Food Engineering Reviews (2024) 16:146–162
https://doi.org/10.1007/s12393-023-09352-4

# Coffee Cherry on the Top: Disserting Valorization of Coffee Pulp and Husk

**Evelin Král[1] · Jakob L. Rukov[2] · Ana C. Mendes[1]**

Received: 31 March 2023 / Accepted: 17 July 2023 / Published online: 9 August 2023


**Abstract**
Coffee is still one of the most consumed beverages in the world. Yet, the large quantities of by-products generated during coffee production are wasted, which is a burden in the sustainability of coffee production. Coffee cherry by-products are rich in several compounds of interest that can be used in several applications, minimize the wastes, and the environmental damage from coffee production. This review article aims to discuss the relevance of coffee processing by-products, namely, the coffee cherry husk and pulp to create value-added food products. Their chemical composition, properties, and extraction methods of valuable compounds are discussed, and possible food applications showcased, thereby aiming at increasing and supporting a more environmentally friendly coffee utilization.

**Keywords** Coffee by-products · Up-cycling by-products · Extraction methods · Bioactives

## Introduction

Coffee is one of the most popular beverages in the world with a yearly average production of 9 billion kg tonnes of coffee beans [1, 2]. The demand for coffee is predicted to increase up to 150% by 2050 [3], which will simultaneously lead to increased production of coffee by-products. Coffee plants are farmed in the tropic region with Brazil as the largest producer, followed by Vietnam, Colombia, and Indonesia. The market is dominated by two varieties, *Coffea arabica L.* (Arabica) and *Coffea canephore Pierre* (Robusta) [4, 5].

One of the main burdens on the sustainability of coffee production is the large amount of waste generated during processing [2]. In order to obtain the coffee beans, the coffee cherry has to undergo processing, during which the beans are separated from the outer layers. According to Usva et al. (2020), the carbon footprint of coffee was found to be 0.27–0.70 kg $CO_2$ eq/l coffee, and the irrigation water footprint is 0.15–0.27 $m^3$ eq/l coffee, and the cultivation stage contributes to 32–78% of the total carbon footprint [6]. Therefore, it is worth looking at the by-products produced as possible raw materials to close the circularity gap [7]. The concept of circular economy, which encourages the maximal utilization of existing materials, can also be applied to agricultural production. With the help of a biorefinery strategy, the low-cost, abundantly available raw materials could be harnessed for valorizing several valuable ingredients, contributing to a more sustainable agro-industrial production [8].

Coffee processing by-products are rich in nutrients and bioactive compounds[9, 10], representing potentially valuable ingredients for the food, nutraceutical, and cosmetic industry [8–10]. Previous studies showed antimicrobial [11–13] and antioxidant [13, 14] properties of phytochemicals obtained from coffee by-products, among others [9]. Moreover, the consumer demand for natural ingredients in the food industry, and nutrients with proven health benefits is currently increasing [9].

Besides the environmental impact of coffee production, it is important to mention the social aspect as well. The livelihood of 125 million people is estimated to depend on coffee production worldwide today [15]. Coffee prices have decreased since 2016, reaching 30% lower price compared to the average of 2010 [2]. As a result, farmers have struggled to cover operating costs, the livelihood of workers has become uncertain and many countries' economies depend on coffee production [2]. By harnessing coffee production by-products, coffee growers would be enabled to generate extra income, representing an effective strategy to minimize the impact of increasing production costs [2].

✉ Ana C. Mendes
anac@food.dtu.dk

[1] DTU-Food, Technical University of Denmark (DTU)- National Food Institute, Kemitorvet 202, 2800 Kgs. Lyngby, Denmark

[2] Otto Busses Vej 63, 2450 Copenhagen, SV, Denmark

The increase in world population, and environmental changes, is increasing the need of alternative and sustainable ingredients and foods that sustain healthy lifestyles and well-being. Food industry is looking actively for novel, sustainable, and innovative solutions to feed the world population, and therefore, the management and up-cycling of food industrial by-products could be a solution. Based on these premises, this review article aims to discuss the relevance of coffee processing by-products, namely, the coffee cherry husk and pulp, two of the most produced coffee by-products, to create value-added products for foods and food ingredients. Their chemical composition, properties, extraction methods of valuable compounds, and examples of food applications are discussed, thereby aiming at increasing and supporting a more environmentally friendly coffee utilization in food applications.

## Coffee Cherry Processing and By-products

The coffee plant bears 10–15-mm long fruits that are also called cherries or berries (Fig. 1) [9]. In the middle of the cherry, two seeds are developed, i.e., the coffee beans (endosperm) that are covered by the silver skin. The seeds are enveloped by the parchment, a thin layer of cellulosic, yellowish endocarp which constitutes a durable layer protecting the seeds. The endocarp is surrounded by the mucilage or pectin layer. This layer is viscous, colorless, and translucent. The pulp (outer mesocarp) is found between the mucilage and the skin and is soft, fleshy, fibrous, and yellowish in color. The most outer part is the skin or pericarp, which is green when unripe, and turns red, orange or yellow when ripe, for some particular genotypes [4, 9, 16].

The cherries are processed in order to obtain the seeds or the so-called green coffee beans. The beans are used for the production of coffee powder, and the rest of the cherry contains several by-products which includes coffee pulp (CP), mucilage (CM), parchment (CPm), husks (CH), silver skin (CS) [17], which are currently largely underutilized [5, 18]. Altogether, around 50% of the coffee cherry is discarded causing serious environmental problems for soil and water around farm land [1, 5]. The amount of coffee by-products and its impact generated during the several stages of the coffee production are summarized in Fig. 1. The soil and water problems noticed from the waste of the cherry arise from the high acidity, high content of caffeine, tannins, and other polyphenols [1, 5]. When landfilled, the pH of the soil is acidified causing nutrient unavailability for crops [19]. Furthermore, the long term release of caffeine into waters has a negative impact on the aquatic environment [20].

Depending on the method used, different wastes are created [4], as explained in the sections "Dry Process", "Wet Process", "Semi-dry or Semi-wet Process", and shown in Fig. 1. Drying is an important step in all processing methods. By reducing the moisture content of coffee processing by-products low level, elongated shelf life can be achieved.

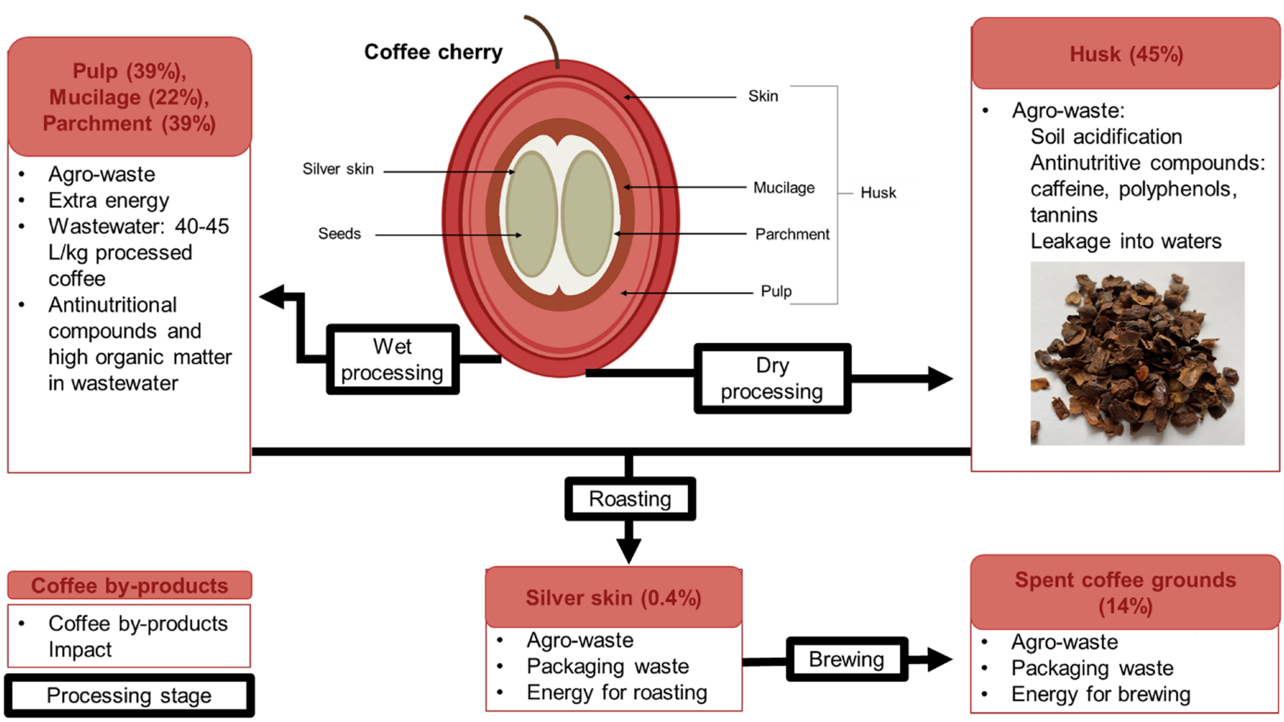


**Fig. 1** Schematic representation of the coffee cherry, the different stages of the coffee production, and its impact [5, 7, 17]

Another preservation method mentioned by Ameca et al. is ensiling which according to some studies leaves the antioxidant capacity unchanged [21].

### Dry Process

Dry process is the simplest and least expensive method, and is therefore often used for Robusta coffee [5]. After harvesting, the coffee fruits are dried in the sun until the moisture content is reduced to 10–11%. The dried fruits are then dehulled mechanically to obtain the beans with the silver skin. The main by-product produced during the dry process is the husk and represents 40–50% of the dried fruit. In this method, no steps are implemented to ensure the separation of ripe and unripe cherries, which is crucial for high quality coffee beans [4, 9, 16].

### Wet Process

During the wet process, the ripe cherries are initially separated from the unripe and damaged cherries by flotation, the latter ones remaining on the surface of the water. The ripe fruits are de-pulped, and the skin and the pulp are obtained as a by-product at the first step [5, 16]. However, the mucilage layer remains around the seeds. Therefore, a fermentation step is applied in order to hydrolyze the sticky layer, mainly composed of pectin. Fermentation takes place for 12–48 h; then, the seeds are washed to completely get rid of the mucilage [5, 9]. Meanwhile, a lot of waste water is created [9]. Then, the parchment coffee beans are dried, and the de-pulping step is repeated which results in separation of the beans and the parchment (another by-product) [5, 9, 16].

Wet processing is associated with superior coffee bean quality and better aroma profile, therefore, the beans produced with this method have higher economic value [9, 16]. Higher content of chlorogenic acids and trigonelline and lower content of sucrose were linked with wet processing [16]. On the other hand, this processing method is more expensive, consumes a lot of water and energy due to the equipment used, and it therefore has a larger environmental impact [5, 9]. It is generally used for Arabica coffee [5].

### Semi-dry or Semi-wet Process

This method differs from the wet method, because the fermentation step is excluded. Thus, after de-pulping, the beans are dried with the mucilage and the parchment layer on and then de-hulled [9]. As described by Esquivel and Jiménez (2012), several by-product fractions can be obtained by this process: the skin and the pulp in one fraction, generally called pulp (~40% w/w of the whole cherry), mucilage and soluble sugars as second fraction (~12% w/w), and the parchment (~6% w/w) [16].

## Coffee Pulp and Husk Composition

Plants are not only a source of essential nutrients such as carbohydrates, lipids, and proteins but also non-nutrient bioactive compounds [9]. The approximate composition of coffee pulp is 50% carbohydrates, 20% fibers, 10% protein, 2.5% fat, and 1.3% caffeine [4]. However, the nutritional composition of the coffee cherry is determined by the variety, altitude, climate, soil, agricultural practices, harvest time, processing method and circumstances, among others [4, 22].

Cheng et al. (2016) summarize the effect of shade and altitude on the content of different components of coffee beans. When the plants were grown in shade, the content of caffeine and lipids were increased while trigonelline, chlorogenic acids, and sucrose content were decreased. Higher growing altitudes resulted in higher content of caffeine, trigonelline, lipids, and chlorogenic acids and in lower sucrose levels in coffee beans [23].

As mentioned previously, depending on the processing method used, the main by-product can either be the husk when dry method is used or the pulp when wet method is applied. The fresh coffee pulp can have a moisture content of 82.4% [24]. Coffee pulp and the coffee husk are slightly different products, since in coffee pulp, the pectin rich mucilage is removed [9, 16]. The nutrient content in the pulp and the husk is shown in Table 1. Of these compounds, some are insoluble in water, including polysaccharides like cellulose, hemicellulose and lignin, lipids, minerals, some of the vitamins, and proteins [9].

### Carbohydrates

Carbohydrates are the most abundant components of coffee pulp and husk by-products, as shown in Table 1. The identified polysaccharides are fibers, such as cellulose, hemicellulose, lignin, and pectin [9]. Coffee pulp and husk contain a significant amount of fermentable sugars making them favorable substrates for fermentation [9]. In green coffee beans, carbohydrates were identified as binders of aroma compounds and they influence the viscosity and foam stability of the brewed coffee [39].

#### Sugars

Sugars are non-volatile compounds that can contribute to the flavor of the beverage. According to Pua et al. (2021), the pulp is rich in mannose, fructose, and also has a relatively high content of galactose, while glucose is less prominent. Lower glucose concentration might be observed due to fermentation occurring during drying of the pulp [40]. Coffee pulp contains 23–27% fermentable sugars on dry weight basis [41]. Rambo et al. (2015) prepared

**Table 1** Nutritional composition of dried coffee pulp and husk

| Nutrient | Nutrient/pulp (g/100 g)* | Reference | Nutrient/husk (g/100 g)* | Reference |
|---|---|---|---|---|
| Carbohydrates | 57 | [25] | 58–85 | [26] |
| Sugars | 9.7 | [24] | 26.5–36.4 | [27, 28] |
| Reducing sugars | 9.6 | [24] | 11.24 | [28] |
| Sucrose | N.M | | 2 | [26] |
| Total dietary fibers | 16–28 | [25, 29] | 43 | [29] |
| Cellulose | 10–33 | [24, 25, 30] | 43 | [26] |
| Hemicellulose | 15–29 | [24, 25] | 7 | [26] |
| Lignin | 26–31.5 | [24, 25] | 9 | [26] |
| Pectin | 11.3 | [24] | 1.6 | [26] |
| Proteins | 7–13 | [13, 21, 24, 25, 30] | 4.8–6.5 | [27, 28] |
| Lipids | 1.3–2.5 | [13, 25, 30] | 1.5–1.66 | [27, 28] |
| Ash | 7.3–8.9 | [13, 24] | 5.6–6.3 | [27, 28] |
| Potassium | N.M | | 2.060 | [31] |
| Calcium | 0.320 | [9] | 0.221 | [31] |
| Magnesium | N.M | | 0.079 | [31] |
| Iron | 0.010–0.050 | [32] | 0.026 | [31] |
| Sulfur | N.M | | 0.110 | [31] |
| Tocopherols | N.M | | 0.006–0.010 | [33] |
| Total phenolic content | 0.255–0.453 | [34] | 0.384–0.455 | [35] |
| Tannin content | 0.7 | [36] | 9.3 | [27] |
| Caffeine | 0.54–4.15 | [13, 25, 36, 37] | 1.2–1.39 | [27, 38] |
| Trigonelline | N.M | | 0.15–0.18 | [11] |
| Moisture after drying | 11.6 | [25] | 12–12.3 | [27, 28] |

*N.M.*, not mentioned; *dry weight

ethanol extraction of the coffee husk and analyzed the sugar composition of the biomass. Contrary to Pua et al. (2021), they found that 35.3% of it was glucose, 21.9% xylose, 1.7% mannose, 1.6% arabinose, 1.5% galactose, and 0.5% rhamnose, and the total sugar content was 62.5%. However, since hemicellulose can be extracted with ethanol, it may contribute to the relatively higher sugar content measured [42]. Since sugars are water soluble, they can be extracted by aqueous extraction [39]. Compared to other plant sources, coffee husk is rich in xylose [42].

### Fibers

Dietary fibers are plant cell wall compounds mainly consisting of cellulose, hemicellulose, pectic substances, and lignin [29]. They consist of sugar monomers [43]. Soluble and insoluble dietary fibers are distinguished based on their water solubility. Soluble dietary fibers, like pectin, β-d-glucan, galactomannans, glucomannans, inulin, and resistant starch, can dissolve in water [44]. The broad definition of fibers, as defined by the European Food Safety Authority (EFSA), is non-digestible carbohydrates that include non-starch polysaccharides, resistant starch, oligosaccharides, and lignin [9]. These materials cannot be digested by human enzymes present in the gastrointestinal track [29, 45], however, the gut microbiota has a wide range of enzymes to break them down while producing beneficial fermentation products for the host [45, 46]. Murthy and Naidu [29] measured 28% total dietary fiber content for coffee pulp of which 18 ± 0.9% being soluble and 10 ± 0.8% insoluble [29]. Coffee pulp is rich in pectin that has gel forming ability at low pH and high sucrose concentration [17]. Pectin is a functional food ingredient that is used as a stabilizer and gelling agent due to its gel forming and viscoelastic properties [18]. Phenolic compounds and other bioactive molecules can be found covalently bound to the plant cell wall [29] in coffee by-products, providing antioxidant properties to dietary fibers. The total antioxidant activity of coffee pulp and coffee husk fiber measured by Murthy and Naidu (2010) was 1.53 ± 0.6 and 1.84 ± 0.5 mmol Trolox equivalent/100 g, respectively, which are in line with that of fresh fruits and vegetables [29]. In another study, the total antioxidant capacity of dietary fiber in coffee husk was about 48.6 mg chlorogenic acid/g [38].

## Lipids

Lipids are flavor carriers and they contribute to mouthfeel and texture [23]. As indicated in Table 1, the lipid composition of coffee pulp and husk was found to be 1.3–2.5 and 1.5–1.7 g/100 g, respectively. Lipids are derived from the coffee peel which is covered by wax. Cutin is the most significant compound [17], although, Duangjai et al. (2016) also identified sterol compounds in the hot water extract of dried coffee pulps [13]. Currently, there is no comprehensive analysis of the lipid composition of the coffee fruit processing by-products available. Since coffee bean is more widely studied, the lipid composition is better described. The major lipids identified were sterols, tocopherols, diterpenes, and triacylglycerols [16], and the lipid content has been measured at 7–17%, including coffee oil found in the endosperm of the coffee beans [23].

## Proteins

Proteins are biopolymers of amino acids. The amino acid sequence influences the complex structure of proteins, as well as the biological function. Proteins are key functional food ingredients due to the capability to form gel, stabilize structures, form emulsions, and foams [47]. The coffee bean has a slightly higher (ca. 13–16%) protein content than that of the pericarp [48]. The foam layer formed on top of an espresso is an important influencer of coffee cup quality and is related to the proteins present in the bean [49]. In green coffee beans, most of the proteins are present as α- and β-legumin type storage proteins [48]. Other fractions include enzymes and arabinogalactan-protein complexes, a fraction of structural elements in cell walls and bound to membranes [39, 48]. The cell wall of fruits typically contain around 5% protein [50]. For instance, Dong et al. (2020) extracted 2.8–5.55 g/100 g protein together with soluble fibers from the coffee peel [51]. As shown in Table 1, the protein content of coffee husk is 5–6%, while 7–13% protein are found in coffee pulp. However, since coffee cherry is rich in other nitrogen containing compounds, such as caffeine and trigonelline, protein content measured by the Kjeldahl method (using the $N \times 6.25$ conversion factor) is likely to result in an overestimation [17]. The proteins found in greatest abundance in ripe cherries are globulins, while the most abundant amino acids in the husk are glutamic acid and aspartic acid accounting for 7.7% and 7.1% of total amino acids [26, 48]. In coffee pulp, 3% of the protein present was found to be in a lignified form which compromises its bioavailability [9].

## Minerals and Vitamins

In plants, minerals can be found in inorganic, and organic forms. When phosphorus is stored in organic form as phytic acid, it often complexes with magnesium, potassium, and calcium salts. Since phytate salts are insoluble in water, the way phosphorus salt is stored influences the solubility of other minerals [52]. As shown in Table 1, the ash content of husk and pulp is 5.6–6.3% and 7.3–8.9%, respectively. In husk, potassium was found to be the predominant mineral, followed by calcium, sulfur magnesium, and iron. However, the number of studies analyzing the mineral content in coffee pulp is limited [9, 31]. Calcium was shown to be more abundant in coffee husk and pulp than in spent coffee or silver skin. Reports on the vitamin content of coffee by-products are limited. As indicated in Table 1, coffee husk contains tocopherols which are also present in the bean and the silver skin, however, the tocopherol profile differs [9].

## Phytochemicals

Coffee cherries are rich sources of phenolic compounds and alkaloids [9]. Several studies focused on the valorization possibility of these compounds from different coffee sources [5, 9, 10].

### Phenolic Compounds

There is a growing interest for phenolic compounds due to their health benefits. Coffee by-products are good sources of phenolic compounds. Iriondo-DeHond et al. (2019) observed that the amount of phenolic compounds increase from the outside to the core of the coffee cherry [38]. The four main groups found in coffee pulp are flavan-3-ols, hydroxycinnamic acids, flavonols, and anthocyanidins [4]. Londono-Hernandez et al. (2020) found 23 phenolic compounds in the ethanol extract of dehydrated coffee pulp of which 17 were identified. Of these molecules, hydroxycinnamic acids, flavanols, hydroxycoumarins, and fatty amides accounted for 59%, 17%, 6%, and 6%, respectively, most corresponding to polyphenols [25]. Murthy and Naidu found chlorogenic acid as the most abundant compound in coffee pulp and cherry husk [29]. Polyphenolic compounds are known for their antioxidant properties, and flavonoid content, as showed in a study with coffee pulp [34].

**Phenolic Acids** Coffee pulp was found to be a rich source of phenolic acids, of which ferulic acid, protocatechuic acid, 5-caffeoylquinic acid (chlorogenic acid), 3-*p*-coumaroylquinic acid, and 3-feruloylquinic acid were reported most frequently [13, 53, 54]. Due to their antioxidant properties, they are widely studied [25]. Hydroxycinnamic acids, such as chlorogenic, ferulic, and caffeic acids, exert antioxidant properties by donating a hydrogen atom to oxidized molecules [13].

Chlorogenic acids (CGAs—a subgroup of phenolic acids) are ubiquitous in plants [55] and are mainly produced by the esterification of trans-hydroxycinnamic acids such as p-coumaric acids, ferulic acids, caffeic acids, and sinapic acids with (-) quinic acid [22, 56, 57]. Caffeic, p-coumaric, ferulic, vanillic, and protocatechuic acids are the most commonly occurring CGAs in coffee [9, 58]. The chlorogenic acid content in coffee can account up to 10% of the dry matter [55], and therefore, coffee is regarded as to be the most abundant source of CGA. In some countries, coffee is the most prominent source of antioxidants, accounting up to 1 g of CGAs per day [22, 56].

CGAs give a flavor-profile of acidity, astringency and bitterness [23]. They are water soluble compounds and are heat labile; therefore,almost all the CGA content of coffee beans are lost when they are subjected to dark roasting [23, 39]. CGAs are susceptible to hydrolysis and isomerization [57]. In beans, caffeoylquinic and feruloylquinic acids are suspected to give off-flavors probably due to degradation products formed prior to roasting [22]. Heeger et al. (2017) analyzed the stability of these compounds during pasteurization and storage of water extracts of coffee pulp. Gallic acid, protocatechuic acid, and rutin were shown to be stable, however, epicatechin was found to disappear, supposedly due to processing and storage of the cherries [4]. Ramírez-Martínez (1988) identified chlorogenic acid (5-caffeoylquinic acid) (42.2% of the total of identified phenolic compounds), epicatechin (21.6%), 3,4-dicaffeoylquinic acid (5.7%), 3,5-dicaffeoylquinic acid (19.3%), 4,5-dicaffeoylquinic acid (4.4%), catechin (2.2%), rutin (2.1%), protocatechuic acid (1.6%), and ferulic acid (1.0%) in fresh coffee pulp by HPLC [59]. The composition of the extract and the amount of CGAs extracted depend on the solvent used for the extraction, characteristics of the raw material, and related factors [9]. For extraction, aqueous alcohol (most often 70% methanol) is frequently used [58].

**Tannins** Tannins are a highly heterogenous group of water soluble phenolic compounds. They are naturally present in plants, providing protection against biotic and abiotic stressors. Tannins can be divided into two groups: hydrolysable and condensable tannins [60]. Hydrolysable tannins can be further separated into gallotannins and ellagitannins. When gallotannins are hydrolyzed, the degradation products are sugar and gallic acid, while ellagitannins result in ellagic acid, besides sugar and gallic acid. These compounds can be hydrolyzed by weak acids and are decomposed when exposed to high temperature, creating a highly irritative substance named pyrogallol [60]. Condensed tannins represent the second most abundant group of phenolics after lignin [61]. These complex tannins are produced by the reaction of gallotannins or ellagitannins with catechin units, being the oligomers of flavan-3-ol and/or flavan-3,4-diol monomers. They are not readily hydrolyzed, but in an acidic alcoholic environment, they can be decomposed resulting in red pigments [25, 60].

On the other hand, increased antioxidant and radical scavenging activity was observed for tannins with higher degree of polymerization [60]. They act as free radical scavengers and can inhibit the xanthine oxidase enzyme, a producer of free radicals [34]. In humans, they exert antioxidant and free radical scavenging activities, antimicrobial, anti-inflammatory, anti-cancer, and cardio protective properties [60, 61]. In order to provide health effects, they need to be present in bioavailable form [60].

Fresh coffee processing by-products are a potentially valuable source of condensed tannins, such as proanthocyanidins [16]. Different anthocyanin compounds were found in coffee husks, pulp, mucilage, and peels [62, 63]. Prata and Oliveira (2007) found cyanidins as the most prominent group of anthocyanins in fresh coffee husk, being cyanidin-3-rutinoside the major one and Vinas et al. (2012) detected cyanidin-3-glucoside and cyanidin-3-O-p-coumaroylglucoside in the peel, pulp, and mucilage of different Arabica varieties [62, 63]. Anthocyanins were more abundant in red genotypes, which is expected due to the peel color [63]. However, anthocyanins in general are easily degraded by light, temperature, and oxidizing agents [62]. Aglycone derivates were observed after tissue browning and increased concentration of condensed tannins during drying [16]. Higher Oxygen Radical Absorbance Capacity (ORAC) values were measured when the concentration of condensed tannins were higher [34].

## Alkaloids

The most well-known alkaloid present in the coffee is caffeine. Trigonelline is the second most abundant alkaloid in green coffee beans and also contributes to bitter flavor and is water soluble. It is degraded during roasting while several desirable aroma compounds are being formed [23, 39]. Duangjai et al. (2016) have also identified trigonelline in the hot water extract of the coffee pulp [13].

**Caffeine** (1,3,7-trimethylxanthine) is an alkaloid synthesized in tea and coffee plants and is distributed in the roots, stems, leaves, and seeds of the plants [64]. It contributes to the bitter taste of the drinks brewed from these plants [23]. Since caffeine is an adenosine receptor antagonist, it stimulates the central nervous system increasing alertness, concentration, learning ability, decreasing fatigue, and boosting performance in exercise when consumed in moderate amounts. Coffee is currently the primary source of caffeine [23].

Caffeine is heat stable and water soluble, and *C. canephora* can contain up to twice as much as *C. arabica* [9, 22]. As indicated in Table 1, 0.5–4.15 g/100 g and

1.2–1.4 g/100 g caffeine was found in pulp and husk, respectively, by different researchers. According to the analysis of Londono-Hernandez et al. (2020), the caffeine content of the pulp was 3% of the dry weight [25]. Compared to the seed, the pericarp contains two to ten times lower amount of caffeine [16]. An *in vitro* test of caffeine metabolites showed antioxidant activity especially for 1-methylxantine and 1-methylurate [22, 65].

## Volatiles

Volatile compounds that contribute to the overall aroma profile of cascara were examined by Pua et al. (2021). They detected 91 components, of which the main groups were alcohols, esters, aldehydes, acids, and ketones, many of them found in other fruits as well. Compounds associated with dried fruits, such as pyrazines, furans were detected, supposedly due to the drying process [40]. Al-Yousef and Amina analyzed the volatile compound profile of dried coffee husk by essential oil isolation and identified 55 compounds [66]. The essential oil was predominantly consisting of aromatic compounds, mainly oxygenated constituents and hydrocarbons. The most abundant compounds were butylated hydroxytoluene (BHT), 1,2-benzenedicarboxylic acid, phenylethyl alcohol, octanoic acid, 2,3-isopropylidene-6-deoxyhexo, decane, 1,1′-oxybis-, nonanoic acid, 1,2-benzenedicarboxylic acid, beta-d-arabino-2-hexulopyran, oxalic acid, 2-ethylhexyl tetra, and hexatriacontane. The isolated oil was soluble in chloroform and ether but not in water [66].

## Extraction of the Main Components from the Coffee Husk and Pulp

As described in the previous section, the coffee cherry comprises of several valuable components. Many studies describe the extraction of bioactives (mainly phenolic compounds) from coffee processing by-products. Since the effectiveness of the extraction of these substances and the final chemical composition of the extract is influenced by several factors, some considerations are summarized in the following sections.

### Extraction Methods

The most conventional extraction method is liquid extraction, when solvents with different polarity can be used to extract the components of interest [67]. Efficiency can be further improved by applying high pressure, employing assistant methods, such as microwaves, ultrasound, and enzymes. These methods can provide quicker, more selective, and environmentally friendly solutions that may also be more gentle, while also less toxic solvents being used [67]. However, the composition of the matrix and the sensitivity, polarity of the extractable compound should be taken into consideration when choosing the extraction method and the solvent [67].

When comparing two different low pressure methods for the extraction of bioactive compounds of coffee husk (i.e., Soxhlet and Ultrasound Assisted Extraction (UAE)) using the same solvent, Soxhlet resulted in higher yields of phenolic compounds and increased antioxidant activity. The lowest yield, and antioxidant activity was achieved when supercritical fluid extraction (SFE) was used [68]. The low antioxidant activity of SFE extracts can be explained by the difference in the polarity of $CO_2$ and phenolic compounds [68].

As shown in Table 2, the amount of extracted total phenolic compounds (TPC) is lower with hot water extraction than with the Soxhlet method, but comparable to SFE. When applying SFE extraction, an increased yield was obtained when pressure was increased at constant temperature, due to better solvation power of $CO_2$, more effective disruption of plant cells, and thus better release of components. Increasing temperature at constant pressure reduced the yield due to the reduced density of the solvent [68]. To produce higher yields, it could potentially be beneficial to apply enzymes that degrade the cell walls and membranes, thereby enabling the reduction of extraction temperature which will assist in conserving thermolabile compounds [69]. Correa et al. (2021) reviewed extraction studies where enzymes were applied to facilitate extraction, some of which are also presented in Table 2 [69]. In general, SFE was proven to be an effective method for the extraction of caffeine and chlorogenic acids [68].

The reported extraction methods for different components of the coffee by-products are summarized in Table 2.

### Sample Preparation

Sample preparation is an important step toward extracting the desired components. However, as the first step, the farming characteristics influence the composition of coffee cherry, as stated above. Furthermore, the processing parameters are also crucial in determining the composition. Extraction from dry samples was seen to be more effective than from fresh fruits [71]. Delgado et al. (2019) tested different drying methods for coffee pulp. They found that when lyophilization was used the total phenolic content of the infusion was significantly higher compared to when oven dried. Even though caffeine is thought to be non-thermo labile, the highest amount of caffeine was observed when freeze drying was used. Conversely, the condensed tannin

**Table 2** Summary of reported extraction methods from coffee husk and pulp by-products

| Coffee by-product | Extracted compound | Extraction method | Solvent | Yield of extraction | Reference |
|---|---|---|---|---|---|
| **Husk** | **Sugars** | EAE[1] | Water | 12.89 g reducing sugar/100 g husk; or 26.93 g reducing sugar/100 g husk (if combined with fungal pre-treatment) | [72] |
| | **Fibers** (hemicellulose and lignin) | Chemical | 1. Alkali treatment (NaOH)<br>2. Bleaching with acetate solution, sodium chloride, and water<br>3. Acid hydrolysis with sulfuric | 61.8 wt% cellulose in sample after bleaching | [73] |
| | **Phenolic compounds** | Soxhlet | Hexane[9] | 3.9% (mass of extract/mass of sample) | [68] |
| | | | Dichloromethane[9] | 2.7% | |
| | | | Ethyl acetate[9] | 3.4% | |
| | | | Ethanol[9] | 4.8% | |
| | | UAE[4] | Hexane[9] | 1.45% (mass of extract/mass of sample) | |
| | | | Dichloromethane[9] | 2.3% | |
| | | | Ethyl acetate[9] | 2.1% | |
| | | | Ethanol[9] | 3.1% | |
| | | SFE[3] | $CO_2$ | 0.55–1.97% (mass of extract/mass of sample) | |
| | | | $CO_2$ + ethanol | 2.1–2.2% | |
| | | Solvent extraction | Ethanol | 45.2 mg CGE[6]/g (TPC[7]) | [71] |
| | | | Water | 45.6 mg CGE[6]/g (TPC[7]) | |
| | | | Water:Ethanol (1:1) | 97.9 mg CGE[6]/g (TPC[7]) | |
| | | UAE[4] | Ethanol | 26.7 mg CGE[6]/g (TPC[7]) | |
| | | | Water | 36.2 mg CGE[6]/g (TPC[7]) | |
| | | | 1 water: 1 ethanol | 91 mg CGE[6]/g (TPC[7]) | |
| | **Anthocyanins** | Solvent extraction | Acidified methanol | 17.2–20.3 mg/100 g | [62] |
| | | | | 19.3–22.5% color contribution | |
| | | Solvent extraction | Acidified ethanol (pH = 1) | 14.49 mg cyanidin 3-glucoside/100 g of coffee fresh exocarp | [74] |
| | **Caffeine** | UAE[4] | Hexane[9] | 5.54 µg/mg extract | [68] |
| | | | Dichloromethane[9] | 139.2 µg/mg extract | |
| | | | Ethanol[9] | 71.1 µg/mg extract | |
| | | Soxhlet | Hexane[9] | 2.1 µg/mg extract | |
| | | | Dichloromethane[9] | 189.9 µg/mg extract | |
| | | | Ethanol[9] | 129.6 µg/mg extract | |
| | | SFE[3] | $CO_2$[9] | 185.7–684.2 µg/mg extract, up to 70% | |
| | | | $CO_2$ + ethanol | 87.8 µg/mg extract | |
| | **Theobromine** | UAE[4] | Dichloromethane[9] | 0.66 µg/g extract | [68] |
| | | Soxhlet | Dichloromethane[9] | 0.75 µg/g extract | |
| | | SFE[3] | $CO_2$ | 1.13 µg/g extract | |

**Table 2** (continued)

| Coffee by-product | Extracted compound | Extraction method | Solvent | Yield of extraction | Reference |
|---|---|---|---|---|---|
| **Pulp** | **Fibers** | Solvent Extraction | 0.1 M HCl solution and ethanol | 9.2% (g SDF[10]/g peel) | [51] |
| | | EAE[1] | Distilled water and 0.2% cellulase, ethanol precipitation | 9.5% (g SDF[10]/g peel) | |
| | | Solvent extraction and EAE[1] | 0.1 M HCl solution, then water (EAE) | 11.4% (g SDF[10]/g peel) | |
| | | UAE[4]-EAE[1] | Enzymatic method combined with ultrasound, ethanol precipitation | 13% (g SDF[10]/g peel) | |
| | | Shear emulsifying- EAE[1] | Distilled water for shear emulsification, then enzymatic method | 14% (g SDF[10]/g peel) | |
| | **Phenolic compounds** | Solvent extraction | Water (100 °C) | 15.6 mg CGE[6]/g (TPC[7]) | [38] |
| | | | Water (85 °C) | 4.85–9.17 mg GAE[8]/g (TPC[7]) | [4] |
| | | | Water (92 ± 3 °C) | 7.61–17.40 mg GAE[8]/L (TPC[7]) | [13] |
| | | | Water (80 °C) | 123.9–209.2 mg GAE[8]/L (TPC[7]) | [34] |
| | | | Water | 254.6–284.1 mg total polyphenols/100 g pulp | [34] |
| | | | HCl | 424–453.2 mg total polyphenols/100 g pulp | |
| | | SURPAS[5] | Hexagonal inverted aggregates of octanoic acid in ethanol:water mixtures | 0.9 mg protocatechuic acid/g pulp | [1] |
| | | EAE[1] | Water (p-coumaroyl esterase) | 85–100% | [75] |
| | | | Water (feruloyl esterases) | 64–100% | [76] |
| | **Anthocyanins** | Solvent extraction | HCl solution | 3.64–4.09 mg/100 g pulp | [34] |
| | **Caffeine** | Solvent extraction | Water (85 °C) | 3.4–6.8 mg/g dry matter | [4] |
| | | | Water (92 ± 3 °C) | N.M | [13] |
| | | | Water (80 °C) | 53.2–101.5 mg/L | [34] |
| | | SUPRAS[5] | Hexagonal inverted aggregates of octanoic acid in ethanol:water mixtures | 3.6 mg/g | [1] |
| | **Trigonelline** | Solvent extraction | Water (92 ± 3 °C) | N.M | [13] |
| | | SURPAS[5] | Hexagonal inverted aggregates of octanoic acid in ethanol:water mixtures | ~0.25 mg/g | [1] |

[1]*EAE*, enzymatic assisted extraction; [2]*MAE*, microwave-assisted extraction; [3]*SFE*, supercritical fluid extraction; [4]*UAE*, ultrasound assisted extraction; [5]*SUPRAS*, supramolecular solvents made up of hexagonal inverted aggregates of octanoic acid in ethanol:water mixtures [1]; [6]*CGE*, chlorogenic acid equivalent; [7]*TPC*, total phenolic compounds; [8]*GAE*, gallic acid equivalent; [9]polarity of hexane, dichloromethane, ethyl acetate, and ethanol were, respectively, 0, 3.1, 4.4, and 5.2; [10]*SDF*, soluble dietary fiber; *N.M.*, not mentioned

content of oven dried samples was higher, suggesting the formation of the tannin molecules when the pulp is exposed to heat. The measured tannin content is similar to that found in medium roasted coffee beans [34]. Heeger et al. (2017) reported the importance of particle size of the dried samples having effect on the amount of bioactives extracted [4].

#### Temperature

Temperature exposure is crucial factor during processing and product preparation. When 70 °C aqueous extraction was used, p-coumaric and ferulic acids were no longer detectable, as they are sensitive to higher temperatures. Extraction at 90 °C resulted in the decomposition of hydroxycinnamic acids as well [34]. Chlorogenic acid tends to form isomers when pasteurization is applied, decreasing its original concentration [4]. In fact, better extraction yield was obtained for water soluble compounds such as phenolic acids, caffeine, melanoidins, and hydrophilic volatile compounds, when higher temperatures and pressures were used [22]. In general, heat improves the solubility of the components, dilution coefficient, and the diffusivity of the solvent [34]. Gallic acid, protocatechuic acid, and caffeine are stable after pasteurization, while the level of polyphenols and flavonoids varied depending on the extraction temperatures [4, 34].

#### Solvent

The yield of extraction is highly dependent on the solvent. To ensure an higher extraction yield, the selection of the solvent needs to be done taking into consideration the component properties like polarity and heat sensitivity of the extractable components [67]. For instance, ethyl acetate can be used to extract flavonoid aglycones, while flavonoid glycosides, phenolic acids, and sugars need polar solvents such as water or methanol (Wei et al. 2012). The extraction yields still differ when solvents of similar polarity are used [61]. The lowest overall yield of phenolic compounds was achieved when hexane was used for Soxhlet extraction from coffee husk, while ethanol showed the highest yield, confirming that this group mainly consists of polar components [68]. The combination of different solvents may result in better extraction yields as shown for water/methanol or water/ethanol mixtures [4, 71]. When supercritical fluid extraction (SFE) was used by Andrade et al. (2012), ethanol as a co-solvent was proven to increase yield [68]. Delgado et al. (2019) found that higher extraction yield of total polyphenols, flavonoids, tannins, and anthocyanins was achieved when acid water (1% HCl) was used instead of non-acidic water for the extraction of coffee pulp, resulting in higher antioxidant activity [34]. Caffeine was not detected when ethyl acetate was used as a solvent [68].

### Other Considerations for Usage of Coffee Husk and Pulp: Microbial Contamination

Due to the high moisture content and wet processing methods, coffee processing by-products are susceptible to microbial spoilage [17]. During the de-pulping process, bacteria, yeasts and filamentous fungi were all present in high numbers [21]. Mold contamination poses a crucial health threat since mycotoxins and biogenic amines can be produced. Therefore, fruit maturation has to be controlled so that contamination can be avoided during downstream processing steps [22]. In coffee beverages ochratoxin A (OTA), aflatoxin B1 and enniatin B were reported as the most common mycotoxins. Furthermore, pesticides may be present as well [38]. In the acute toxicity assay conducted by Iriondo-DeHond et al. (2019) on rats, after single oral administration of 2000 mg/kg body weight raw coffee husk, parchment, and silver skin, no sign of toxicity was found. Coffee-cascara (husk) is authorized in the US, while it has undergone the novel food evaluation by EFSA and was found to be safe for infusion preparation [38, 77].

## Application of Coffee Cherry By-products

### Application of Coffee Husk and Pulp By-products in the Food Sector

As shown in Table 3, coffee husk and pulp have the potential to be used as functional food ingredients. Some of the main food related applications are described below.

#### Dietary Fibers

Coffee husk and pulp are highly rich in dietary fibers, as seen in Table 1. Some soluble dietary fibers also contribute to food formulations since they influence texture by providing viscosity, gel formation, and emulsifying properties [51]. Soluble dietary fibers were shown to reduce sugar and cholesterol absorption, increase calcium absorption, and decrease serum cholesterol and postprandial blood glucose. The recommended daily intake of fibers is 30 g [9]. Bakery products are consumed in a large amount worldwide, however, they often lack fibers [78]. Isolated coffee cascara dietary fiber was tested in gluten-free breads [79]. Results showed that the inclusion of isolated coffee cascara dietary fiber facilitated the increase of the dough yield, less crumb firmness, and a higher crumb elasticity and overall improved the nutritional and sensory quality of the breads [79]. Cookies could be easily enriched with dietary fiber, without significantly imparting sensory characteristics, as shown by Belmiro et al. (2022). Coffee cherry dietary fibers

**Table 3** Food applications of coffee husk and pulp

| Plant material | Compound | Application | Function | | References |
|---|---|---|---|---|---|
| **Husk** | Phenolic compounds | Beverage | Antioxidant | | [35] |
| | Carbohydrates lipids, phenolic compounds | Active food packaging material | Improved properties of packaging | | [17] |
| | Fiber and phenolic compounds | Cookie | Nutritional and functional enrichment | | [78] |
| | | Gluten-free cookie | | | [82] |
| | Anthocyanins | Natural food colorant | Color | | [62] |
| | Cascara-extract | Yoghurt | Appetite control by α-glucosidase inhibition | | [98] |
| | Phenolic compounds, dietary fiber | Food ingredients: extract and fiber | Health-promotion | | [38] |
| | Phenolic compounds, melanoidins | Gluten-free bread | Antioxidant, α-glucosidase inhibition, colorant | | [99] |
| | Organic matter | Substrate for fermentation | Production of citric acid | | [93] |
| | Organic matter | Substrate for fermentation | Bioconversion to gibberellic acid | | [88] |
| | | | Production of fruity aroma | | [100] |
| | | | Enzyme production | Tannase | [86] |
| | | | | Protease | [90] |
| | | | | Xylanase | [84] |
| | | | | Cellulase | [87, 89] |
| | | | | α-Amylase | [91] |
| | Phenolic compounds | Natural preservative | Antimicrobial | | [38] |
| | Phenolic compounds, caffeine | Beverage | Antioxidant | | [4] |
| | Phenolic compounds | Functional drink | Antioxidant | | [34] |
| | Fiber | Gluten-free bread | Nutritional and functional enrichment | | [81] |
| | Fiber and phenolic compounds | Salty cookies | | | [80] |
| | | Cookies | | | [78] |
| | | Gluten-free cookies | | | [82] |
| | Fiber | Coffee flour as food ingredient | Reduce blood glucose level in diabetes mellitus patients | | [101] |
| | Cascara-extract | Yoghurt | Appetite control by α-glucosidase inhibition | | [98] |
| | Pectin | Food ingredient | Gelling agent | | [18, 83] |
| | Polyphenols | Food ingredient | Antioxidant | | [18] |
| | Anthocyanins | Natural food colorant | Color | | [102] |
| | Carbohydrates lipids, phenolic compounds | Active food packaging material | Improved properties of packaging | | [17] |
| | Organic matter | Substrate for fermentation | Enzyme production | Pectinase | [92] |
| | | | | Xylanase | [84] |
| | | | | α-Amylase | [91] |
| | | | | Protease | [85] |
| | | | | Tannase | [94] |

techno functional properties can be also improved by physical modification using dynamic high pressure (DHP) [78]. DHP method enabled the incorporation of 6% coffee cherry ground without compromising the sensory and physical attributes of the cookies. Similar results were found by other studies when applying the husk and pulp in baked goods, resulting in enhanced nutritional and functional qualities, such as higher dietary fiber content and increased antioxidant activity [80–82].

## Stabilizer and Gelling Agents

Pectin is a functional food ingredient that is used as a stabilizer and gelling agent due to its gel forming and viscoelastic properties [18]. Reichembach and de Oliveira Petkowicz (2020) also extracted pectin from coffee pulp, with high methoxyl content and gel forming properties. The pectin can be used for the production of candies, jams, and acidified dairy products [83].

## Beverages

Notably, Heeger et al. (2017) prepared cascara beverages from the coffee pulp, which contained 226 mg/L caffeine. This amount is lower than most coffee drinks, but similar to black tea. The authors emphasized the importance of standard quality, since the amount of bioactive compounds may vary depending on plantation [4].

## Enzyme Production

Coffee processing by-products are optimal substrates for the production of enzymes in solid-state fermentation. They are rich in carbohydrates (e.g., celluloses and hemicelluloses) and proteins, being comparable to the natural habitat of microbes used for fermentation [84]. Coffee husk and pulp were used to identify new sources of substrate [85], to solve pollution problems [86–91], also being a cheap and readily available resource [84, 92, 93]. Kandasamy et al. (2016) used coffee pulp and corncob simultaneously for protease production by *Bacillus* sp. These were identified to be feasible substrates, also reducing the cost of enzyme production [85]. Marín et al. (2019) assessed the mixture of coffee husk and wood chips for cellulase production and evaluated different zero waste strategies for the residue after fermentation, such as biogas production, composting, and anaerobic digestion [89]. *Penicillium verrucosum* was used for the production of tannase to degrade coffee pulp tannin [94]. The produced tannase was applied to fruit juices where the efficiency was proven [94].

#### Food Colorants

Colorants are used in the food industry to recover the color lost during processing or create color characteristic to the specific product. Fruits and vegetables are rich sources of pigments that can be used as natural colorants in the food industry [62]. Prata et al. (2007) identified fresh coffee husks as potential source of anthocyanins [62]. Parra-Campos and Ordóñez-Santos (2019) optimized the extraction of anthocyanins form the outer skin of coffee and applied it to French meringue. According to their results, the extract was found to be a good substitute of Ponceau 4R (E124) [74].

#### Antioxidant Ingredients

Foods rich in unsaturated fatty acids are susceptible for oxidation, resulting in off-flavors and quality degradation of food [95]. The extracts of coffee by-products are rich in compounds with high antioxidant activity; therefore, they have the potential to be used for shelf-life extension [8, 96]. According to Faria et al. (2020), the extracts of green coffee fruits containing chlorogenic acids and alkaloids applied in 0.04% to sunflower oil were successful in delaying oxidation, and giving comparable results to 0.02% butylated hydroxytoluene (BHT) [97].

#### Antimicrobial Activities

Polyphenols, caffeine, and chlorogenic acids found in coffee by-products were shown to exert antimicrobial activities, mainly being effective against bacteria and fungi [8, 96]. Many articles have focused on the antimicrobial activity of coffee by-products; however, fewer explores that of the coffee pulp or husk. The coffee pulp extracts obtained by Duangjai et al. (2016) showed inhibitory (bacteriostatic) effect against *S. aureus*, *S. epidermidis*, *P. aeruginosa*, and *E. coli* [13]. According to the data summarized by Mirón-Mérida et al. (2021), the aqueous and/or alcoholic extracts of coffee by-products could be applied against food-borne pathogens to prevent microbial growth in food and agricultural products [8].

**Other Food Applications** Most of the ingredients used in food production are dried and pure as possible to ensure consistent standard quality and defined chemical composition, which requires the highest purity and makes food production energy-intensive [103]. Likewise, manufacturing pure ingredients from coffee by-products requires often additional processing steps (e.g., extractions, concentration, and drying), which contributes to costs and environmental impact. However, in some situations, coffee husk and pulp by-products have been used without further extraction of ingredients. For example, the dried husk of the fruit of *Coffea arabica* L. has been applied to produce beverages [77], sprits, and as dietary fibers supplements, while dried coffee pulp has been used as flour for breads, cookies, muffins, squares, brownies, pastas, sauces, and beverages [104]. Using coffee by-products as novel foods, minimize the required interventions for ingredients production, toward de development of more sustainable food products.

Furthermore, the high value of coffee by-products has been demonstrated through development and commercialization of different food products. For instance, The Coffee Cherry Co. upcycles coffee cherry pulp to manufacture flour for the baking, snack, and beverage industry. In baked goods, the product is claimed to act as a natural colorant, flavor enhancer for chocolate and spice notes, enhancer of nutritional qualities, and beneficial for moisture retention. In beverage products, the use of coffee by-products can enhance clean fruit notes and are high in antioxidants [105]. Pectcof, a company based in the Netherlands, explores opportunities to upcycle coffee pulp soluble dietary fiber. "Dutchgum" is a soluble dietary fiber extracted from the coffee cherry with stabilizer and emulsifier properties. Furthermore, this company also commercializes coffee by-products to be used in food products as antioxidants, colorants, sugars, and fibers [106]. Starbucks has introduced the Cascara Latte, when syrup made out of the husk of the coffee cherry is added to the drinks . Discarded Spirits Co. brews spirits of discarded food and cascara. From cascara, a vermouth is brewed having the aroma of bitter chocolate, cherry, coffee, red wine, figs, and cinnamon . Cascara, the tea brewed from dried coffee pulp, might be available at some specialty coffee places. In Denmark, Kaffe Bueno uses green chemistry and biotechnology to up-cycle coffee by-products into active and functional ingredients for nutraceuticals and functional foods.

The multifunctionality of commercial applications of coffee by-products is also well described elsewhere [38, 106].

### Other Applications

Coffee production by-products have also the potential to be used outside food industry. For instance, those have been exploited within cosmetic industry due to their anti-oxidant, anti-aging, anti-inflammatory [5], and antimicrobial properties [5, 13]. Furthermore, due to their biodegradability, coffee by-products have been used as biosorbents for water treatment and as substrates for the production of enzymes [17]. Coffee by-products extracted compounds can impart antioxidant, antimicrobial, surface hydrophobicity, gas impermeability, and increased mechanical resistance to packaging materials, and therefore, be used in active food packaging [17]. The coffee husk also has great potential as filler for wood polymer composites dues to the high content of cellulose, lignin, and proteins [107]. The carbohydrates facilitate the improvement of certain mechanical properties of the composite materials, while the relatively high amount of proteins within the coffee husk can function as plasticizers, which is a relevant property to facilitate the processing of composite polymers. Examples of composite polymers, where an increase in tensile strength and modules was observed post inclusion of coffee husk, include HDPE [108] and LLDPE [107]. Proof of the efficacy of up-cycling coffee husk has already been shown through the commercialization of construction composite materials made of coffee husk plastic to create durable, fireproof, and insects resistant composite materials [109]. Coffee production by-products can also be used for biofuel production (e.g., biogas and bioethanol) [110]. The biogas produced could be used for roasting coffee processing solid wastes, which can be used to produce briquettes with 70% less processing cost and 80% more energy density, in comparison with briquettes made from raw biomass [111]. Overall, briquettes and pellets with a high caloric value and performance can be made from coffee by-products [110].

## Concluding Remarks

Coffee production is increasing and consequently the production of coffee by-products and solid residues that are mostly wasted in the environment are increasing too. Under an environmental point of view, this can be a concern. The minimization of the environmental constrains can be supported by implementing sustainable approaches, e.g., up-cycling coffee by-products toward the creation of value-added products.

Coffee processing by-products are rich sources of bioactive compounds and other nutrients that can be widely utilized in the food industry.

Based on the nutritional composition of coffee pulp and husk by-products, dietary fibers are the main component. Coffee pulp and husk have both soluble and insoluble types of dietary fibers, which suits a broad range of food applications. Those can be extracted using mostly a combination of extraction methods, e.g., solvent extraction; ultrasound assisted followed by enzymatic assisted extraction, mainly for the non-soluble fibers. Soluble dietary fibers can be extracted using solvent extraction.

Coffee cherry and pulp also contain considerable amount of proteins (the second main component). Proteins can also be extracted and used as food ingredients. Although limited research has been done regarding the extraction of proteins from coffee husk and pulp by-products, enzyme-assisted extraction is known to facilitate the process of extraction from green coffee beans [70]. Furthermore, significant amounts of proteins were detected, in extracts of dietary fibers.

Lipids are also part of the coffee pulp and husk by-products. Up to date, there is no comprehensive analysis of the lipid composition of the coffee processing by-products. Still lipids can be extracted from green coffee beans using $CO_2$ super critical extraction [112] and enzyme-assisted extraction [70].

The coffee by-products discussed in this review are also a source of micronutrients, vitamins, and minerals, such as potassium, calcium, and magnesium. The main phenolic compounds found in coffee by-products are chlorogenic acids, with potential health-promoting properties, such as antioxidant, anti-diabetic, and anti-obesity. Due to their health-related benefits, phenolic compounds have been the most extracted compounds from coffee pulp and husk. The phenolic compounds can be extracted by various extraction techniques, being the most popular solvent extraction, with differing yields and antioxidant capacities. Researchers have reported the parameters that influence the extraction process, starting from the origin of the raw material, to processing, sample preparation, extraction method, solvent, and temperature, to name a few. Due to the sensitivity and location of some of the bioactive compounds, effective cell disruption methods, and gentle extraction techniques may be beneficial. The use of polar solvents was shown to result in higher yield of extracted phenolic compounds.

The protein, mineral, vitamin, and lipid composition of the cascara are still under-investigation. This highlights the need for conducting further studies on the retrieval of these compounds as well. Furthermore, some extraction techniques should be optimized to become industrially viable.

The different components from coffee husk and pulp are sources of bioactives compounds that can fulfill the growing markets of functional foods and alternative plant-based ingredients with high nutritional value. Furthermore, those by-products can be used as food pigments, anti-oxidants, anti-microbial ingredients, gelling agents, and stabilizers, or either be used as extracts for enzyme production. The high value of coffee by-products has been already recognized by food industry, through the commercialization of different food products, as presented in this review.

Coffee production already accounts for significant environmental footprint, which is predicted to further increase due to the increasing tendency of coffee consumption. Applying biorefinery approaches on coffee production by-products to reduce wastes will contribute to a circular economy and ultimately lower the negative environmental impacts from coffee production. If implementing circular economy in coffee production, a more efficient use of the coffee cherry is foreseen, as most of the coffee production products (coffee and its by-products) can contribute to improve both environmental and economical impacts. By revalorizing coffee pulp and husk, valuable compounds can be obtained while less waste will be produced, and revenue issues for coffee farmers can be addressed simultaneously (promoting a social impact). Therefore, further research on the utilization of the coffee fruit has the potential to provide a combined (partial) solution to acute environmental, social, and health issues.

**Acknowledgements** Ana C. Mendes thanks PROBIO project from Innovation Fund Denmark (project number 7076-00053B). Jakob L. Rukovs work on Cascara is supported by Innovation Fund Denmark (project number 0172-01373B).

**Author Contribution** EK and ACM wrote the manuscript. EK, JLR, and ACM revised the manuscript.

**Funding** ACM thanks Innovation Fund Denmark (project number 7076-00053B), and JLR thanks Innovation Fund Denmark (project number 0172-01373B).

**Data Availability** No datasets were generated in this study. All data has been taken from cited articles.

## Declarations

**Ethical Approval** Not applicable.

**Competing Interests** The authors declare no competing interests.

## References

1. Torres-Valenzuela LS, Ballesteros-Gómez A, Rubio S (2020) Supramolecular solvent extraction of bioactives from coffee cherry pulp. J Food Eng 278:. https://doi.org/10.1016/j.jfoodeng.2020.109933
2. Campos RC, Pinto VRA, Melo LF et al (2021) New sustainable perspectives for "coffee wastewater" and other by-products: a critical review. Futur Foods 4:100058. https://doi.org/10.1016/j.fufo.2021.100058
3. Millard E (2017) Still brewing: fostering sustainable coffee production. World Dev Perspect 7–8:32–42. https://doi.org/10.1016/j.wdp.2017.11.004
4. Heeger A, Kosińska-Cagnazzo A, Cantergiani E, Andlauer W (2017) Bioactives of coffee cherry pulp and its utilisation for production of cascara beverage. Food Chem 221:969–975. https://doi.org/10.1016/j.foodchem.2016.11.067
5. dos Santos ÉM, de Macedo LM, Tundisi LL et al (2021) Coffee by-products in topical formulations: a review. Trends Food Sci Technol 111:280–291
6. Usva K, Sinkko T, Silvenius F et al (2020) Carbon and water footprint of coffee consumed in Finland—life cycle assessment. Int J Life Cycle Assess 25:1976–1990. https://doi.org/10.1007/S11367-020-01799-5/FIGURES/10
7. Gebreeyessus GD (2022) Towards the sustainable and circular bioeconomy: insights on spent coffee grounds valorization. Sci Total Environ 833:155113. https://doi.org/10.1016/j.scitotenv.2022.155113
8. Mirón-Mérida VA, Barragán-Huerta BE, Gutiérrez-Macías P (2021) Coffee waste: a source of valuable technologies for sustainable development. Valorization of Agri-Food Wastes and By-Products 173–198. https://doi.org/10.1016/B978-0-12-824044-1.00009-X
9. Gemechu FG (2020) Embracing nutritional qualities, biological activities and technological properties of coffee byproducts in functional food formulation. Trends Food Sci Technol 104:235–261. https://doi.org/10.1016/j.tifs.2020.08.005
10. Janissen B, Huynh T (2018) Chemical composition and value-adding applications of coffee industry by-products: a review. Resour Conserv Recycl 128:110–117. https://doi.org/10.1016/J.RESCONREC.2017.10.001
11. Castaldo L, Graziani G, Gaspari A et al (2018) Study of the chemical components, bioactivity and antifungal properties of the coffee husk. J Food Res 7:p43. https://doi.org/10.5539/JFR.V7N4P43
12. Mirón-Mérida VA, Yáñez-Fernández J, Montañez-Barragán B, Barragán Huerta BE (2019) Valorization of coffee parchment waste (Coffea arabica) as a source of caffeine and phenolic compounds in antifungal gellan gum films. LWT 101:167–174. https://doi.org/10.1016/J.LWT.2018.11.013
13. Duangjai A, Suphrom N, Wungrath J et al (2016) Comparison of antioxidant, antimicrobial activities and chemical profiles of three coffee (Coffea arabica L.) pulp aqueous extracts. Integr Med Res 5:324–331. https://doi.org/10.1016/J.IMR.2016.09.001
14. Yashin A, Yashin Y, Wang JY, Nemzer B (2013) Antioxidant and antiradical activity of coffee. Antioxidants 2013, Vol 2, Pages 230–245 2:230–245. https://doi.org/10.3390/ANTIOX2040230
15. 1043886 airtrade F 2023. R charity number (2023) Coffee farmers. https://www.fairtrade.org.uk/farmers-and-workers/coffee/. Accessed 22 Jun 2022
16. Esquivel P, Jiménez VM (2012) Functional properties of coffee and coffee by-products. Food Res Int 46:488–495. https://doi.org/10.1016/J.FOODRES.2011.05.028
17. Oliveira G, Passos CP, Ferreira P et al (2021) Coffee by-products and their suitability for developing active food packaging materials. Foods 10:683. https://doi.org/10.3390/foods10030683
18. Manasa V, Padmanabhan A, Anu Appaiah KA (2021) Utilization of coffee pulp waste for rapid recovery of pectin and polyphenols for sustainable material recycle. Waste Manag 120:762–771. https://doi.org/10.1016/j.wasman.2020.10.045
19. Jayachandra T, Venugopal C, Anu Appaiah KA (2011) Utilization of phytotoxic agro waste— coffee cherry husk through pretreatment by the ascomycetes fungi Mycotypha for biomethanation. Energy Sustain Dev 15:104–108. https://doi.org/10.1016/J.ESD.2011.01.001
20. Fernandes AS, Mello FVC, Thode Filho S et al (2017) Impacts of discarded coffee waste on human and environmental health. Ecotoxicol Environ Saf 141:30–36. https://doi.org/10.1016/J.ECOENV.2017.03.011
21. Ameca GM, Cerrilla MEO, Córdoba PZ et al (2018) Chemical composition and antioxidant capacity of coffee pulp. Ciência e Agrotecnologia 42:307–313. https://doi.org/10.1590/1413-70542018423000818
22. Farah A (2012) Coffee constituents. Coffee Emerg Heal Eff Dis Prev 21–58. https://doi.org/10.1002/9781119949893.CH2
23. Cheng B, Furtado A, Smyth HE, Henry RJ (2016) Influence of genotype and environment on coffee quality. Trends Food Sci Technol 57:20–30. https://doi.org/10.1016/J.TIFS.2016.09.003

24. Bonilla-Hermosa VA, Duarte WF, Schwan RF (2014) Utilization of coffee by-products obtained from semi-washed process for production of value-added compounds. Bioresour Technol 166:142–150. https://doi.org/10.1016/J.BIORTECH.2014.05.031
25. Londoño-Hernandez L, Ruiz HA, Cristina Ramírez T et al (2020) Fungal detoxification of coffee pulp by solid-state fermentation. Biocatal Agric Biotechnol 23:101467. https://doi.org/10.1016/J.BCAB.2019.101467
26. Hoseini M, Cocco S, Casucci C et al (2021) Coffee by-products derived resources. A review. Biomass and Bioenergy 148
27. Brand D, Pandey A, Roussos S, Soccol CR (2000) Biological detoxification of coffee husk by filamentous fungi using a solid state fermentation system. Enzyme Microb Technol 27:127–133. https://doi.org/10.1016/S0141-0229(00)00186-1
28. Woiciechowski AL, Pandey A, Machado CMM, et al (2000) Hydrolysis of coffee husk: process optimization to recover its fermentable sugar. Coffee Biotechnol Qual 409–417. https://doi.org/10.1007/978-94-017-1068-8_38
29. Murthy PS, Naidu MM (2010) Recovery of phenolic antioxidants and functional compounds from coffee industry by-products. Food Bioprocess Technol 897–903. https://doi.org/10.1007/s11947-010-0363-z
30. Pleissner D, Neu AK, Mehlmann K et al (2016) Fermentative lactic acid production from coffee pulp hydrolysate using Bacillus coagulans at laboratory and pilot scales. Bioresour Technol 218:167–173. https://doi.org/10.1016/J.BIORTECH.2016.06.078
31. Da Silva MCS, Naozuka J, Da Luz JMR et al (2012) Enrichment of Pleurotus ostreatus mushrooms with selenium in coffee husks. Food Chem 131:558–563. https://doi.org/10.1016/J.FOODCHEM.2011.09.023
32. Setyobudi RH, Zalizar L, Wahono SK et al (2019) Prospect of Fe non-heme on coffee flour made from solid coffee waste: mini review. IOP Conf Ser Earth Environ Sci 293:012035. https://doi.org/10.1088/1755-1315/293/1/012035
33. Tavares KM, Lima AR, Nunes CA et al (2016) Free tocopherols as chemical markers for Arabica coffee adulteration with maize and coffee by-products. Food Control 70:318–324. https://doi.org/10.1016/J.FOODCONT.2016.06.011
34. Delgado SR, Arbelaez AFA, Rojano B (2019) Antioxidant capacity, bioactive compounds in coffee pulp and implementation in the production of infusions. Acta Sci Pol Technol Aliment 18:235–248. https://doi.org/10.17306/J.AFS.0663
35. Das Neves JVG, Borges MV, de Silva DM et al (2019) Total phenolic content and primary antioxidant capacity of aqueous extracts of coffee husk: chemical evaluation and beverage development. Food Sci Technol 39:348–353. https://doi.org/10.1590/FST.36018
36. Ulloa Rojas JB, Verreth JAJ, Van Weerd JH, Huisman EA (2002) Effect of different chemical treatments on nutritional and antinutritional properties of coffee pulp. Anim Feed Sci Technol 99:195–204. https://doi.org/10.1016/S0377-8401(02)00050-0
37. Clifford MN, Ramirez-Martinez JR (1991) Phenols and caffeine in wet-processed coffee beans and coffee pulp. Food Chem 40:35–42. https://doi.org/10.1016/0308-8146(91)90017-I
38. Iriondo-DeHond A, Aparicio García N, Fernandez-Gomez B et al (2019) Validation of coffee by-products as novel food ingredients. Innov Food Sci Emerg Technol 51:194–204. https://doi.org/10.1016/j.ifset.2018.06.010
39. Arya M, Rao LJM (2010) An impression of coffee carbohydrates. 47:51–67. https://doi.org/10.1080/10408390600550315
40. Pua A, Choo WXD, Goh RMV, et al (2021) A systematic study of key odourants, non-volatile compounds, and antioxidant capacity of cascara (dried Coffea arabica pulp). LWT 138:. https://doi.org/10.1016/j.lwt.2020.110630
41. Woldesenbet AG, Woldeyes B (2016) Chandravanshi BS (2016) Bio-ethanol production from wet coffee processing waste in Ethiopia. Springerplus 51(5):1–7. https://doi.org/10.1186/S40064-016-3600-8
42. Rambo MKD, Schmidt FL, Ferreira MMC (2015) Analysis of the lignocellulosic components of biomass residues for biorefinery opportunities. Talanta 144:696–703. https://doi.org/10.1016/J.TALANTA.2015.06.045
43. Lojkova L, Vranová V, Formánek P et al (2020) Enantiomers of carbohydrates and their role in ecosystem interactions: a review. Symmetry (Basel) 12:. https://doi.org/10.3390/SYM12030470
44. Mudgil D (2017) The interaction between insoluble and soluble fiber. Diet Fiber Prev Cardiovasc Dis Fiber's Interact between Gut Micoflora, Sugar Metab Weight Control Cardiovasc Heal 35–59. https://doi.org/10.1016/B978-0-12-805130-6.00003-3
45. Pimentel-Moral S, Cádiz-Gurrea M de la L, Rodríguez-Pérez C, Segura-Carretero A (2020) Recent advances in extraction technologies of phytochemicals applied for the revaluation of agri-food by-products. Funct Preserv Prop Phytochem 209–239. https://doi.org/10.1016/B978-0-12-818593-3.00007-5
46. Haller D (2018) The gut microbiome in health and disease. Gut Microbiome Heal Dis 1–356. https://doi.org/10.1007/978-3-319-90545-7
47. Coultate T (2016) Chapter 5: proteins. In: Food - the Chemistry of Its Components (6th Edition), 6th ed. The Royal Society of Chemistry, pp 179–236
48. Hall RD, Trevisan F, de Vos RCH (2022) Coffee berry and green bean chemistry – opportunities for improving cup quality and crop circularity. Food Res Int 151:110825. https://doi.org/10.1016/J.FOODRES.2021.110825
49. Lopes GR, Passos CP, Petronilho S et al (2021) Carbohydrates as targeting compounds to produce infusions resembling espresso coffee brews using quality by design approach. Food Chem 344:128613. https://doi.org/10.1016/J.FOODCHEM.2020.128613
50. Nyman M, Haskå L (2013) Vegetable, fruit and potato fibres. Fibre-Rich Wholegrain Foods Improv Qual 193–207. https://doi.org/10.1533/9780857095787.2.193
51. Dong W, Wang D, Hu R et al (2020) Chemical composition, structural and functional properties of soluble dietary fiber obtained from coffee peel using different extraction methods. Food Res Int 136:109497. https://doi.org/10.1016/j.foodres.2020.109497
52. Batista dos Santos Espinelli Junior J, von Brixen Montzel Duarte da Silva G, Branco Bastos R et al (2020) Evaluation of the influence of cultivation on the total magnesium concentration and infusion extractability in commercial arabica coffee. Food Chem 327:127012. https://doi.org/10.1016/J.FOODCHEM.2020.127012
53. Farah A, Donangelo CM (2006) Phenolic compounds in coffee. Brazilian J Plant Physiol 18:23–36. https://doi.org/10.1590/S1677-04202006000100003
54. Martínez JRR, Clifford MN (2000) Coffee pulp polyphenols: an overview. Coffee Biotechnol Qual 507–515. https://doi.org/10.1007/978-94-017-1068-8_47
55. Mullen W, Nemzer B, Stalmach A et al (2013) Polyphenolic and hydroxycinnamate contents of whole coffee fruits from China, India, and Mexico. J Agric Food Chem 61:5298–5309. https://doi.org/10.1021/JF4003126
56. Sato Y, Itagaki S, Kurokawa T et al (2011) In vitro and in vivo antioxidant properties of chlorogenic acid and caffeic acid. Int J Pharm 403:136–138. https://doi.org/10.1016/J.IJPHARM.2010.09.035
57. Clifford MN, Jaganath IB, Ludwig IA, Crozier A (2017) Chlorogenic acids and the acyl-quinic acids: discovery, biosynthesis, bioavailability and bioactivity †. https://doi.org/10.1039/c7np00030h
58. Clifford MN, Jaganath IB, Ludwig IA, Crozier A (2017) Chlorogenic acids and the acyl-quinic acids: discovery,

biosynthesis, bioavailability and bioactivity. Nat Prod Rep 34:1391–1421. https://doi.org/10.1039/C7NP00030H
59. Ramirez-Martinez JR (1988) Phenolic compounds in coffee pulp: quantitative determination by HPLC. J Sci Food Agric 43:135–144. https://doi.org/10.1002/JSFA.2740430204
60. Smeriglio A, Barreca D, Bellocco E, Trombetta D (2017) Proanthocyanidins and hydrolysable tannins: occurrence, dietary intake and pharmacological effects. Br J Pharmacol 174:1244. https://doi.org/10.1111/BPH.13630
61. Wei SD, Lin YM, Liao MM et al (2012) Characterization and antioxidative properties of condensed tannins from the mangrove plant Aegiceras corniculatum. J Appl Polym Sci 124:2463–2472. https://doi.org/10.1002/APP.35258
62. Prata ERBA, Oliveira LS (2007) Fresh coffee husks as potential sources of anthocyanins. LWT - Food Sci Technol 40:1555–1560. https://doi.org/10.1016/j.lwt.2006.10.003
63. Viñas M, Gruschwitz M, Schweiggert RM et al (2012) Identification of phenolic and carotenoid compounds in coffee (Coffea arabica) pulp, peels and mucilage by HPLC electrospray ionization mass spectrometry. San José, Costa Rica
64. Gutiérrez-Sánchez G, Roussos S, Augur C (2012) Effect of caffeine concentration on biomass production, caffeine degradation, and morphology of Aspergillus tamarii. Folia Microbiol 583(58):195–200. https://doi.org/10.1007/S12223-012-0197-3
65. Lee C (2000) Antioxidant ability of caffeine and its metabolites based on the study of oxygen radical absorbing capacity and inhibition of LDL peroxidation. Clin Chim Acta 295:141–154. https://doi.org/10.1016/S0009-8981(00)00201-1
66. Al-Yousef HM, Amina M (2018) Essential oil of Coffee arabica L. husks: a brilliant source of antimicrobial and antioxidant agents. Biomed Res 29:174–180. https://doi.org/10.4066/BIOMEDICALRESEARCH.29-17-867
67. Joana Gil-Chávez G, Villa JA, Fernando Ayala-Zavala J et al (2013) Technologies for extraction and production of bioactive compounds to be used as nutraceuticals and food ingredients: an overview. Compr Rev Food Sci Food Saf 12:5–23. https://doi.org/10.1111/1541-4337.12005
68. Andrade KS, Gonalvez RT, Maraschin M et al (2012) Supercritical fluid extraction from spent coffee grounds and coffee husks: antioxidant activity and effect of operational variables on extract composition. Talanta 88:544–552. https://doi.org/10.1016/J.TALANTA.2011.11.031
69. Corrêa CLO, Penha EM, Freitas-Silva O et al (2021) Enzymatic technology application on coffee co-products: a review. Waste and Biomass Valorization 12:3521–3540. https://doi.org/10.1007/S12649-020-01208-W/TABLES/3
70. Souza Almeida F, Furlan Goncalves Dias F, Kawazoe Sato AC, Nobrega L, de Moura Bell JM (2021) From solvent extraction to the concurrent extraction of lipids and proteins from green coffee: an eco-friendly approach to improve process feasibility. Food Bioprod Process 129:144–156. https://doi.org/10.1016/J.FBP.2021.08.004
71. Silva M de O, Honfoga JNB, Medeiros LL de et al (2020) Obtaining bioactive compounds from the coffee husk (Coffea arabica L.) using different extraction methods. Molecules 26:. https://doi.org/10.3390/molecules26010046
72. Sabogal-Otálora AM, Palomo-Hernández LF, Piñeros-Castro Y (2022) Sugar production from husk coffee using combined pretreatments. Chem Eng Process - Process Intensif 176:108966. https://doi.org/10.1016/J.CEP.2022.108966
73. Collazo-Bigliardi S, Ortega-Toro R, Chiralt Boix A (2018) Isolation and characterisation of microcrystalline cellulose and cellulose nanocrystals from coffee husk and comparative study with rice husk. Carbohydr Polym 191:205–215. https://doi.org/10.1016/J.CARBPOL.2018.03.022
74. Parra-Campos A, Ordóñez-Santos LE (2019) Natural pigment extraction optimization from coffee exocarp and its use as a natural dye in French meringue. Food Chem 285:59–66. https://doi.org/10.1016/J.FOODCHEM.2019.01.158
75. Nieter A, Kelle S, Linke D, Berger RG (2017) A p-coumaroyl esterase from Rhizoctonia solani with a pronounced chlorogenic acid esterase activity. N Biotechnol 37:153–161. https://doi.org/10.1016/J.NBT.2017.01.002
76. Nieter A, Kelle S, Linke D, Berger RG (2016) Feruloyl esterases from Schizophyllum commune to treat food industry side-streams. Bioresour Technol 220:38–46. https://doi.org/10.1016/J.BIORTECH.2016.08.045
77. Turck D, Bohn T, Castenmiller J et al (2022) Safety of dried coffee husk (cascara) from Coffea arabica L. as a novel food pursuant to regulation (EU) 2015/2283. EFSA J 20:. https://doi.org/10.2903/j.efsa.2022.7085
78. Belmiro RH, Oliveira L de C, Tribst AAL, Cristianini M (2022) Techno-functional properties of coffee by-products are modified by dynamic high pressure: a case study of clean label ingredient in cookies. LWT 154:112601. https://doi.org/10.1016/J.LWT.2021.112601
79. Rios MB, Iriondo-dehond A, Iriondo-dehond M, et al (2020) Physicochemical, nutritional and sensory properties. Molecules 1–16
80. Moreno J, Cozzano S, Pérez AM et al (2019) Coffee pulp waste as a functional ingredient: effect on salty cookies quality. J Food Nutr Res Vol 7, 2019, Pages 632–638 7:632–638. https://doi.org/10.12691/JFNR-7-9-2
81. MB Rios A Iriondo-DeHond M Iriondo-DeHond (2020) Effect of coffee cascara dietary fiber on the physicochemical, nutritional and sensory properties of a gluten-free bread formulation. Mol, et al 2020 Vol 25 Page 1358 25 1358 https://doi.org/10.3390/MOLECULES25061358
82. Damat D, Anggriani R, Setyobudi RH, Soni P (2019) Dietary fiber and antioxidant activity of gluten-free cookies with coffee cherry flour addition. Coffee Sci - ISSN 1984–3909(14):493–500
83. Reichembach LH, de Oliveira Petkowicz CL (2020) Extraction and characterization of a pectin from coffee (Coffea arabica L.) pulp with gelling properties. Carbohydr Polym 245:116473. https://doi.org/10.1016/J.CARBPOL.2020.116473
84. Murthy PS, Naidu MM (2012) Production and application of xylanase from Penicillium sp. utilizing coffee by-products. Food Bioprocess Technol 5:657–664. https://doi.org/10.1007/S11947-010-0331-7
85. Kandasamy S, Muthusamy G, Balakrishnan S et al (2016) Optimization of protease production from surface-modified coffee pulp waste and corncobs using Bacillus sp. by SSF. 3 Biotech 6:. https://doi.org/10.1007/S13205-016-0481-Z
86. Battestin V, Macedo GA (2007) Effects of temperature, pH and additives on the activity of tannase produced by Paecilomyces variotii. Electron J Biotechnol 10:191–199. https://doi.org/10.2225/VOL10-ISSUE2-FULLTEXT-9
87. Cerda A, Gea T, Vargas-García MC, Sánchez A (2017) Towards a competitive solid state fermentation: cellulases production from coffee husk by sequential batch operation and role of microbial diversity. Sci Total Environ 589:56–65. https://doi.org/10.1016/J.SCITOTENV.2017.02.184
88. Machado CMM, Oliveira BH, Pandey A, Soccol CR (2000) Coffee husk as substrate for the production of gibberellic acid by fermentation. Coffee Biotechnol Qual 401–408. https://doi.org/10.1007/978-94-017-1068-8_37
89. Marín M, Artola A, Sánchez A (2019) Optimization of downstream for cellulases produced under solid-state fermentation of coffee husk. Waste and Biomass Valorization 10:2761–2772. https://doi.org/10.1007/S12649-018-0327-5

90. Murthy PS, Naidu MM (2010) Protease production by Aspergillus oryzae in solid-state fermentation utilizing coffee by-products. World Appl Sci J 8:199–205
91. Murthy PS, Naidu MM, Srinivas P (2009) Production of α-amylase under solid-state fermentation utilizing coffee waste. J Chem Technol Biotechnol 84:1246–1249. https://doi.org/10.1002/JCTB.2142
92. Murthy PS, Madhava Naidu M (2011) Improvement of robusta coffee fermentation with microbial enzymes. Eur J Appl Sci 3:130–139
93. Shankaranand VS, Lonsane BK (1994) Coffee husk: an inexpensive substrate for production of citric acid by Aspergillus niger in a solid-state fermentation system. World J Microbiol Biotechnol 102(10):165–168. https://doi.org/10.1007/BF00360879
94. Bhoite RN, Murthy PS (2015) Biodegradation of coffee pulp tannin by Penicillium verrucosum for production of tannase, statistical optimization and its application. Food Bioprod Process 94:727–735. https://doi.org/10.1016/J.FBP.2014.10.007
95. Horn AF, Nielsen NS, Jacobsen C (2009) Additions of caffeic acid, ascorbyl palmitate or γ-tocopherol to fish oil-enriched energy bars affect lipid oxidation differently. Food Chem 112:412–420. https://doi.org/10.1016/j.foodchem.2008.05.094
96. Bondam AF, Diolinda da Silveira D, Pozzada dos Santos J, Hoffmann JF (2022) Phenolic compounds from coffee by-products: extraction and application in the food and pharmaceutical industries. Trends Food Sci Technol 123:172–186. https://doi.org/10.1016/J.TIFS.2022.03.013
97. Silva Faria WC, Oliveira MG de, Cardoso da Conceição E et al (2020) Antioxidant efficacy and in silico toxicity prediction of free and spray-dried extracts of green Arabica and Robusta coffee fruits and their application in edible oil. Food Hydrocoll 108:106004. https://doi.org/10.1016/J.FOODHYD.2020.106004
98. M Iriondo-DeHond A Iriondo-DeHond T Herrera (2020) Sensory acceptance, appetite control and gastrointestinal tolerance of yogurts containing coffee-cascara extract and inulin. Nutr, et al 2020 Vol 12 Page 627 12 627 https://doi.org/10.3390/NU12030627
99. Guglielmetti A, Fernandez-Gomez B, Zeppa G, Del Castillo MD (2019) Nutritional quality, potential health promoting properties and sensory perception of an improved gluten-free bread formulation containing inulin, rice protein and bioactive compounds extracted from coffee byproducts. Polish J Food Nutr Sci 69:157–166. https://doi.org/10.31883/pjfns-2019-0012
100. Soares M, Christen P, Pandey A, Soccol CR (2000) Fruity flavour production by Ceratocystis fimbriata grown on coffee husk in solid-state fermentation. Process Biochem 35:857–861. https://doi.org/10.1016/S0032-9592(99)00144-2
101. Mindarti S, Zalizar L, Damat et al (2020) Characterization of fiber fraction, physical and chemical properties of coffee flour (Coffea sp.) as functional foodstuff for diabetes mellitus patient. IOP Conf Ser Earth Environ Sci 462:012017. https://doi.org/10.1088/1755-1315/462/1/012017
102. Murthy PS, Manjunatha MR, Sulochannama G, Madhava Naidu M (2012) Extraction, characterization and bioactivity of coffee anthocyanins. Eur J Biol Sci 4:13–19. https://doi.org/10.5829/idosi.ejbs.2012.4.1.6149
103. Van Der Goot AJ, Pelgrom PJM, Berghout JAM et al (2016) Concepts for further sustainable production of foods. J Food Eng 168:42–51. https://doi.org/10.1016/j.jfoodeng.2015.07.010
104. Klingel T, Kremer JI, Gottstein V, De RTR (2020) A review of coffee by-products including leaf. Foods 9:1–20
105. Home - The Coffee Cherry Company - All Rights Reserved Pectcof How the Starbucks Cascara Latte brings coffee full circle Discarded Vermouth 6 Ways the Coffee Industry Is Turning Waste Into a Resource (2019) Kaffe Buenno. https://www.kaffebueno.com/
106. Iriondo-Dehond A, Iriondo-Dehond M, Del Castillo MD (2020) Applications of compounds from coffee processing by-products. Biomolecules 10:1–20. https://doi.org/10.3390/biom10091219
107. Hejna A (2021) Potential applications of by-products from the coffee industry in polymer technology – current state and perspectives. Waste Manag 121:296–330. https://doi.org/10.1016/j.wasman.2020.12.018
108. Huang L, Mu B, Yi X et al (2016) (2016) Sustainable use of coffee husks for reinforcing polyethylene composites. J Polym Environ 261(26):48–58. https://doi.org/10.1007/S10924-016-0917-X
109. Sethuraman S (2021) This home in Colombia is made from coffee and could revolutionize housing as we know it. https://scoop.upworthy.com/this-house-in-colombia-is-made-from-coffee
110. Sugebo B (2022) A review on enhanced biofuel production from coffee by-products using different enhancement techniques. Mater Renew Sustain Energy 11:91–103. https://doi.org/10.1007/s40243-022-00209-0
111. Murthy PS, Madhava Naidu M (2012) Sustainable management of coffee industry by-products and value addition - a review. Resour Conserv Recycl 66:45–58. https://doi.org/10.1016/j.resconrec.2012.06.005
112. Cornelio-Santiago HP, Gonçalves CB, de Oliveira NA, de Oliveira AL (2017) Supercritical CO2 extraction of oil from green coffee beans: solubility, triacylglycerol composition, thermophysical properties and thermodynamic modelling. J Supercrit Fluids 128:386–394. https://doi.org/10.1016/J.SUPFLU.2017.05.030