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Review

Sustainable management of coffee industry by-products and value addition—A review

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ABSTRACT

Coffee is one of the popular beverages of the world and second largest traded commodity after petroleum. Coffee is cultivated in about 80 countries across the globe and entangles huge business worldwide. Coffee dispensation requires an elevated degree of processing know how and produces large amounts of processing by-products such as coffee pulp and husk, which have limited applications such as fertilizer, livestock feed, compost and such others. Biotechnological applications in the field of industrial residues management promote sustainable development of country's economy. The objectives pertaining to food processing by-products, waste and effluents include the recovery of fine chemicals and production of precious metabolites via chemical and biotechnological processes. Pre-treatments, followed by recovery procedures endow value-added products (natural antioxidants, vitamins, enzymes, cellulose, starch, lipids, proteins, pigments) of high significance to the pharmaceutical, cosmetic and food industries. With the background of high crop production in the upcoming years, there is an imperative need to counterpart this production with some utilization and industrial application of coffee by-products since coffee industry emerges enormous amounts of coffee by-products which are thriving nutrient resources. The present review highlights explorations of value addition to coffee by-products which can be achieved with valorization strategy, integration of techniques and applications of bioengineering principles in food processing and waste management and secondly conserve environment with disposal problem accelerating both ecological and economical resources.

Contents

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1. Introduction

Applications in the field of industrial residue management promote sustainable development of country's economy. The hindrance concerning food processing by-products, waste and effluents is the recovery of fine chemicals and production of valuable metabolites via chemical and biotechnological processes (Federici et al., 2009; Mussatto et al., 2011b). Pre-treatments with physical and biological agents followed by tailored recovery experiments certainly provide value-added natural antioxidants, antimicrobial agents, vitamins, etc., along with macromolecules (enzymes, cellulose, starch, lipids, proteins and pigments) which are of immense interest to the pharmaceutical, cosmetic and food industries. Several other compounds occurring in the hydrolyzate obtained through by-products/waste pre-treatment can be further transformed through customized biotechnological processes (Laufenberg et al., 2003; Wyman, 2003).

A more recent approach has been the use of processing technologies to fractionate potentially high value components from them, thereby turning waste streams into value addition products (Laufenberg et al., 2003; Wyman, 2003; D'Annibale et al., 2003). Other bioactive components present are carotenoids, phytoestrogens, natural antioxidants, such as phenolic compounds and functional compounds (Llorach et al., 2002; Moure et al., 2001; Schieber et al., 2001). Phenolic and flavonoid compounds have recently attracted a lot of interest because they are potent antioxidants and exhibit various physiological activities like anti-inflammatory, anti-microbial, anti-allergic, anti-carcinogenic and anti-hypertensive activities (Akkarachiyasit et al., 2009). The recovery of such value added compounds from processing by-products has increased due to their availability. In addition, pertinent amounts of these by-products which remain unexploited might pose environmental problem (Wyman, 2003). Thus, the currently adopted valorization steps, lead to the complete exploitation of the by-products and waste biomass, with remarkable improvements in the environmental and economic sustainability. The overall approach is use of enzymatic pre-treatment and extraction/recovery (precipitation, membrane, chromatography technologies, supercritical fluid extraction) of natural chemicals, biomaterials and food ingredients (antioxidants, pigments, vitamins, gelling agents, pectin, oligosaccharides, dietary fibers) followed by biotechnological conversion of a few of the obtained chemicals/bio-products into more sophisticated tailored bio-compounds, such as flavorings, pharmaceuticals, secondary building blocks, etc. (Benoit et al., 2006). Agro-wastes can also represent as a resource of potentially useful chemical substances after direct recovery of simple and complex carbohydrates that could be used in fermentation processes (Crognale et al., 2006).

Coffee industry liberates enormous amounts of coffee by-products which are rich in carbohydrates, proteins, pectins, bioactive compounds like polyphenols and are cheap renewable resources (Murthy and Madhava Naidu, 2010). With high coffee production projected in the upcoming years, there is an imperative need to balance this production with proper utilization and industrial application of coffee by-products for development of nutraceuticals. With this background, this review addresses coffee by-products that are liberated during processing, for efficient recovery of bioactive molecules and production of value added products which is a new frontier in waste management of coffee by-products. Further explorations for value addition to coffee by-products by the integration of techniques and adoption of current bioengineering principles in food processing and waste management, is also attempted simultaneously conserving environment and improving the country's economy.

1.1. Coffee

Coffee is one of the world's most popular beverages and has grown steadily in commercial importance during the last 150 years (Daglia et al., 2000). The word Coffee has originated from the Arabic word *Quahweh*. Today its popularity is identified by various terms in several countries such as *cafe* (French), *caffe* (Italian), *kaffee* (German), *koffie* (Dutch) and coffee (English) (Smith, 1985). The stimulatory effects of roasted coffee beans were well known and the Arabs brought *Coffea arabica* seeds from Ethiopia to Yemen (Arabian Peninsula) during the 13th century, and established the first plantation (Monaco et al., 1977). The province of Kaffa in Ethiopia is considered to be the original habitat of Arabica coffee and Central Africa is reckoned to be the native of robusta coffee. With extensive and wide spread cultivation of coffee across the globe, at present Brazil is the largest producer and exporter of coffee in the world.

1.1.1. Coffee classification and botany

Coffee is an important plantation crop belonging to the family *Rubiaceae*, subfamily *Cinchonoideae* and tribe *Coffeae* (Clifford et al., 1989). The *Rubiaceae* members are largely tropical or subtropical

Fig. 1. The coffee plant.

comprising nearly 400 genera and 4800–5000 species. Botanically, coffee belongs to the genus *Coffea* of the family Rubiaceae. The sub-genus *Coffea* is reported to comprise over 80 species, which are prevalent in Africa and Madagascar (Bridson and Verdcourt, 1988). Coffee is a perennial plant and evergreen in nature (Fig. 1). It has a prominent vertical stem with shallow root system, the feeder roots of arabica coffee penetrate relatively deeper into the soil whereas robusta has feeder roots concentrated very close to the soil surface.

Classification

Kingdom	*Plantae*
Subkingdom	*Tracheobionta*
Division	*Magnoliophyta*
Class	*Magnoliopsida*
Subclass	*Asteridae*
Order	*Rubiales*
Family	*Rubiaceae*
Genus	*Coffea*

Coffee leaves are opposite decussate on suckers. The leaves appear shiny, wavy, and dark green in color with conspicuous veins. The inflorescence is a condensed cymose type subtended by bracts. Coffee is a short day plant and hence the floral initiation takes place in short day conditions of 8–11 h of day light. Pollination takes place within 6 h after flowering (Fig. 2). Arabica coffee is autogamous with different degrees of natural cross-pollination in contrast to Robusta coffee, which is strictly allogamous with an inbuilt ametophytic system of self-compatibility. The process of fertilization is completed within 24–48 h after pollination. Seeds are elliptical or egg shaped and the seed coat is represented by the silver skin which is also made up of scleroides. The size, thickness or number of pits in the walls of scleroides is considered as important taxonomic characters in differentiating between species. Germination takes place in about 45 days.

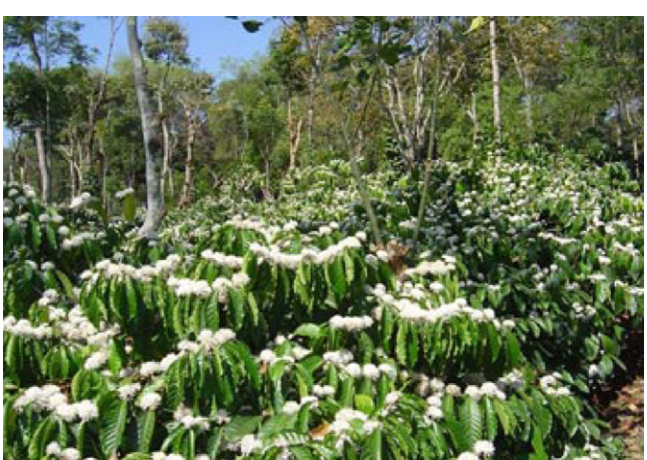

Fig. 2. Coffee flowers blossomed in the estate.

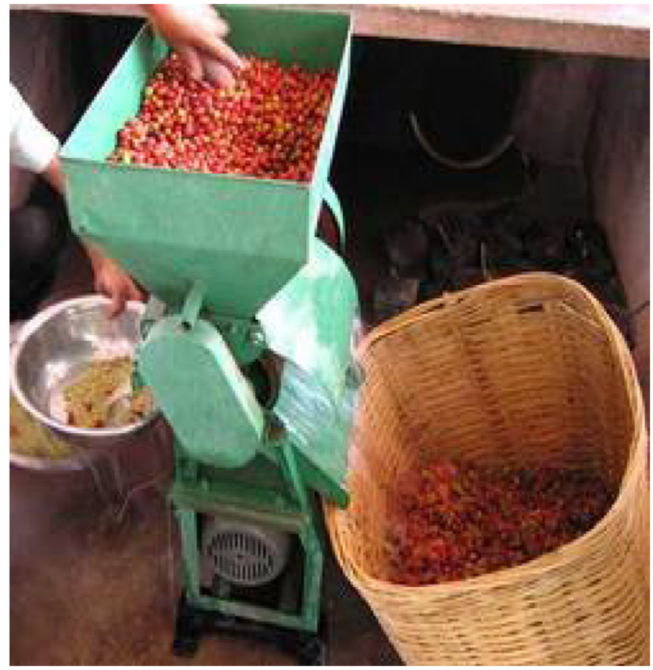

Fig. 3. Coffee pulping using pulper in wet processing of coffee.

1.1.2. Coffee – cultivation, process, production and export

Coffee trees grow in tropical regions, between the tropic of Cancer and Capricorn, that have abundant rainfall, year round warm temperature averaging 70 °F, and no frost. They grow at altitudes ranging from sea level to 6500 feet and even above. It takes about five years for a coffee tree to bear its first full crop of beans and will be productive for about fifteen years. Only ripe fruits are harvested by selective picking from each dominant variety situated at particular elevation separately and kept as separate independent lot. Following are sorting of greens/immature, overripe fruits and are dried separately because they affect the final quality of coffee by impregnating foul flavor (Murthy et al., 2001).

1.2. Coffee processing techniques

Processing is a major activity in coffee industry which converts raw coffee fruit into liquid coffee. The two basic methods of coffee processing which differ in complexity and the quality of the resultant raw coffee and the liquor are wet method and dry method.

1.2.1. Wet method

Coffee processed by wet method is called washed or parchment coffee. In the wet process, the fruit pulp covering the seeds/beans are removed by pulper before they are dried (Fig. 3). Wet method requires reliable pulping equipment and adequate supply of clean water. Whatever may be the type of pulper used (drum pulper, disk pulper, vertical spiral drum pulper), for demucilaging, the final objective is to ensure complete removal of mucilage from the parchment cover for production of high quality coffee (Murthy et al., 2001). The purpose of fermentation is to break down the mucilage layer on the parchment into simple

Fig. 4. Coffee drying in the drying yards after wet processing.

non-sticky substances. The mucilage is digested through natural fermentation. Over fermentation is avoided because it results in a loss of bean color and poor cup and under fermentation leads to moisture absorption by the beans due to the sticky mucilage on the parchment and causes mustiness in the final cup. The optimum temperature for fermentation is 30–35 °C (Fig. 4). The coffee masses are stirred 2–3 times during fermentation period with help of a raker. The degradation of mucilage takes approximately 24–36 h for arabica and 72 h for robusta depending on the inherent concentration of pectinolytic enzymes ambient temperature and elevation. Correct washing is ensured by hand feel where the parchment will not stick to the hand after washing.

In addition, there is also mechanical way of removal of mucilage. Use of the machine is advocated to completely/partially fermented beans basically to achieve total washing of the beans, to reduce the quantum of water usage and to get desirable flavor in coffee. After washing, soaking the parchment in clean water for 12 h is practiced. Soaking improves visual appearance of the beans and also quality by removing diterpenes and polyphenolic substances which impart hardness to brew. The washed parchment are drained off excess moisture, conveyed to the drying barbecues and spread evenly to a thickness of 5 cm, stirred with wooden rakes to ensure uniform drying and reduce parchment splits. Strong solar radiations are avoided on the 3rd and 4th day of drying during noon by providing shade with tarpaulin or stitched knitted bags. Coffee beans are dried until the moisture reaches around 10%. Too thin layer of parchment leads to rapid drying which causes splitting of parchment skin and shrunken beans. Improper and uneven drying of parchment results in mottled roast.

1.2.2. Cherry or dry method

In this method, the freshly harvested fruits are spread evenly to a thickness of about 8 cm on clean drying yard. They are stirred and ridged once every hour. The cherries are considered as dried when a fistful of coffee produces a rattling sound when shaken (Murthy et al., 2001). The cherry coffees normally get fully dried in 12–15 days under bright weather conditions. Dry cherry coffees are not exposed to wet condition to avoid mould formation which may adversely affect coffee quality. Each lot of cherry is bagged separately in clean dry gunny bag. Proper drying contributes to the quality of coffee with respect to color, shape and aromatic constituents. Drying rate of parchment is dependent on the initial moisture of the parchment, ambient air temperature, humidity, thickness of the spread and periodicity of stirring.

Fig. 5. Coffee roasting to obtain volatiles.

1.3. Green coffee, roasting and brewing

The green coffee is classified into washed and unwashed with regard wet or dry processing. The green coffee is composed of both volatile and non-volatile compounds. The major components of green coffee are carbohydrates, protein, lipid, minerals, ash, caffeine, chlorogenic acid, trigonelline, water, etc. The consumable form of green coffee beans is obtained after roasting. The quality evaluation of green coffee is based on odor and flavor tests, as well as on the size, shape, color, hardness, and presence of defects (Clarke and Macrae, 1985; Feria-Morales, 2002). The characteristic flavor and aroma of coffee result from the combination of hundreds of chemical compounds produced by the reactions that occur during roasting (Fig. 5) and brewing (Castillo et al., 2002). This process can be divided into the following three consecutive stages: (i) drying, (ii) roasting or pyrolysis and (iii) cooling. The first stage is characterized by a slow release of water and volatile substances, during the first half of processing. Bean changes its color from green to yellow. Pyrolysis reactions take place during the second stage, resulting in considerable changes in both physical and chemical properties of beans and results in transformation of naturally occurring polyphenolic constituents into a complex mixture of Maillard reaction products (Sacchetti et al., 2009). Coffee brewing is heterophase ranging from smooth pure solution to emulsion (Drip filter coffee, Nordic boiled coffee, Turkish style brew, Espresso, and cappuccinos). Coffee processing is an art as well as science and involves a series of stages each of which has a distinct purpose. To produce high quality coffees, it is imperative that all stages are taken utmost care in accordance to the recommended procedures.

1.4. Coffee production and export

Coffee is an important commodity and a popular beverage. Globally, 25 million small producers rely on coffee for their living. Brazil, Vietnam and Colombia account for more than half of world's production. The global coffee production per year on an average accounts to about 7.0 million metric tons (Table 1). According to the International Coffee Organization (ICO), output of coffee brew in 2011-12 seasons is estimated at 130 million bags. Over 2.25

Table 1
Worldwide coffee production as per International Coffee Organization.

Period	Coffee production*
2005–2006	110,181
2006–2007	129,139
2007–2008	118,949
2008–2009	128,073
2009–2010	123,600
2010–2011	134,000

* Million bags each of 60 kg.

billion cups of coffee are being consumed in all over the world every day (Stefano Ponte, 2002). Over 90% of coffee production takes place in developing countries, while consumption is mainly in the industrialized economies (Stefano Ponte, 2002).

2. Coffee by-products utilization and management

Coffee is the second largest traded commodity in the world and generates large amount of coffee by-products/residues during processing from fruit to cup (Nabais et al., 2008; Mussatto et al., 2011b). Industrial processing of coffee cherries is done to separate coffee powder by removing shell and mucilaginous part from the cherries (Fig. 6). Depending upon the method of coffee cherries processing, i.e. wet or dry process, roasting and brewing solid residues like pulp husk, silver skin and spent are obtained (Fig. 7a and b). The coffee husks/peel/pulp, comprise of nearly 45% cherry, and are the main by-products of coffee-industry. They are used for various purposes including extraction of caffeine and polyphenols (Esquivel and Jiménez, in press) because they are rich in nutrients (Table 2).

2.1. Coffee pulp (CP)

Coffee pulp is the first by-product obtained during processing and represents 29% dry-weight of the whole berry. Coffee pulp is obtained during wet processing of coffee and for every 2 tons of coffee produced 1 ton of coffee pulp is obtained (Roussos et al., 1995). Coffee pulp is essentially rich in carbohydrates, proteins and minerals (especially potassium) and it also contains appreciable amounts of tannins, polyphenols and caffeine (Bressani et al., 1972). The organic components present in coffee pulp (dry weight) includes tannins 1.80–8.56%, total pectic substances 6.5%, reducing sugars 12.4%, non-reducing sugars 2.0%, caffeine 1.3%, chlorogenic acid 2.6%, and total caffeic acid 1.6%.

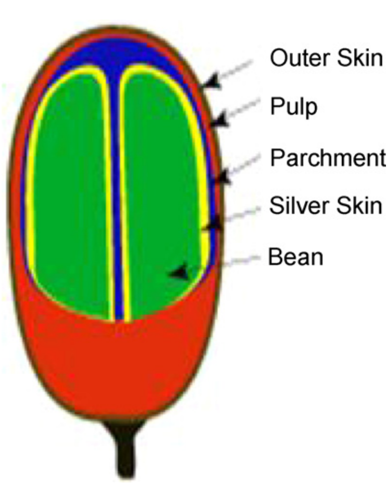

Fig. 6. Cross-section of the coffee cherry.

Table 2
Chemical composition of coffee by-products.

Parameters (%)	Coffee pulp	Coffee husk	Silver skin	Coffee spent
Cellulose	63.0 ± 2.5	43.0 ± 8.0	17.8 ± 6.0	8.6 ± 1.8
Hemicellulose	2.3 ± 1.0	7.0 ± 3.0	13.1 ± 9.0	36.7 ± 5.0
Protein	11.5 ± 2.0	8.0 ± 5.0	18.6 ± 4.0	13.6 ± 3.8
Fat	2.0 ± 2.6	0.5 ± 5.0	2.2 ± 1.9	ND
Total fiber	60.5 ± 2.9	24 ± 5.9	62.4 ± 2.5	ND
Total polyphenols	1.5 ± 1.5	0.8 ± 5.0	1.0 ± 2.0	1.5 ± 1.0
Total sugars	14.4 ± 09	58.0 ± 20.0	6.65 ± 10	8.5 ± 1.2
Pectic substance	6.5 ± 1.0	1.6 ± 1.2	0.02 ± 1.0	0.01 ± 0.005
Lignin	17.5 ± 2.2	9.0 ± 1.6	1.0 ± 2.0	0.05 ± 0.05
Tannins	3.0 ± 5.0	5.0 ± 2.0	0.02 ± 0.1	0.02 ± 0.1
Chlorogenic acid	2.4 ± 1.0	2.5 ± 0.6	3.0 ± 0.5	2.3 ± 1.0
Caffeine	1.5 ± 1.0	1.0 ± 0.5	0.03 ± 0.6	0.02 ± 0.1

From Mussatto et al. (2011b), Franca et al. (2009) and Murthy and Madhava Naidu (2010).
ND: not determined.

2.2. Coffee husks (CH)

Coffee cherry husks are obtained when coffee berries are processed by dry method. Coffee husk encloses the coffee beans and represents about 12% of the berry on dry-weight basis. About 0.18 ton of husk is produced from 1 ton of coffee fruits (Adams and Dougan, 1981). Coffee husks compose 15.0% moisture, 5.4% ash, 7.0% protein, 0.3% lipids and 72.3% carbohydrates (Gouvea et al., 2009). Coffee husk contains 24.5% cellulose, 29.7% hemicelluloses, 23.7% lignin and 6.2% ash (Bekalo and Reinhardt, 2010).

2.3. Coffee sliver skin (SS)

Coffee silver skin is an integument of coffee bean obtained as a by-product of the roasting process. It is a residue with high concentration of soluble dietary fiber (86% of total dietary fiber) and having high antioxidant capacity, probably due to the concentration of phenolic compounds, as well as due to the presence of other compounds formed by the Maillard reaction such as melanoidins during the roasting process (Borrelli et al., 2004). The main components of these fibrous tissues are cellulose and hemicellulose. Glucose, xylose, galactose, mannose, and arabinose are the monosaccharides present in coffee silver skin along with proteins (Carneiro et al., 2009; Mussatto et al., 2011a).

2.4. Spent coffee (SC)

Almost 50% of the worldwide coffee produced is processed for soluble coffee preparation (Ramalakshmi et al., 2009). On an average one ton of green coffee generates about 650 kg of SC, and about 2 kg of wet SC are obtained to each kg of soluble coffee produced (Pfluger, 1975). SC is richer in sugars containing mannose and galactose along with significant fraction of proteins (Mussatto et al., 2011a).

Chemical composition of varies from plant to plant, and within different parts of the same plant. It also varies within plants from different geographic locations, ages, climate, and soil conditions. Knowledge of the physical and chemical properties will lead to a better understanding of application of coffee.

3. Coffee by-products disposal, environment and its demerits

In coffee producing countries, coffee wastes and by-products constitute a source of severe contamination and pose serious environmental problem. Coffee processing units that are located in almost each coffee estate pose threat to the environment because of unsafe disposal of coffee pulp, husk and effluents leading to

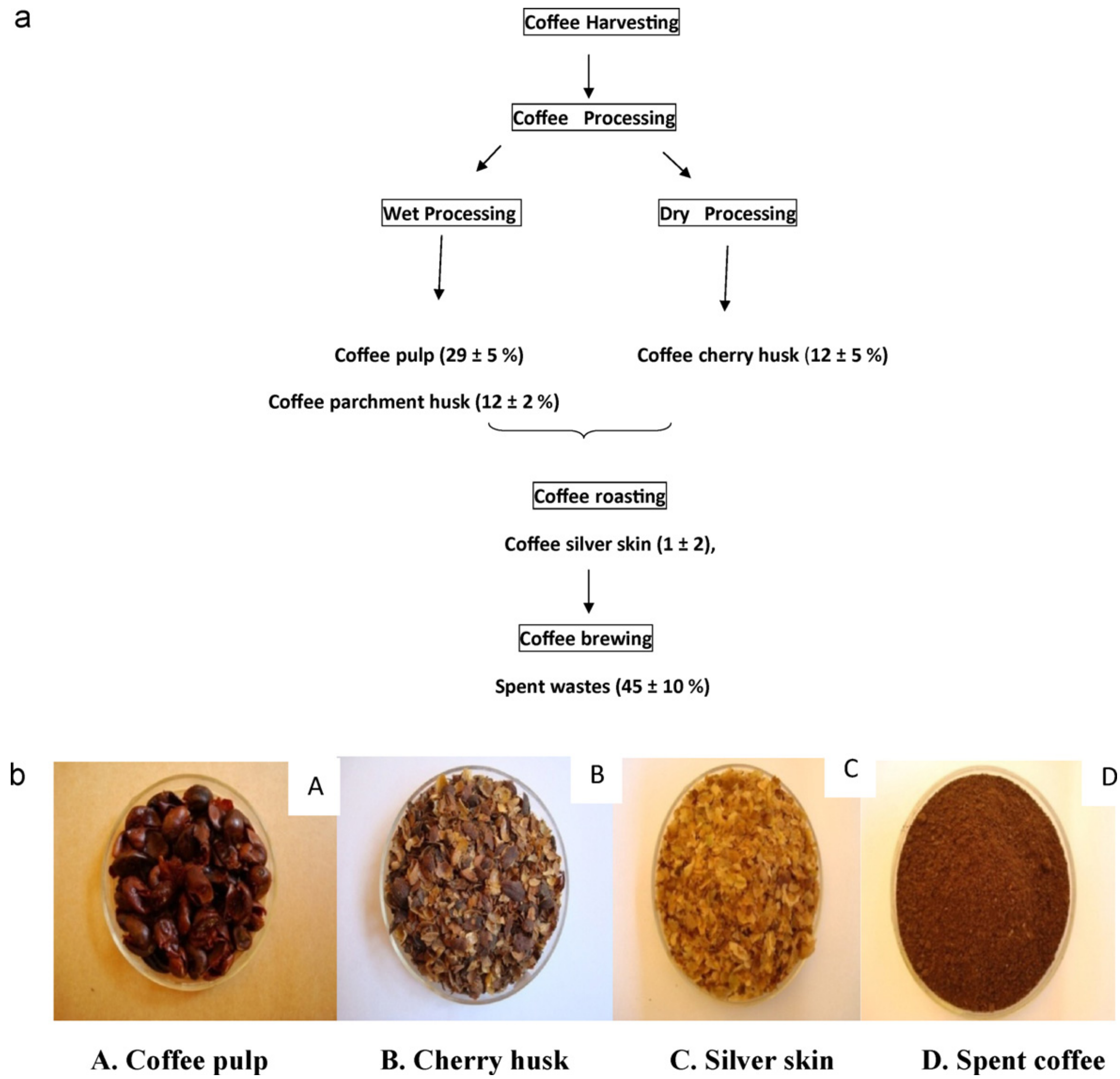

Fig. 7. (a) Sketch of the production of various by-products from coffee industry. (b) Coffee by-products obtained during coffee processing.

pollution of water and land around the processing units. Coffee pulp is the chief by-product with its high moisture content poses problems of disposal, due to putrefaction. It causes severe environmental pollution if it is not disposed with appropriate pretreatment (Zuluaga, 1989). Pollution awareness and policies have played a minor role in finding uses for coffee pulp. Coffee pulp is an agro-waste product which is now becoming an environmental problem. However, large-scale utilization and management of coffee wastes around the world still remains a challenge due to its content of caffeine, free phenols and tannins (polyphenols), which are known to be very toxic to many life processes (Fan et al., 2003). Previous studies have confirmed that toxic materials can be minimized by hot water pretreatment, microbial biodegradation and aerobic fermentation (Gaime-Perraud et al., 1993). To that effect, production of bioproducts such as silage, biogas, and worms, animal feed, ethanol, vinegar, single-cell protein, enzymes, biopesticides, and probiotics have been established at small scale but demonstration of the technology application at pilot scale is yet to be achieved.

Apart from these, tannins are generally considered to be anti-nutritional and restrict coffee pulp from being used at more than 10% level in animal feeds. Information on coffee pulp tannins is contradictory and as such present data available are difficult to interpret because of non-specific analytical methods used (Colmenares et al., 1994). Depending upon the type of cultivar, the tannin content may vary. The change of paradigm however has come not only from new work on soluble dietary fiber and antioxidants, but also from the realization of benefits of coffee pulp when used at less than 10% of the diet. Traditionally, coffee pulp and husk had found only a limited application as fertilizer, livestock feed, compost, etc. These applications utilize only a fraction of available quantity as they are not technically very efficient. However, considering the high amounts of waste generated, there is still a need to find other alternative uses for this solid residue.

3.1. Biological detoxification of coffee pulp and husk by microbes

Due to the presence of some anti-physiological and anti-nutritional factors, coffee pulp and husk are not suitable substrates for bioconversion processes. Consequently, most of the pulp and husk generated during coffee processing remain unutilized or under-utilized. If the toxic constituents could be removed, or, at least degraded to a reasonably safe level then it would open up new avenues for their utilization as substrates for bioprocesses. With this in mind, several authors have worked on detoxification of coffee pulp and husk through various means.

Studies were carried out on detoxification of coffee husk in solid state fermentation using three different strains of *Rhizopus*,

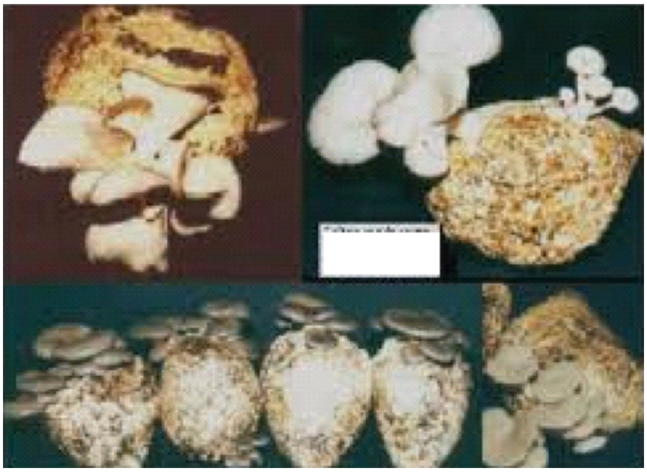

Fig. 8. Mushrooms grown on coffee by-products.

Phanerochaete, and *Aspergillus* spp. The results showed good prospects for using these fungal strains, in particular *Aspergillus* spp., for the detoxification of coffee husk (Brand et al., 2000; Pandey et al., 2000). SSF was carried out by *Aspergillus niger* in glass column fermenter using factorial design experiments and surface response methodology to optimize bioprocess parameters such as substrate pH, moisture and aeration rate using coffee husk by Raimbault (1998). Changes in coffee pulp treated with *Streptomyces* through the application of analytical pyrolysis revealed that the bacteria can upgrade to useful level and the pollutant residue can be used for feeding purposes (Orozco et al., 2008).

4. Utilization of coffee by-products for value addition

Methods of coffee waste management are outlined to create awareness of the opportunities and constraints associated with the maximization of coffee by-product utilization and the reduction of environmental pollution. The application of environmentally sound disposal methods requires an understanding of the range of waste utilization, treatment and recycling options. Traditionally, coffee pulp and husk have found only limited applications as fertilizer, livestock feed, compost, etc. These applications utilized only a fraction of available quantity and the methods were not technically very efficient. Recent attempts have focused on its application as substrate in bioprocesses and vermi-composting. Attempts have also been made to detoxify them for improved application as feed, and to use them as an efficient substrate for producing several value-added products such as enzymes, organic acids, flavor and aroma compounds, mushrooms, etc. Since these waste-products contain a substantial amounts of fermentable sugars, these constitute as an appropriate substrate for the cultivation of moulds and yeasts

4.1. Production of mushrooms

The nutritional and organoleptic properties along with therapeutic value of mushrooms have paved way for improved methods of their cultivation all over the world. First attempt on mushroom cultivation on coffee industry residues was made by Fan et al. (2001). A systematic study on cultivation of *L. edodes*, *Pleurotus* spp. and *Flammulina velutipes* using such residues as coffee husk, leaves and spent ground either, individually or in mixture are reported (Fig. 8) (Murthy and Manonmani, 2008). SSF was carried out using coffee husk, coffee spent ground and a consortium of the coffee substrates under different conditions of moisture and spawn rate. The biological efficiency reached 85.8, 88.6 and 78.4% for treated

Fig. 9. Vermicompost using coffee by-products.

coffee husk, spent ground and mixed substrate, respectively and has showed the feasibility of using coffee husk and coffee spent as substrates without any pre-treatment for cultivation of edible fungus.

4.2. Citric and gibberellic acid

Coffee husk was used as an inexpensive substrate for production of citric acid by *A. niger* in a solid-state fermentation system by Shankaranad and Lonsane (1999). Machado et al. (2002) reported the production of gibberellins (plant hormones) in SmF and SSF utilizing coffee husk as the carbon source. Five strains of *Gibberella fujikuroi* and one of its imperfect states, *Fusarium moniliforme* were used for comparison. Production of gibberellic acid reached 1100 mg/kg when dry coffee husk was used as a sole substrate of fermentation. In all the fermented samples, SSF appeared superior to submerged fermentation in the production of gibberellic acid (Machado et al., 2000).

4.3. Vermicomposting

Residues from agriculture and the food industry consist of large and varied wastes. Composting and vermicomposting is a cost effective technology which could be used at industrial level for recycling the industrial wastes. These recycled products enhance soil nutrients, provide better growth and possess commercial appreciation. Coffee husks were found suitable for composting and vermicomposting (Fig. 9). Though, coffee pulp contains higher proportions of cellulose besides potash and lignin, it has excellent moisture retaining capacity but is slow in decomposition. The high bacterial growth in the earthworm intestines improves soil fertility and stimulates plant growth making vermicasts as good organic manure and potting media (Sathyanarayana and Khan, 2008; Adi and Noor, 2009).

4.4. Enzymes and secondary metabolites

Approximately 90% of all industrial enzymes are produced in submerged fermentation, frequently using specifically optimized and genetically manipulated microorganisms. Most of the recent research activities on SSF are being done in developing nations as a possible alternative for conventional SmF, which are the main processes in pharmaceutical and food industries in industrialized nations. The use agro-industrial residues as substrates for bioprocesses, enzymes degrading agro-industrial residues, their production and bioconversion of agro-industrial residues have niched in recent days (Nigam Singh and Pandey, 2009).Coffee pulp and husk offer potential opportunities to be used as substrates for bioprocesses. Recent studies have shown their feasibility for the production of enzymes, aroma compounds, mushrooms, etc., thus adding value to the by-product. One of the earliest approaches on the application of coffee pulp and husk was for the production of enzymes such as pectinase, tannase and caffeinase. Tannase production by using coffee husk with *P. variotii* at optimum conditions were studied by Battestin and Macedo (2007) who succeeded in getting 8.6-fold more enzyme production. Exploration using coffee by-products for the production of enzymes like amylase, protease and xylanase was carried out using fungal organisms such as *N.crassa, A.oryzae*, *Penicillium* sp. and *A. niger* (Murthy and Naidu, 2010a,b). SmF is often viewed disadvantage owing to its high operation cost (Viniegra-González et al., 2003) therefore enzyme production by SSF using agro by-products not only brings down the cost of production (both of fermentation and downstream processing), but also provides an alternative path for the effective and productive utilization of such nutrient-rich agro residues.

In a recent study, coffee silver skin was proved to be an excellent material for use as support and nutrient source during fructooligosaccharides and β-fructofuranosidase production by *Aspergillus japonicus* under SSF conditions. This process was interesting and a promising strategy to synthesize both products at the industrial level (Mussatto and Teixeira, 2010). Chemical composition of coffee silver skin and spent coffee ground opens up possibilities for application of these residues in the production of different value-added compounds.

4.5. Ethanol

Recent studies indicate excellent potential for residue utilization in bio-ethanol production. Furthermore, it is estimated that ethanol production from agricultural residues could be increased by 16 times from the current quantum of production (Saha and Cotta, 2008). Machado (2009) reused spent coffee as raw material for ethanol production. Spent coffee was subjected to acid hydrolysis process and the obtained hydrolysate was used as fermentation medium by *Saccharomyces cerevisiae*, the ethanol production resulted in 50.1% yield. Similarly, Sampaio (2010) used spent coffee for the production of a distilled beverage. Gouvea et al. (2009) have indicated that coffee husks present excellent potential for residue-based ethanol production. They evaluated the feasibility of ethanol production by fermentation of coffee husks by *S. cerevisiae*. Best results were obtained when whole coffee husks were used with, 3 g yeast/l substrate and the temperature was at 30 °C. Under these conditions ethanol production achieved was 8.49 ± 0.29 g/100 g (dry basis) (13.6 ± 0.5 g ethanol/l), a value comparable to literature data for other residues such as corn stalks, barley straw and hydrolyzed wheat stillage (5–11 g ethanol/l). The study by Burton et al. (2010) reported the feasibility of using coffee oil extracted from spent coffee grounds as raw material to produce ASTM standard biodiesel and 98.5% conversion was achieved by using enzymatic catalysis, thus demonstrating the feasibility of this approach to process low quality coffee oil from spent coffee grounds for biodiesel production.

4.6. Biogas

Coffee husk, an important agro-industrial waste, cultivated with thermophilic *Mycotypha* to enable biomethanation (Jayachandra et al., 2011). The water drained from coffee cherry extract is another potential source for biogas production. The biogas produced can best be used to run an engine to generate electricity, and all the lower grade waste heat from cooling and exhaust can still be used for drying coffee (Rathanivelu and Graziosi, 2005).

4.7. Compost

Coffee pulp solids are a good source of humus and organic carbon. If coffee pulp is turned over every few days in a heap as in conventional compost making, it will compost in three weeks. The by-products of instant coffee production are solid wastes with high organic content. Studies on the applicability of the forced aeration composting process to a mixture of this coffee waste and agricultural wastes were satisfactory and the experiments led to the production of high quality compost having a carbon to nitrogen ratio of the order of 13:1 to 15:1 (Nogueira et al., 1999). Conversion of 350 thousand tons of coffee pulp would yield approximately 87 thousand tons of organic manure. These could be used in coffee nurseries, etc.

4.8. Dyes

Spent coffee has also demonstrated to be an inexpensive and easily available adsorbent for the removal of cationic dyes in wastewater treatments (Franca et al., 2009). Nakamura et al. (2009) concluded that coffee endocarp can be used as precursor for the production of activated carbons and contributes to the reduction of industrial residues in the Portuguese coffee industry creating economic surplus for a residue, which exists in abundance and also at low price. Carbonaceous materials were produced from coffee grounds by microwave treatment and would be useful for carbonization of organic wastes to save energy (Hirata et al., 2002).

4.9. Bioactive compounds

Bioactive compounds are extra nutritional constituents that typically occur in small quantities in foods and are being intensively studied to evaluate their effects on health. Agro-industrial by-products are good sources of phenolic compounds, and have been explored as sources of natural antioxidants (Fki and Allouche Nandsayadi, 2005). Coffee pulp in the extraction of polyphenols has been explored (Sera et al., 2000). Using coffee by-products such as coffee silver skin, Machado (2009) has recently evaluated the ability of seven different fungal strains from the genus *Aspergillus*, *Mucor*, *Penicillium* and *Neurospora* to grow and release phenolic compounds from under solid-state cultivation conditions, aiming at the biological detoxification of this residue. According to this author, *Penicillium purpurogenum*, *A. niger AA20*, *Neurospora crassa*, and *Mucor* released high amounts of phenolic compounds (between 2.28 and 1.92 g/l) from the material structure and hence succeeded in the detoxification of coffee silver skin, which would be beneficial for their subsequent disposal to the environment.

It is also reported that coffee silver skin has antioxidant capacity, and hence could be considered as a new potential functional ingredient (Borrelli et al., 2004). The recovery process of the phenolic compounds from the coffee industry by-products and their antioxidant activity were investigated and the results are presented in Table 3. Coffee by-products (pulp, husk, silver skin, and spent coffee) were obtained from coffee processing industry, the bioactive conserves prepared from coffee by-products possessed 65–70% antioxidant activity (Murthy and Naidu, 2010a,b; Rocha et al., 2010). Determination of bioactivity (Ramalakshmi et al., 2009), amino acids (Lago and Antoniassi, 2001), sugars (Mussatto et al., 2011a), and oil contents (Freitas et al., 2000; Kondamudi et al., 2008) in spent coffee have also been performed aiming to find alternatives for the reuse of this residue.

4.10. Dietary fiber

Agro wastes are great sources of dietary fiber, which include cellulose, hemicelluloses, lignin, pectin, gums, and other

Table 3
Phenolic compounds obtained from coffee by-products.

By-product	Phenolic compounds	Levels	Reference
Coffee by-products	Chlorogenic acid	2.3–3.0%	Murthy and Madhava Naidu (2010)
Spent coffee	Chlorogenic acid	16 mg gallic acid equivalents/g	Ramalakshmi et al. (2009)

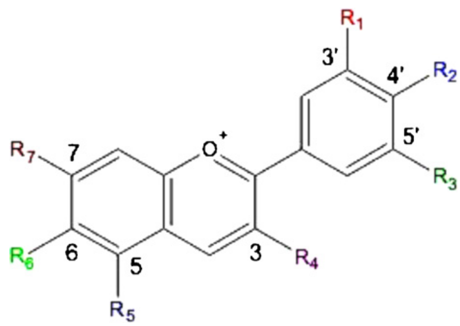

Fig. 10. Basic structure of coffee anthocyanins.

polysaccharides. The soluble and insoluble dietary fiber fractions (SDF and IDF) are known to confer a wide range of health benefits, including reduction in the risks of gastrointestinal diseases, cardiovascular diseases, and obesity (Figuerola et al., 2005). Among the coffee residues, silver skin contains high amount of total fiber (80%) followed by cherry husk and spent waste. Coffee fibers possess antioxidant properties. The synergy of antioxidant activity and the fiber complex in coffee by-products, like few cereals, attribute beneficiary effects than just a fiber moiety (Murthy and Naidu, 2010a,b). Taking into account that coffee by-products are obtained in millions of tons in coffee-producing countries, the functional compounds extracted from coffee by-products such as coffee pulp, cherry husk, silver skin, and spent wastes could be used as natural antioxidant sources, nutraceuticals, and preservatives in food formulations.

4.11. Anthocyanins

Anthocyanins are flavonoid compounds responsible for the red/blue coloration of many fruits and flowers (Stintzing and Carle, 2004). In the wet process, coffee pulp is removed prior to drying, while still fresh, and its color rapidly gets degraded by the action of enzymes (peroxidases and polyphenoloxidases) liberated by the damaged cells of the outer skin and pulp during the de-hulling process or by other oxidizing agents, such as oxygen. Thus, large amounts of natural colorants are wasted in this process. Thus, fresh coffee husk, comprising of outer skin and pulp, was investigated as potential source of anthocyanins for application as natural food colorant. Characterization of anthocyanins from coffee pulp was investigated by Emille et al. (2007). Cyanidin 3-rutinoside was characterized as the dominant anthocyanin in fresh coffee husks and its quantification recommended fresh coffee husks to be a good candidate as pigment source (Fig. 10). Coffee anthocyanins have reported to comprise of multiple biological effects (Murthy et al., 2012). The coffee pulp, a source of anthocyanins can find an opportunity as colorant and bioactive ingredient for formulated foods.

4.12. Food products and aroma compounds

The use of agro-industrial residues as substrates in biotechnological processes seems to be a valuable alternative to overcome the high manufacturing cost of industrial fermentations. Fresh coffee pulp can be easily processed into various food commodities like jam, juice, concentrate, jelly, and flavoring (Madahava Naidu et al., 2004). Spent coffee after defatting and extract lyophilization allowed to obtain spent coffee extract powder with high antioxidant capacity that can be used as an ingredient or additive in food industry with potential preservation and functional properties (Bravo et al., in press). Soares et al. (2000a,b) studied fruity flavor production by *Ceratocystis fimbriata* grown on steam-treated coffee husk supplemented with glucose. The results elucidated strong pineapple and banana aroma compounds formed during fermentation, when different concentrations of glucose (20–46%) were used. While leucine was enhanced in the medium, the total volatiles were evident, especially ethyl acetate and isoamyl acetate, resulting in a strong banana odor. Other aldehydes, alcohols and esters were also identified in the headspace of the cultures. Adriane et al. (2003) have reported that there is great potential for the use coffee pulp and coffee husk as substrates to microbial aroma production by solid state fermentation using two different strains of *C. fimbriata*.

4.13. Production of particle board

Recent interest in environment-friendly materials has led to the use of agricultural by-products as raw material for the production of particle boards. Coffee husk and hulls which are residues of coffee processing contain a great amount of cellulose and hemicellulose which make them almost comparable to wood. Bekalo and Reinhardt (2010) have reported that the coffee husk-wood board showed great promise for use in structural and non-structural panel products based on superior flexural and internal bond properties. Their results collate potential for substituting wood up to 50% with coffee husk in the production of particle board products.

4.14. Fuels

Production of energy from renewable and waste materials is an attractive alternative to the conventional agricultural by-products. Spent coffee ground is used as fuel in industrial boilers of the same industry due to its high calorific power of approximately 5000 kcal/kg, which is comparable with other agro-industrial residues (Silva et al., 1998). An attempt to extract oil from spent coffee grounds and to further transesterify the processed oil to convert it into biodiesel has been made by Kondamudi et al. (2008). This process yields 10–15% oil depending on the coffee species (*Arabica* or *Robusta*). The biodiesel derived from the coffee grounds (100% conversion of oil to biodiesel) was found to be stable for more than 1 month under ambient conditions. They project 340 million gallons of biodiesel production from the waste coffee grounds produced around the world. The coffee grounds after oil extraction are ideal materials as garden fertilizer, feedstock for ethanol, and as fuel pellets (Sendzikiene et al., 2004; Kondamudi et al., 2008). In this direction, further feasibility of using supercritical fluid extraction processes to obtain lipid fraction from spent coffee has also been explored (Couto et al., 2009).

4.15. Animal feed

Coffee husks and pulp have been reported to be used to feed farm animals (Mazzafera, 2002). The possibility of spent coffee use as animal feed for ruminants, pigs, chickens, and rabbits have also been demonstrated by Claude (1979) and Givens and Barber (1986). Ambiguously, the high lignin content (≈25%) is considered as a limiting factor for its application (Cruz, 1983). The pulp has 12% protein

Table 4
Coffee industry by-products and its application.

By-product	Applications	References
Coffee pulp	Mushroom production	Fan et al. (2001) and Murthy and Manonmani (2008)
	Compositing	Nogueira et al. (1999)
	Food commodities	Madahava Naidu et al. (2004)
	Polyphenol extraction	Sera et al. (2000)
	Anthocyanins	Emille et al. (2007) and Murthy et al. (2012)
	Animal feed	Ajebu Nurfeta., 2010
	Biosorbents	Irawaty et al. (2004)
Coffee husk	Citric acid	Shankaranad and Lonsane (1999)
	Gibberellic	Machado et al. (2000, 2002)
	Vermicompost	Sathyanarayana and Khan (2008) and Adi and Noor (2009)
	Flavor	Soares et al. (2000a,b)
	Particle board	Bekalo and Reinhardt (2010)
	Biosorbents	Oliveira et al. (2008)
	Tannase	Battestin and Macedo (2007)
Coffee pulp and husk	Animal feed	Mazzafera (2002)
	Amylase	Murthy et al. (2009)
	Protease	Murthy and Madhava Naidu (2010)
	Pectinase	Murthy and Madhava Naidu (2011)
	Xylanase	Murthy and Madhava Naidu (2010)
	Fructooligosaccharides and β-furctofuranosidase	Mussatto and Teixeira (2010)
	Ethanol production	Gouvea et al. (2009)
	Biogas	Jayachandra et al. (2011) and Rathanivelu and Graziosi (2005)
	Aroma	Adriane et al. (2003)
Coffee silver skin	Phenolic compounds	Borrelli et al. (2004) and Machado (2009)
	Dietary fiber	Murthy and Naidu (2010a,b)
Spent waste	Animal feed	Claude (1979) and Givens and Barber (1986)
	Ethanol	Machado (2009) and Sampaio (2010)
	Coffee oil	Burton et al. (2010)
	Adsorbent	Franca et al. (2009)
	Activated carbon	Nakamura et al. (2009) and Namane et al. (2005)
	Carbonaceous materials	Hirata et al. (2002)
	Antioxidants	Ramalakshmi et al. (2009)
	Spent coffee extracts	Bravo et al. (in press)
	Fuel, biodiesel, bioethanol	Silva et al. (1998), Sendzikiene et al. (2004) and Kondamudi et al. (2008)

content and its incorporation up to 20% in cattle diet, 5% in poultry feed, 3% in bird and 16% in pig feed has been recommended. Nurfeta (2010) has reported that the use of poultry litter as a component of a diet with coffee pulp could play beneficial role in neutralizing the anti-nutritional factors in coffee pulp and also help in increasing its utilization as feed.

4.16. Activated carbon and biosorbents

Pyrolysis of coffee pulp impregnated with phosphoric acid produces materials with a well developed pore structure with high adsorption capacity. The impregnation ratio has a strong influence on the pore structure. Irawaty et al. (2004) have reported, soaking

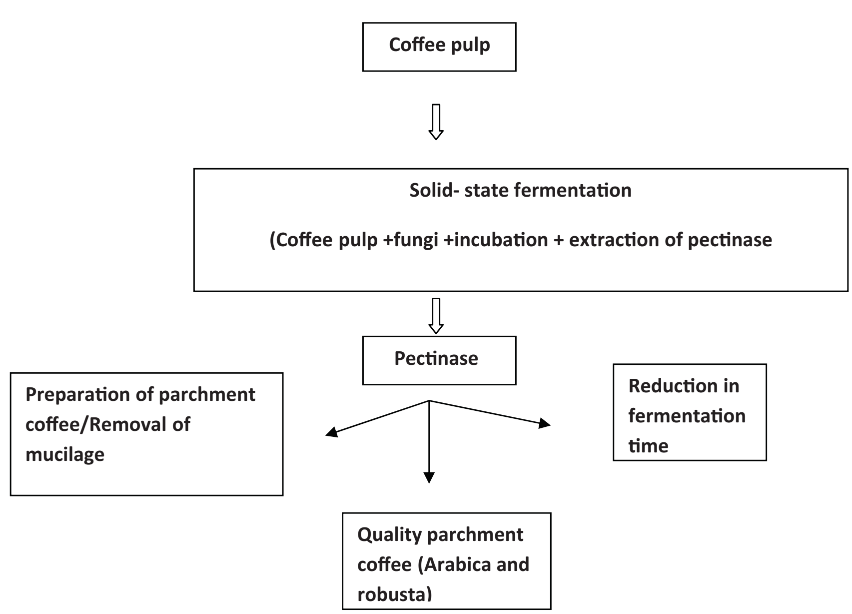

Fig. 11. Applications of coffee pulp at the coffee estate.

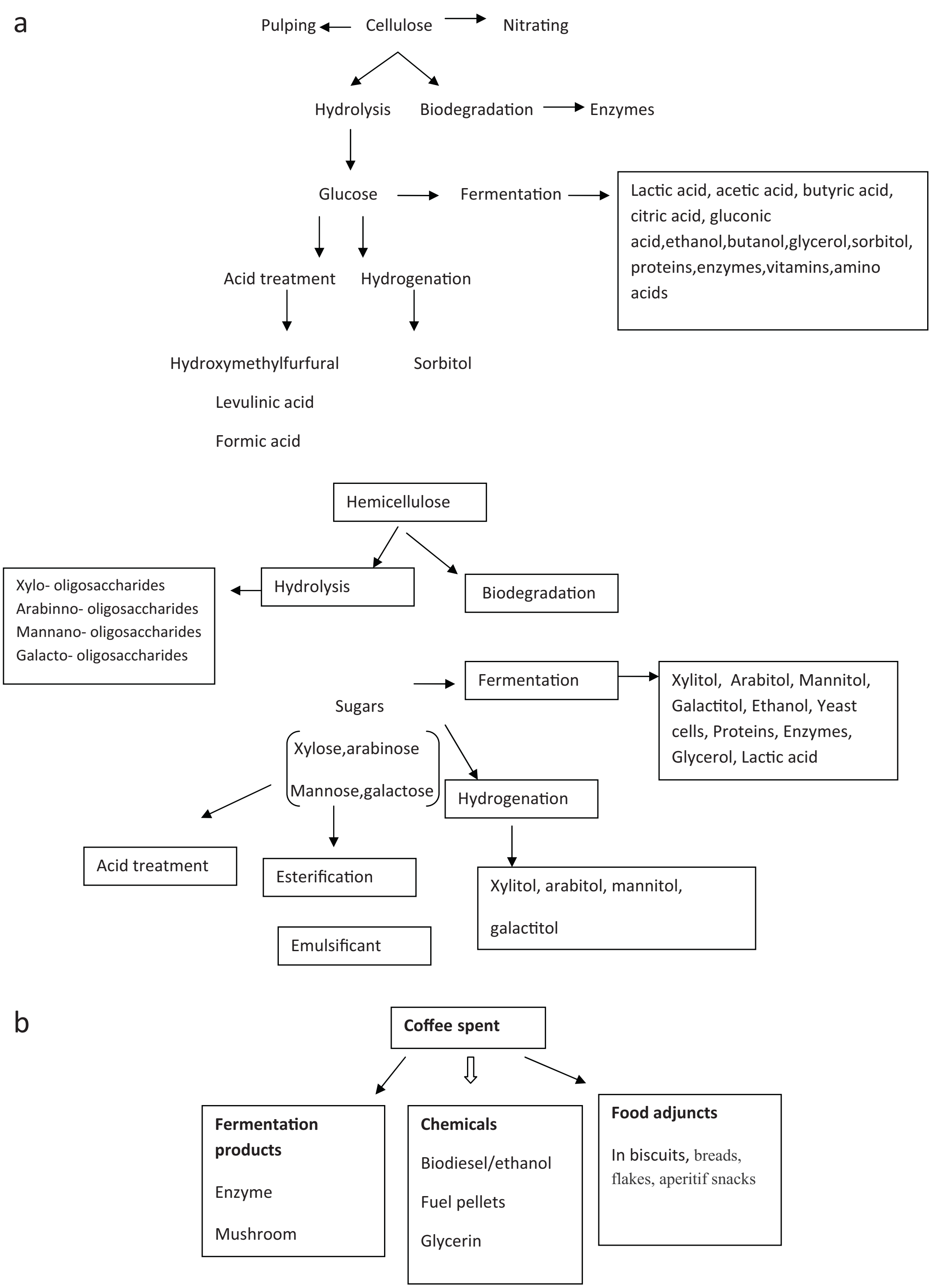

Fig. 12. (a) Applications for cellulose and hemicelluloses fractions present in coffee silver skin and spent coffee grounds (Mussatto et al., 2011a). (b) Feasible applications of coffee spent and silver skin.

of pulp with phosphoric acid produced high adsorption capacity. An alternative use of coffee husk is as untreated sorbent for the removal of heavy metal ions from aqueous solutions as reported by Oliveira et al. (2008) who established coffee husks as suitable candidate for use as biosorbent in the removal of heavy metals from aqueous solutions. Defective coffee press cake, a residue from coffee oil biodiesel production, was evaluated as raw material for production of an adsorbent for removal of methylene blue (MB) from aqueous solution. Studies carried out by Anne et al. (2009) indicate that coffee press cake is suitable candidate for removal of cationic dyes. Thomas et al. (2008) have highlighted the potential to utilize waste biomass to produce electrode materials for cost-effective energy storage systems. Activated carbon was produced from waste coffee grounds by treatment with $ZnCl_2$ (Namane et al., 2005). Supercapacitor electrodes prepared from coffee grounds carbon exhibited excellent stability with high charge–discharge rates

(Thomas et al., 2008). In a two-electrode cell a specific capacitance as high as 368 F g^{-1} was observed, with rectangular cyclic voltammetry curves and stable performance over 10,000 cycles at a cell potential of 1.2 V and current load of 5 A g^{-1}. The good electrochemical performance of coffee grounds carbon is attributed to develop porosity, with distribution of micropores and mesopores of 2–4 nm wide, and the presence of electrochemically active quinone oxygen groups and nitrogen functional groups. From the purview of food and bioprocess industry, possibility to fractionate coffee by-products using appropriate processes represent an exciting opportunity to attain new functional ingredients with high nutritional value (Table 4).

5. Future utilization of coffee industrial residues

Sustainable utilization of agro-industrial wastes through integration of bio-energy and mushroom production proposes to integrate mushroom cultivation from coffee processing for more value addition. The techno-economic feasibility of the integrated technologies benefit agro processing industries, diversify their products through utilization of coffee wastes to produce bioproducts with high economic value with competitive advantage. Utilization of coffee wastes for oyster mushroom cultivation is still in its infancy. Growing oyster mushrooms by utilizing coffee wastes holistically help in obtaining high mushroom yields, making the venture technically realistic and feasible at large scale. One of the easy approaches is the use of coffee pulp and husk for production of mushrooms in the coffee estates and curing works itself where the material is readily obtained and also could be seasonal occupation developing value addition. This process has now commercially established and valorization would be interesting from environmental and economic standpoints and will be a sustainable measure for coffee industry. Production of bioproducts such as silage, biogas, animal feed, ethanol, vinegar, single-cell protein, enzymes, biopesticides, and probiotics have been established at small scale and demonstration of technologies at pilot scale is yet to be achieved.

The criterion for any process to be industrially favorable is its cost-effectiveness and eco-friendly nature. Robusta coffee takes longer time (more than 48 h) for the completion of fermentation process compared to arabica coffee. Conventional post-harvest coffee processing is carried out to remove mucilage by fermentation using water. Quite often the mucilage breakdown is not complete even after 72 h of fermentation. If the coffee beans are fermented for long period, stinker beans (over fermented beans) develop. Most of the quality defects of coffee are attributed to inadequate control during fermentation and drying. Additional economic losses are due to uncontrolled fermentation. Thus, alternate postharvest processes have been under investigation for several years. The duration for digestion in conventional coffee demucilage varies from 48 to 72 h depending on temperature and thickness of mucilage (Avallone et al., 2001).

The use of coffee pulp as a substrate for pectinase production is more economical as commercial pectin is expensive. Pectinase was produced by SSF using coffee pulp as sole carbon source with *A. niger*. Coffee pulp was pre-treated with activated carbon and used for fermentation to enable degradation of the pectins/mucilage. Pectinase effectively demucilaged robusta coffee in the fermentation process, with accelerated fermentation in 3 h and also have resulted to have good organoleptic characters (Murthy et al., 2012). Use of pectinase for demucilaging the same signifies waste recycle with value addition and is also economical for coffee industry. The first batch of coffee pulp obtained could be used for production of pectinase and subsequently for fermentation process to reduce cost and labor (Fig. 11). Fermentation period and processing difficulties can be overcome by these economical methods and will be a boon for the coffee processing and for production of washed robusta which otherwise requires long fermentation duration. Further research are necessary in order to elucidate the potential of these coffee residues in bioprocesses, mainly in the area of fermentation technology, and to explore some more enzymes such as cellulase and tannase in their possible applications. Isolation of wild strain of microbe which can efficiently metabolize coffee by-products, Bioprocess optimization using factorial design and surface response experiments could be useful in selecting production parameters. Application in bioprocesses helps in substrate utilization and also pollution problems.

Potential applications for cellulose and hemicellulose fractions present in coffee silver skin and spent coffee grounds are illustrated by Machado et al. (2012) and are presented in Fig. 12a and b. The protein content present in CS and SCG is significant. Due to the large continuous supply and relative low cost, both the coffee residues could be considered as adjunct for human food, similar to brewer's spent grain which has been evaluated for nutritional enrichment of food products (Miranda et al., 1994). Incorporation of CS and SCG for the manufacture of flakes, breads, biscuits, and aperitif snacks would be interesting alternatives for application of these materials and should be evaluated. Another innovative approach is biogas production (Neves et al., 2006). The biogas produced could be used for roasting of coffee processing solid wastes and the waste heat from the roasting unit could be used for pre-drying of the wastes. The roasted coffee waste would produce briquettes with 70% less processing cost and 80% more energy density than the ones made from raw biomass. However, the feasibility of this concept is yet to be investigated and demonstrated at pilot scale.

6. Conclusions

Coffee is one of the important products, its subsequent processes such as cultivation, processing, trading, transportation, and marketing, provide employment and is a huge business worldwide. With the high crop production projected in the future, there is a vital need to counterpart this production with proper utilization and industrial application of coffee by-products. Valorization of these by-products could be value addition from environmental point of view.

SSF is an appropriate technology for value-addition and utilization of coffee processing by-products. The substrate compositions as well the microorganisms evince their application for the production of enzymes, organic acids, mushrooms, flavor and aroma compounds, pigments, polysaccharides and hormones. The cost and availability of substrates are important in the development of any efficient process in food and pharmaceutical industries. Integration of coffee by-products and use of efficient microorganisms to metabolize can serve dual purpose of value addition as well as waste management with environment conservation. However, much remains to be done in these areas to develop commercial processes with techno-economic feasibility.

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