to donate hydrogen atoms leading to reduction of free radicals as well as inhibition of oxidation reactions (Liang and Kitts, 2016). Moreover, these acids have an important role in the prevention of low-density lipoprotein oxidation brought about by different oxidizing agents (Gordon and Wishart, 2010) and prevent deoxyribonucleic acid (DNA) damage *in vitro* (Cinkilic et al., 2013). In addition, they can chelate transition metals for instance Fe^{2+} for them to scavenge free radicals and cause interruption to their chain reactions (Upadhyay and Mohan Rao, 2013).

Another important biological activity of CGA that has been reported by several authors is its anti-inflammatory activity (Shin et al., 2015; Liang and Kitts, 2016). According to Liang and Kitts (2016), inflammation is a complex physiological response to tissue injury induced by either endogenous or exogenous inducers (sources). A controlled inflammatory response is required in our bodies to fight these inducers resulting in the return of tissue homeostasis. Nonetheless, an imperfect regulation of inflammatory response may bring about effective resolution failure, consequently resulting in excessive tissue damage and chronic or acute disease states (Elenkov et al., 2005). Some studies have shown that CGAs exerts a strong anti-inflammatory effect by reducing pro-inflammatory cytokine secretion such as interleukins 8 and 6 (IL-8 and IL-6) in Caco-2 cells which are stimulated with tumour necrosis factor-alpha (TNF-α), lipopolysaccharide (LPS), interferon-γ (IFN-γ), and interleukin-1β (IL-1β) (De Magalhaes et al., 2012). In another cell study conducted by Shan et al. (2009), the anti-inflammatory effect of CGAs on murine RAW 264.7 macrophages was shown to result from suppression of LPS-induced cyclooxygenase-2 (COX-2) expression by weakening the activation of c-Jun N-terminal kinase/ activator protein-1 (JNK/AP-1) and factor nuclear kappa B (NF-κB) signalling pathways. Shin et al. (2015) conducted in vivo study on the effect of CGAs using dextran sulphate sodium (DSS)-induced colitis in mice. From the findings, CGA was reported to attenuate DSS-induced loss of body weight, diarrhoea, faecal blood, as well as colon shortening and significantly improved colitis histological scores. Additionally, CGA supplementation significantly suppressed the increase in the mRNA expression of IL-1β and colonic macrophage inflammatory protein 2 because of dextran sulphate sodium inducement. These findings point to the ability of dietary CGA in preventing intestinal inflammatory conditions.

Anti-mutagenic and anti-carcinogenic effects of CGA have also been reported in the literature (Farah, 2017; Ramos, 2008). Studies have pointed to the fact that CGA is an eff ;ective electrophilic trapping agent possessing beneficial eff ;ects against diseases whose pathogenesis encompasses augmented oxidative stress as well as damage (Newmark, 1984; Valko et al., 2007). Several chemopreventive action mechanisms of CGA in respect to its anti-mutagenic property have been reported in the literature. These mechanisms include modulation of enzyme expression significant in endogenous antioxidant defences, replication of DNA, cell ageing and cell differentiation (Feng et al., 2005; Ramos, 2008; Jurkowski & Jeltsch, 2011), reactive compounds inactivation, chelation of metal, and changes of metabolic pathways (Kasai et al., 2000). Ramos (2008) reported that CGA has the ability to prevent the initiation step of cancer through inhibition of DNA damage resulting from free carcinogenic agents or radicals. A study conducted by Hoelzl et al. (2010) revealed that consumption of coff ;ee with high levels of CGA reduced 3-nitrotyrosine by 16.1 % and 8-isoprostaglandin F2α by 15.3 %, therefore revealing CGA's protective eff ;ect against the damage brought about by free radicals.

Chlorogenic acids have also been shown to have beneficial effects against liver disease. Yang et al. (2017) reported a possibility of CGA relieving liver fibrosis disease through inhibition and regulation of MicroRNA-21-regulated TGF-β1/Smad7 signalling pathway. According to Cui et al. (2010), transforming growth factor β1 (TGF-β1) is a major profibrotic cytokine involved in the liver fibrosis process while the signalling pathway of TGF-β-Smad is a significant signal transduction pathway in hepatic fibrosis. Therefore, the regulation of the TGF-β-Smad signalling pathway and the inhibition of TGF-β1 expression are effective methods for liver fibrosis prevention (Bai et al., 2016). In another study conducted by Shi et al. (2016), CGA was evaluated for its ability to prevent carbon tetrachloride (CCl_4)-induced liver fibrosis. This was done through improvement of anti-oxidant capacity via activation of nuclear factor erythroid-2-related factor-2 (Nrf-2) pathways and suppression of platelet-derived growth factor-induced profibrotic action via inhibition of nicotinamide adenine dinucleotide phosphate oxidase, reactive oxygen species (ROS) and mitogen-activated protein kinase (MAPK) pathways. CGA protected against CCl_4-induced liver fibrosis via oxidative stress suppression in hepatic stellate cells as well as in the liver. Tan et al. (2016) investigated the ability of CGA in inhibiting cholestatic liver injury induced by α-naphthylisothiocyanate (α-ANIT). From the findings, it was revealed that CGA inhibits both liver injury as well as ANIT-induced intrahepatic cholestasis through signalling of nuclear factor kappa B (NFκB) and signal transducer and activator of transcription 3 (STAT 3) down-regulation.

Chlorogenic acids have also been shown to have an anti-diabetic effect since they have a significant role in the metabolism of glucose in our bodies (Battram et al., 2006; Karthikesan et al., 2010). Huxley et al. (2009) observed a 30 % risk reduction of type-2 diabetes mellitus disease in individuals who drunk three to four cups of decaff ;einated coff ;ee with high CGA content. On the contrary, a study conducted by Kempf et al. (2010) on the effects of coffee consumption on subclinical inflammation and other risk factors for type 2 diabetes showed no changes in the metabolism of glucose with coffee consumption. According to Ogden et al. (2007), obesity is one of the major risk factors of cardiovascular diseases and it is a global health concern, recently. Epidemiological studies have shown that the consumption of both decaffeinated and regular coffees is linked to loss of body weight (Lopez-Garcia et al., 2006; Greenberg et al., 2005) and the major compound associated with this positive effect is CGA (Thom, 2007). The mechanism linked to the anti-obesity properties of CGA relates to its ability to demonstrate a major improvement in the tolerance of glucose that could be a result of body mass index reduction as well as its eff ;ects on body weight (Rodriguez de Sotillo et al., 2006). On the other hand, Ma et al. (2015) noted that CGA, specifically 5-CQA, scavenges reactive ROS as a result of high-fat diet consumption thus suppressing inflammation expression. This, therefore, results in a reduction of fat accumulation, insulin resistance as well as weight gain.

Anti-microbial effects of coffee extracts and CGA on some harmful microorganisms that might grow on different parts of our body have also been reported in a number of studies. Almeida et al. (2006) conducted a study on the antibacterial activity of coffee extracts and selected coffee chemical compounds against Enterobacteria. The findings demonstrated the anti-microbial activity of the samples against the nine enterobacteria investigated. Chlorogenic acids, protocatechuic acid and caffeine demonstrated a strong effect against *Enterobacter cloacae* and *Serratia marcescens*. In another study, 5-caffeoylquinic acids showed a bacteriostatic effect against *Streptococcus mutans* with a minimum inhibitory effect of 0.8 mg/mL. However, at this concentration, no bactericidal activity was observed (Antonio et al., 2010).

Some studies exploring the association between coffee diterpenes and health benefits have been published. Diterpenes have shown their effectiveness in protecting against damage of DNA and hydrogen peroxide (H_2O_2)-induced oxidative stress by scavenging free oxygen radicals due to their antioxidant activity (Lee and Jeong, 2007). In this study, the effects of cafestol and kahweol were investigated on the H_2O_2-induced oxidative stress and damage of DNA in NIH_3T3 cells. The findings showed a significant reduction in lipid peroxidation, cytotoxicity and ROS production induced by H_2O_2 upon treatment of the cells with cafestol or kahweol in a dose-dependent manner. Similarly, some researchers have described kahweol and cafestol as inhibitors of cytochrome P450, an enzyme responsible, among other factors, for carcinogen activation and therefore leading to DNA damage (Cavin et al., 2002; Huber et al., 2003). Coffee diterpenes have also been reported to have anti-inflammatory effects. Cárdenas et al. (2011) demonstrated the ability of diterpene kahweol to reduce monocyte chemo-attractant protein-1 (MCP-1) secretion, an inflammatory regulator and expression of cyclooxygenase-2 (COX-2), a pro-inflammatory enzyme, in human umbilical vein endothelial cells. In another study, inhibition of the constitutive phosphorylation as well as transcriptional activity of STAT-3, a transcription factor important in proliferation, inflammation and angiogenesis was observed upon treatment of MDA-MB-231 cells with 10 μM of kahweol (Kim et al., 2012). On the contrary, some observational studies have linked coffee diterpenes to increased concentrations of low-density lipoproteins cholesterol and serum total cholesterol (Jee et al., 2001).

Caffeine, an alkaloid in coffee, has also been reported to have a hepatoprotective effect, as it possesses protective mechanisms that prevent oxidative stress damage and apoptosis of cells owing to activation of anti-inflammatory systems and natural antioxidants (Machado et al., 2014). According to these researchers, consumption of caffeine above 123 mg per day was linked to decreased hepatic fibrosis affirming its hepatoprotective effect. The mechanism underlying caffeine's potential protective effect against liver disease relates to its ability to lower the risk of elevated activity of alanine aminotransferase enzyme in the body (Ruhl and Everhart, 2005). Metabolites of caffeine particularly 1-methylurate and 1-methylxantine have demonstrated antioxidant activity *in vitro*, and regarding *in vivo* decaffeinated coffee iron-reducing capacity showed to be lower than regular coffee (Lee, 2000). Almeida et al. (2012) reported the antimicrobial effect of caffeine against *Streptococcus mutans*. The study was conducted to evaluate the effect of coffee extracts, natural coffee compounds as well as increased caffeine levels on the *Streptococcus mutans* inhibition. From the study, the concentration of caffeine in Arabica coffee could temporarily inhibit *Streptococcus mutans*. A longer-lasting and stronger inhibitory effect was reported with high caffeine levels. In another study, caffeine showed a strong inhibitory effect against the growth of *Serratia marcescens* and *Enterobacter cloacae* (Almeida et al., 2006).

Some beneficial health effects such as prevention or delayed onset of type 2 diabetes have been linked to consumption of coffee which in turn has been associated with reduced oxidative damage, energy/nutrient uptake and body fat mass (Lin et al., 2011; Zhang et al., 2009). Trigonelline has been shown to have an anti-diabetic effect thus conferring these beneficial effects. An investigation conducted by van Dijk et al. (2009) on the acute effects of trigonelline and chlorogenic acid on glucose tolerance in humans showed that these compounds significantly lower insulin and glucose concentrations fifteen minutes after an oral glucose load. It was observed that ingestion of trigonelline and chlorogenic acid resulted in a significant reduction of glucose (0.5 mmol/l, $P=$ 0.024 and 0.7 mmol/l, $P = 0.007$, respectively) and insulin (117 pmol/l, $P=$ 0.007 and 73 pmol/l, $P = 0.038$) concentrations fifteen minutes following an oral glucose tolerance test compared with placebo. In another study, trigonelline was reported to significantly reduce total cholesterol, triglycerides levels and blood glucose of diabetic rats. The hypoglycaemic effect of trigonelline was attributed to its anti-oxidative potential as well as its protective effects on β cells, which were demonstrated, by a significant quenching effect on the lipid peroxidation extent and improvement of antioxidant defence systems in rat pancreatic tissue (Zhou et al., 2013).

Anticancer activity of trigonelline has also been demonstrated in the literature. However, its mechanisms do not directly exert cytotoxicity to kill cancer cells. Hirakawa et al. (2005) demonstrated the ability of trigonelline to inhibit cancer cell invasiveness *in vitro*. According to Arlt et al. (2013), trigonelline can increase the sensitivity of colon cancer and pancreatic cancer cell lines to anticancer drugs by inhibiting the activity of Nrf2 in tumor-bearing mice. The transcription factor Nrf2 has been reported to take part in regulating the drug resistance of cancer cells.

5. Coffee phytochemicals and post-harvest handling processes

5.1. Effect of processing methods on coffee phytochemicals

According to Silva et al. (2005), the chemical composition of green coffee beans is affected by many factors including genetic make-up, harvesting factors, processing methods, environmental conditions (climate, soil) as well as agronomic practices. Harvested coffee cherries can be processed by either wet, dry or semi-dry methods (Fig. 1). In the wet processing method, the cherries are pulped in a pulping machine to remove the outer fleshy part that is mesocarp and exocarp. This is followed by the fermentation process (dry or wet) done to loosen the mucilage layer by the action of microbial and coffee natural enzymes. Washing is then done and the resulting parchment coffee dried to the desired moisture content. For the dry process, whole cherries are dried immediately after harvesting to give what is known as 'natural' or 'unwashed' green coffee. It is a combination of fermentation and drying where the drying period takes longer compared to the wet process. The semi-dry processing method, also known as the "pulped natural" method, is a hybrid technique of dry and wet processing method where the coffee cherries are mechanically de-pulped and dried while the resulting beans are still covered partly by mucilage. In this method, the fermentation step is not done (Ghosh and Venkatachalapathy, 2014). Differences in the treatments specific to each processing method have been reported to produce coffees with different chemical composition (Table 2).

Arruda et al. (2012) observed that different methods of coffee processing lead to significant differences in the concentrations of reducing sugars, phenolic compounds and free amino acids present in green coffee beans of the same variety. Scholz et al. (2018) noted differences in the chemical composition of green coffee beans in terms of caffeine, lipids, chlorogenic acids and phenolic compounds of coffees processed differently. Leloup et al. (2005) reported similar observations on coffees processed by wet and dry methods. The wet processing method resulted in an increase in chlorogenic acids, lipids and cell-wall polysaccharides (mannans, arabinogalactans) and a reduction in trigonelline, free carbohydrate (glucose, fructose), minerals (K, Ca, Mg, Cu) and organic acids (ixalic, quinic). In another study, wet-processed coffees recorded high caffeine contents as opposed to dry-processed ones, which on the other hand recorded high sucrose contents (Rodriguez et al., 2020; Tolessa et al., 2019).

Changes in the chemical composition of green coffee beans processed with different methods could be attributed to the metabolic processes, which are specific to each type of post-harvest treatment (Selmar et al., 2006). Another hypothesis for the variation in the final composition of the coffee bean is the longer drying time, which is linked to the lower rate of water removal. This condition is believed to be a possible factor responsible for the occurrence of reactions that degrade different compounds, observed with greater intensity in dry-processed coffees as compared to wet-processed ones (Leloup et al., 2005). Another explanation associated with differences in the chemical composition of the bean processed differently is based on the physiological point of view. According to Bytof et al. (2005) removal of some parts that constitute the fruit favors germination of the embryo. It is believed that the process

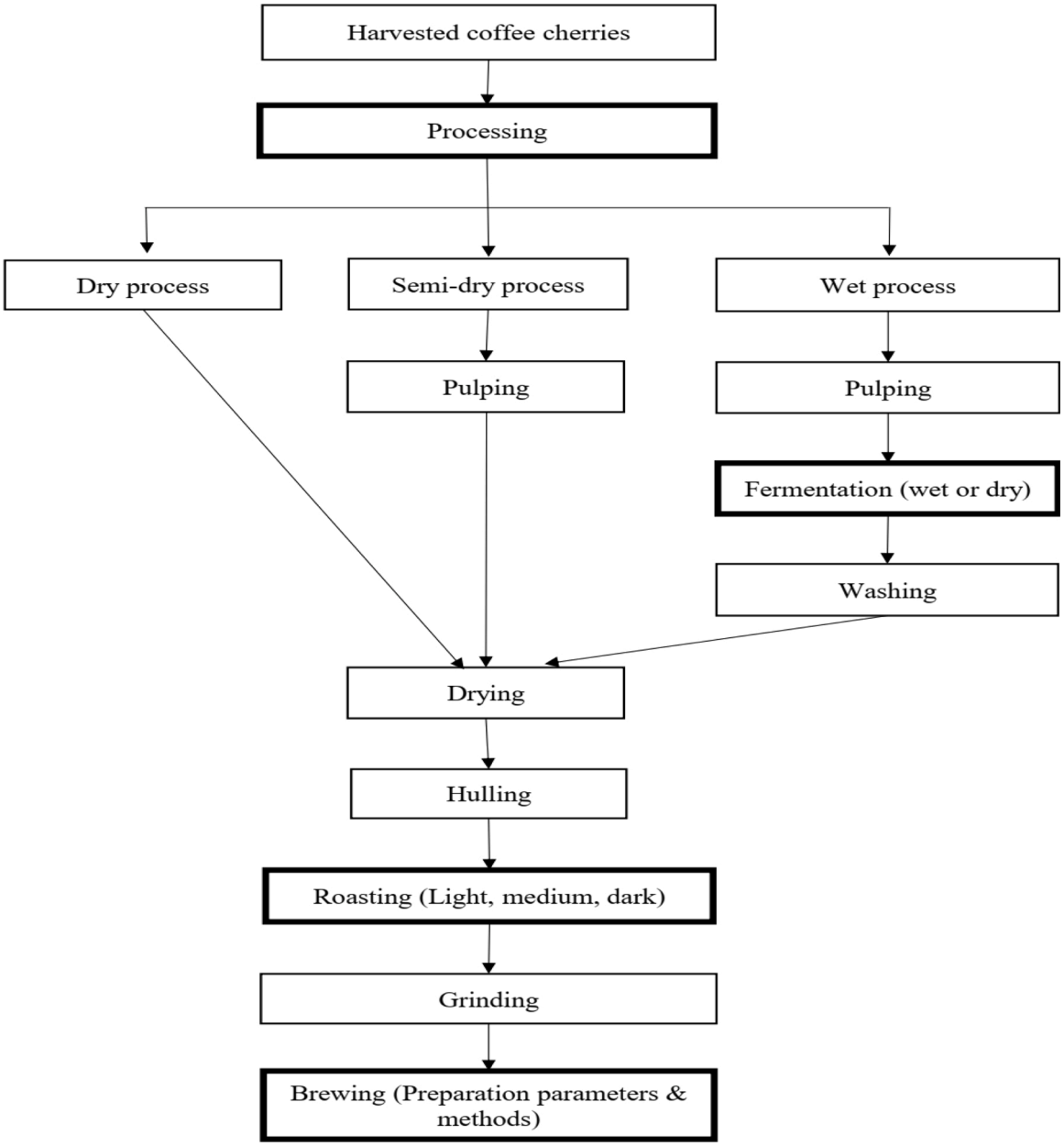

Fig. 1. Flow chart of coffee processing, from farm to cup. Critical steps that affects concentration of phytochemicals are highlighted in bold.

of germination happens differently in seeds during pulping, owing to the removal of inhibitors present in the mesocarp and exocarp parts. Coffee demucilaging and pulping involved in wet processing would, therefore, trigger various reactions linked to germination, for instance, reserve mobilization, bringing about different metabolic profiles unlike the dry method of processing. Additionally, compounds present in beans at lower concentrations, for instance, organic acids and some phytochemicals, may also show important variations as a function of transformations resulting from processing (Ribeiro et al., 2016).

5.2. *Effect of roasting on phytochemicals in coffee*

According to Poisson et al. (2017), roasting is defined as a dry heating process of food that starts with a drying phase that is endothermic followed by an exothermic phase that results in the formation of most of the flavor compounds, and lastly a cooling phase. The process of coffee roasting provides appropriate conditions for the necessary chemical as well as physical changes to occur besides the change in color of the bean from green to brown. Some of the major chemical and physical transformations that occur during the process of roasting include formation of melanoidins, reduction in amino acids, protein, arabinogalactan, caffeine, chlorogenic acids, trigonelline, reducing sugars, sucrose and water, many of which are involved in Maillard, pyrolysis and caramelization reactions (Table 2). Phytochemicals present in green beans are involved in these changes resulting in beans with high sensory quality due to the development of intricate flavors as well as color which enhance the coffee beverage taste (Franca et al., 2005).

Song et al. (2018) noted a significant reduction in the content of caffeine of Robusta and Arabica coffee with an increase in roasting degree, which could be attributed to its sublimation at elevated temperatures. The findings were however not in line with others reported in the literature which show that caffeine is heat stable during the process of roasting (Hecimovic et al., 2011; Ludwig et al., 2014). Additionally, chlorogenic acids also decreased with an increase in roasting degree from 15.72 to 1.71 % for Arabica coffee and from 19.42 to 1.72 % for Robusta coffee. The loss in CGAs as roasting degree increased can be

Table 2
Effect of post-harvest handling processes on coffee phytochemicals.

Post-harvest handling processes	Study parameters	Major findings	Reference
Processing method	Dry, semi-dry and wet methods.	Significant differences in the concentrations of reducing sugars, phenolic compounds and free amino acids.	Arruda et al. (2012).
	Dry and semi-dry methods.	Differences in the content of phenolic compounds, caffeine and lipid.	Scholz et al. (2018).
	Wet and dry methods.	Wet method: increase in CGAs, caffeine and lipids and decrease in trigonelline, minerals and simple sugars. Dry method: increase in sucrose.	Leloup et al. (2005); Rodriguez et al. (2020).
Roasting	Temp: 220 °C, time: 11–13 min (ML: 11 min, M: 12 min, MD: 13 min).	Significant decrease in caffeine and CGAs content with increase in roasting degree.	Song et al. (2018).
	Temp: 230 °C, time: 5–15 min.	More than 50 % loss of CGA as roasting time increase.	Farah et al. (2005a); Upadhyay and Mohan Rao (2013).
	Temp: 230 °C, time: 2–10 min.	Degradation of kahweol and cafestol with increased roasting time (60−75% loss).	Dias et al. (2014); Sridevi et al. (2011).
	5 min (160 °C), 10 min (225 °C).	50 % reduction in trigonelline levels with increased roasting time and temperature.	VotaVoVá et al. (2009).
	Temp: 200 °C, time: 1 h (in the oven).	50−80% loss of trigonelline.	Franca et al. (2005).
Preparation parameters and methods of the brew	Coffee amounts, water quantity, extraction time, particle size, water temperature and water pressure.	Increase in total diterpenes and lipid content with an increase in coffee amounts, water temperature, pressure, percolation time and use of fine coffee grounds.	Moeenfard et al., 2014a, 2014b; Buchmann et al. (2010).
	Different extraction time – 0−8 s, 8−16 s and 16−24 s.	Significant decrease in all three isomers of CQA i.e. 3-, 4-, and 5-CQA as extraction time increased.	Ludwig et al. (2012).
	Different preparation methods and addition of milk.	Brews prepared by boiling recorded high caffeine, diterpene esters and CGA content. Addition of milk significantly reduced total phenolic content of the brews.	Niseteo et al. (2012); Moeenfard et al. (2016).

Note: medium light (ML); medium (M); medium dark (MD).

explained by the integration of these acids into melanoidins (Perrone et al., 2012). Further degradation can be attributed to the conversion of about 30 % of the CGAs into their equivalent chlorogenic lactones brought about by the loss of the water molecule from quinic acid moiety and by the chlorogenic acid hydrolysis into quinic and caffeic acid, which degrades later into different volatile chemicals (Moon and Shibamoto, 2010). Similar observations were reported by Farah et al. (2005a) who reported a substantial reduction in the levels of 5-CQA after five minutes of roasting while 4-CQA and 3-CQA levels doubled their original values. This could be attributed to the fact that isomerization of CGA occurs at the beginning of roasting, as previously reported by other authors in literature (Trugo and Macrae, 1984; Leloup et al., 1995). Roasting periods of more than five minutes brought about a reduction in total chlorogenic acid content. Upadhyay and Mohan Rao (2013) noted that the process of roasting degrades a big percentage of CGAs into lactones, caffeic acid, as well as other derivatives of phenol through Strecker's and Maillard reactions, which bring about increased astringency, bitterness as well as aroma in the beverage.

The roasting process has also been shown to affect the diterpene profile in coffee. Dias et al. (2014) reported diterpene degradation occurs more extensively after eight minutes of roasting, for Arabica coffee. Kahweol and cafestol content expressed on a lipid basis decreased by approximately 75 % after 2–10 min of roasting for Arabica coffee, compared with less than a 60 % decrease for cafestol in the Robusta coffee samples. In another study, Arabica coffee recorded the highest concentrations of free cafestol and kahweol in light roast followed by medium and dark roasts. In light roast, 453 mg of kahweol and 622 mg of cafestol per 100 g were reported. Significant reduction in both cafestol and kahweol profiles were observed as the roasting temperature increased. A similar trend was observed in Robusta coffee though the diterpenes were less compared to Arabica coffee (Sridevi et al., 2011).

VotaVoVá et al. (2009) noted a 50 % reduction in the trigonelline levels during roasting at different times and temperature from its initial content in raw coffee beans. The observations were attributed to the degradation of trigonelline during roasting into N-methylpyridinium, a chief contributor to the antioxidant activity of the roasted bean. Stadler et al. (2002) noted a positive correlation between the levels of 1-methylpyridinium in roasted coffee and roasting degree. Farah et al. (2005b) reported a 90 % average loss of trigonelline during roasting from unroasted coffee beans to dark roasted beans. In another study, trigonelline losses of 50−80% after roasting were observed (Franca et al., 2005). Murkovic and Bornik (2007) noted that trigonelline content in roasted beans is dependent on the roasting temperature and time as well as species. During roasting, this compound is rapidly degraded to form volatile compounds for instance N-methylpyrrole, nicotinic acid and pyridines. Hecimovic et al. (2011) reported the highest total phenolic and flavonoid content in coffees roasted to medium and light roasting degrees. The findings highlighted that the roasting process has an effect on the polyphenolic compounds present in coffee, and medium and light roasting degrees proved to be more favorable in terms of preserving these useful compounds during the coffee roasting process. Similar findings were observed by Somporn et al. (2011) who reported an increment in total phenolic content following medium roast and light roast (27.8 % and 51.1 %, respectively) and a decrease upon dark roasting (1.55 %).

5.3. Impact of preparation parameters and methods on the phytochemical composition of coffee brews

The method of brew preparation and preparation parameters are significant in the phytochemical composition and health properties of the brew (Table 2). Different preparation parameters such as coffee weight, water quantity, particle size, extraction time, water temperature and pressure have been reported to significantly affect the phytochemical content of the brew. Moeenfard et al., 2014a, 2014b observed an increment in total diterpenes and lipid content with an increment of coffee amounts. Buchmann et al. (2010) who reported a positive association between diterpene content and coffee amounts also observed comparable findings. Brewing coffee with very fine coffee grounds, high water temperature, increased percolation time and pressure have also been reported to lead to an increased content of total lipids and diterpenes in the beverage (Moeenfard et al., 2014a, 2014b; Masella et al.,

2015; Andueza et al., 2003). Petracco (2005) highlighted that fine coffee grounds have increased extraction surface area as compared to course grounds and, therefore, compounds are released and dissolve quickly and easily when they come into contact with water. In addition, more percolation time is needed in the production of a specific volume of the brew when fine grounds are used allowing more contact between water and grounds and thus more compounds are extracted. An increase in total lipids and diterpenes as pressure increases is explained by the fact that water enters into the matrices of grounds, which may assist in the extraction of certain compounds trapped in the pores within the matrix (Teo et al., 2010).

In another study, a significant decrease in all three isomers of CQA, i. e. 3-, 4-, and 5-CQA, was observed with an increase in extraction time of espresso coffee brews. Extraction time of 0–8 s, 8−16 s and 16−24 s accounted for about 70 %, 17 % and <14 % of the total amounts of CQA found in an espresso coffee brew, respectively (Ludwig et al., 2012). Moeenfard et al., 2014a, 2014b investigated the effect of diff ;erent brewing conditions on the concentration of 4-CQA, 5-CQA and 3-CQA. Isomer 3-CQA was present in high levels in most of the samples that were considered and it accounted for approximately 34–50 % of the total CQAs. This was followed by 25–28 % and 23–36 % for 4-CQA and 5-CQA, respectively. In general, the total CQAs content in studied samples varied depending on the brewing method and it ranged from 45.8 mg/L in iced cappuccino to 1662 mg/L in pod espresso.

In addition to preparation parameters, the methods of coffee brew preparation significantly influence its composition. Three different extraction methods, namely infusion, pressure and decoction, have been developed recently. Each method differs from the other in terms of granulation of coffee grounds, water temperature, brewing time as well as water/coffee proportion (Niseteo et al., 2012). From literature, variations in such factors alter the composition of the brew. Niseteo et al. (2012) carried out a study on the effect of preparation technique and addition of milk on antioxidant potential and bioactive composition of different frequently consumed coffee brews. From the study, instant coffee brews recorded the highest CGA content while the lowest content was recorded by filter coffee brew. Turkish/Greek coffee brews often reheated during domestic preparation, showed a significant increment in the content of caffeine and CGA when reheated to boiling state in comparison to the brews that had been prepared initially.

In another study, cafestol extraction yield from roast and ground Arabica coffee beans at different intensities of roasting (roast time) in four brew methods (Turkish, Scandinavian boiled, Mocha and French press) was examined. Brews prepared by boiled, Turkish and French press methods recorded the highest cafestol content while those from the Mocha method recorded the lowest content at all roast colors (Zhang et al., 2012). A huge variability amongst esters of diterpenes content had also been reported in coffee brews with respect to the preparation method. Boiled coffee showed the highest total kahweol esters (1016 mg/L) and total cafestol esters (232 mg/L) content (Moeenfard et al., 2016). Coffee brews can also be prepared by adding different amounts of milk. However, milk has been shown to modify the brew's antioxidant capacity and bioactive composition. Niseteo et al. (2012) reported a significant reduction in total phenolic content of coffee brews with the addition of milk. Studies on the polyphenols ability to interact with dietary proteins including whey and casein proteins revealed the possibility of these compounds forming polyphenol–protein complexes (Yuksel et al., 2010), which could explain the findings reported by Niseteo et al. (2012).

6. Potential applications of phytochemicals extracted from coffee

Phytochemicals present in coffee have a potential application in the medical field owing to their biological activities. Compounds such as chlorogenic acids, caffeine, diterpenoid, caffeic acid and heterocyclic molecules have been reported to have an anticancer effect. They reduce the possibility of cancers of the liver, kidney, colon and premenopausal breast by preventing the cancer initiation step through DNA-damage inhibition, which is brought about by carcinogenic agents or free radicals (Ramos, 2008). Oxidative stress occurs when the balance between the formation of ROS and detoxification favors a rise in the levels of reactive oxygen species resulting in disturbed functions of the cells. This condition has been linked to the initiation as well as propagation of many degenerative diseases for example cancer, diabetes, inflammatory and cardiovascular diseases (Durak et al., 2014; Khansari et al., 2009).

Caffeine, diterpenes and chlorogenic acids which are examples of phytochemicals have exhibited antioxidant activity both in vivo and in vitro (Liang and Kitts, 2016; Lee and Jeong, 2007; Lee, 2000) and can be used to prevent some diseases since they are able to fight against cellular damage brought about by free radicals present in the body. Phytochemicals in coffee have also been shown to have anti-inflammatory effects. According to Cotran et al. (1994), unregulated or exaggerated protracted process of inflammation may induce damage of tissues, which is the main cause of numerous chronic diseases. Chlorogenic acids have demonstrated inflammation reduction because of enhanced healing of wounds (Liang and Kitts, 2016). According to a Planning Committee for a workshop on potential health hazards associated with consumption of caffeine in food and dietary supplements (2014), caffeine has a stimulant effect on the central nervous system. Several studies have also demonstrated coffee extract to have an antibacterial effect against various types of harmful microorganisms such as bacteria causative of caries, detrimental intestinal bacteria etc. (Antonio et al., 2011; Ferrazzano et al., 2009). Almeida et al. (2012) observed a significant inhibitory effect of caffeine against *Streptococcus mutans* with increased concentrations. In another study, extracts and brews of Arabica and Robusta coffee exhibited antibacterial activity against *Streptococcus mutans* as well as other oral types of bacteria (Antonio et al., 2010).

7. Conclusion

In conclusion, the effect of various post-harvest handling practices of coffee from farm to cup on phytochemicals highlights the significance of appropriate handling of coffee for it to confer both good sensory and functional characteristics. Based on the reviewed literature, different processing methods affects the content of phytochemicals differently. Roasting affects the phytochemical content as these compounds are degraded to produce compounds that contribute to the color, taste, aroma and flavor of the beverage. An increase in roasting degree results in a significant reduction of chlorogenic acids, diterpenes and trigonelline content. However, the caffeine content is less affected since it has been reported to be heat stable. Preparation methods and parameters such as coffee weight, water quantity, particle size, extraction time, water temperature and pressure affect the phytochemical content in the beverage. Therefore, the contribution of phytochemicals to the functional and sensory characteristics of coffee is dependent on a number of factors, which should be considered to produce beverages with better health benefits and good sensory characteristics. Research indicates that coffee has the potential to exert beneficial effects against diabetes, cancer, cardiovascular diseases and obesity. These beneficial effects are associated with the biological activities of the phytochemicals present in coffee, which must be present in considerable amounts at the time of consumption. Further research on how coffee phytochemicals are affected during post-harvest handling practices would unlock the health benefits of this popular beverage and hence immensely benefit the consumer.

Author statement

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