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Review

Coffee Agroindustrial Lignocellulosic Biomass in Brazil and Colombia: Types, Composition, and Potential Applications

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Abstract

Coffee is one of the most widely consumed beverages worldwide and plays an important cultural, economic, and social role in producing and consuming regions. This review provides an overview of the residues generated throughout the coffee production chain in Brazil and Colombia and critically evaluates their composition, valorization pathways, and potential contribution to a circular bioeconomy. Coffee consumption exceeds 2 billion cups daily, generating substantial amounts of residues from fruit processing, roasting, and beverage preparation. Dry, wet, and semidry processing generate distinct residual streams, including coffee hulls, pulp, parchment, and wastewater, while silverskin and spent coffee grounds (SCG) are generated during roasting and beverage preparation, respectively. These residues contain lignocellulosic fractions and bioactive compounds, supporting their application in food ingredients, bioactive extracts, biofuels, biopolymers, biocomposites, fertilizers, and other value-added products. However, the review indicates that their valorization remains fragmented and faces important technical, logistical, economic, safety, and regulatory barriers. In addition, techno-economic and life-cycle assessments remain unevenly available across residues and valorization routes, limiting the identification of economically viable and environmentally beneficial alternatives. Future research should prioritize process scale-up, standardized residue management, integrated biorefinery strategies, and combined techno-economic and life-cycle assessments to support sustainable circular coffee value chains.

Keywords: coffee hulls; coffee beneficiation; circular economy; *Coffea arabica*; *Coffea canephora*

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1. Introduction

Coffee (*Coffea* spp.) is one of the most extensively consumed beverages globally, wielding cultural, socioeconomic, and ethnographic significance across diverse geographical regions, especially in South America. Historically, coffee cultivation plays an important role as a driver of economic and social development in countries like Brazil and Colombia [1,2].

Global coffee production for 2026/27 is estimated at a historic maximum of 189.7 million 60-kg bags, while global consumption is expected to rise to a record 179.7 million 60-kg bags [3], and although the genus Coffea currently comprises 133 validly recognized species,

the global economy relies almost exclusively on the cultivation of *Coffea arabica* and *Coffea canephora* [4,5].

According to the United States Department of Agriculture—USDA [3], the global coffee market is characterized by a distinct geopolitical bifurcation between primary producing nations and major consumer markets. Brazil, Vietnam, Colombia, Ethiopia, and Indonesia are the five major coffee producers, while the European Union (EU), the United States of America (USA), and Brazil are the world's largest coffee consumers, followed by Japan and China (Figure 1).

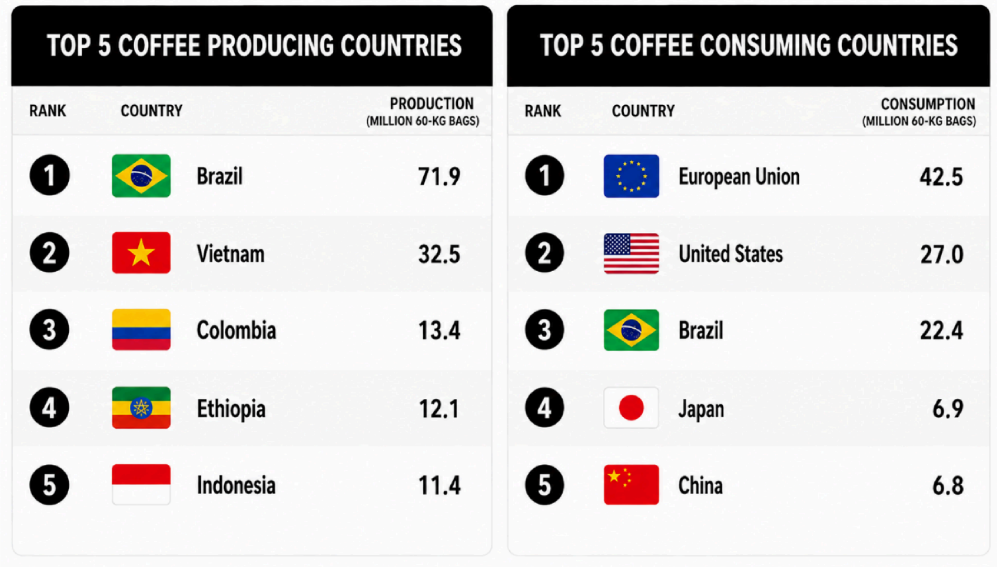


Figure 1. Top five coffee-producing and coffee-consuming countries in the 2026/27 marketing year. Production and consumption are expressed as million 60-kg bags. Data adapted from USDA [3].

Brazil, Vietnam, and Colombia together account for 62.1% (117.8 million 60-kg bags) of total world coffee production (Figure 1), and together, these countries represent the core of global coffee supply, with Brazil alone producing nearly one-third of the total output among the five leading producers.

Although Vietnam ranks second in global coffee production, Brazil and Colombia were selected for this comparative analysis because, in addition to their major contributions to global coffee supply, both countries share a Latin American context while exhibiting markedly different postharvest processing practices. Dry or natural processing is widely employed in Brazil, whereas wet or washed processing has historically predominated in Colombia. These contrasting processing models directly influence the types, proportions, and characteristics of the residues generated throughout the coffee production chain, providing a relevant basis for comparative analysis. Thus, the Brazil–Colombia comparison allows the influence of distinct postharvest practices on residue generation and subsequent valorization opportunities to be examined within a shared broader regional context.

C. arabica is the most widely cultivated coffee species worldwide and accounts for approximately 55% of global production, with an estimated 105.9 million 60-kg bags for 2026/27, while *C. canephora* accounts for 45% of global coffee production, with 83.8 million 60-kg bags estimated for the same period (Figure 2). Brazil and Colombia supply 57.5% of global *C. arabica* (60.9 million 60-kg bags), and Vietnam and Brazil supply 66.6% of global *C. canephora* (55.8 million 60-kg bags) [3].

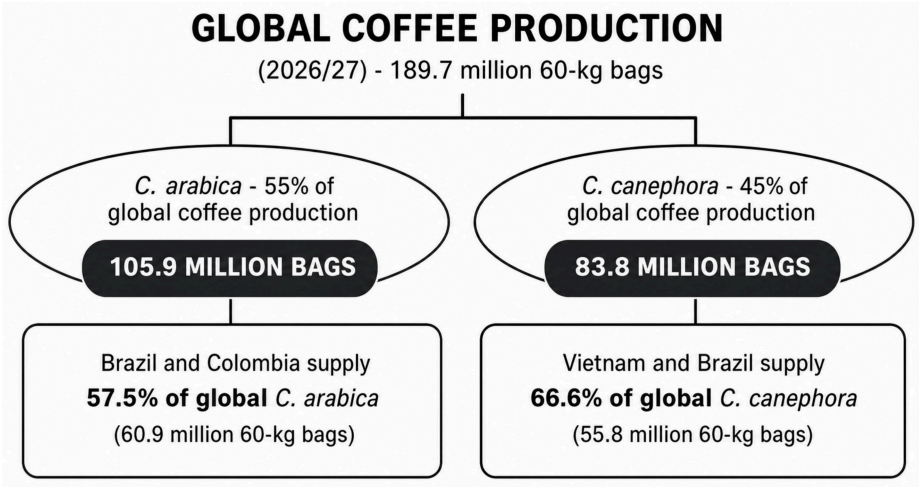


Figure 2. Global coffee production by species. Data adapted from USDA [3].

Global daily coffee consumption exceeds 2 billion cups, with over a billion people worldwide drinking coffee every day. The EU and the USA together consume approximately 69.5 million 60-kg bags (Figure 1), emphasizing their dominant influence on global coffee demand. Around 66% of Americans drink the beverage, with 35% of them consuming coffee prepared outside the home. Furthermore, 61% believe coffee is beneficial to health, a point of view aligned with the new ruling by the FDA (Food and Drug Administration), the USA agency regulating the food and drug market, which classified black coffee as healthy for the first time, thereby permitting this claim to appear on product labels [6–9].

Alongside the exponential growth in coffee consumption, there has been a proportional increase in coffee residues generation; the coffee production chain results in approximately two billion tons of solid residues per year [10].

Coffee cherries undergo post-harvest processing primarily via two methods, the dry process and the wet process, resulting in products that differ in their technological requirements, as well as in the types and quantities of residues generated. In the dry process, the beans are dried whole immediately after harvesting; this type of processing is widely used in Brazil. The wet process involves the mechanical removal of the skin, and the removal of mucilage via mechanical centrifugation or biological degradation, a method predominantly used in Colombia [11,12]. A third method, the semidry, is a postharvest method intermediate between dry and wet processing.

From the dry process, the cherries that are completely dried result in hulls as the major residue, which account for 40–50% (w/w) of the starting raw material. In the wet process, the fruits are mechanically depulped in direct contact with water; and the coffee pulp resulted from this process is discarded, representing approximately 30–50% (w/w) of the total mass of the fruit, whereas the bean accounts for only 39% (w/w) [13,14]. During the roasting, silverskin is the only residue released from the green bean, which can be attributed to the thermal expansion and moisture loss [15]. Finally, SCG that result from the coffee brewing process are considered the most abundant coffee residue worldwide, representing a rich source of bio-based chemicals [16,17].

Thus, the objective of this review is to provide a comprehensive overview and comparative analysis of the residues generated throughout the coffee production chains of Brazil and Colombia. These countries were selected based on their major contributions to global coffee production, their shared Latin American context, and their contrasting postharvest processing practices, which result in distinct residue profiles. In addition, the coffee markets of the two countries are compared, the main residues generated throughout

their respective coffee supply chains are described, and their potential applications and valorization strategies are evaluated.

2. Methodology

This review was conducted through a comprehensive literature search to gather recent information and relevant data on coffee production, postharvest processing methods, residue generation throughout the coffee production chain, and the potential valorization of these residues, with particular emphasis on the production systems of Brazil and Colombia. The search strategy included multiple electronic databases, namely Google Scholar, Scopus, ScienceDirect, and PubMed, to ensure broad coverage of relevant scientific publications. Articles published between 2020 and 2025 were prioritized to encompass recent advances and updated perspectives on the generation, characterization, and utilization of coffee residues. Earlier studies were also considered when they provided fundamental information or relevant data for understanding coffee production and processing.

The main keywords used in the searches included "coffee production", "coffee processing", "coffee residues", "coffee by-products", "agro-industrial residues", "coffee hull", "coffee pulp", "coffee parchment", "coffee silverskin", "spent coffee grounds", "dry processing", "natural processing", "wet processing", "washed processing", "Brazilian coffee market", "Colombia coffee market", "*Coffea arabica*" and "*Coffea canephora*". In addition, the reference lists of the selected articles were screened to identify additional relevant studies that were not retrieved in the initial search.

The selection of publications was guided by inclusion and exclusion criteria. Studies were included if they addressed: (i) coffee production and consumption; (ii) postharvest processing methods, particularly dry/natural and wet/washed processing; (iii) the generation and characterization of residues from the coffee production chain; (iv) the chemical composition and properties of coffee residues; (v) residue management and valorization strategies; and/or (vi) potential applications of coffee residues and their value-added compounds. Publications unrelated to the scope of the review, duplicate studies, and papers that did not provide information relevant to the objectives of the review were excluded. Peer-reviewed research articles and review papers were prioritized, whereas official reports and other reliable technical sources were included when relevant, particularly for data related to coffee production, consumption, and market trends.

The selected studies were comparatively assessed considering the main residues generated throughout the coffee production chains of Brazil and Colombia, their relationship with different postharvest processing methods, their characteristics, and their potential for valorization. Particular attention was given to the differences between dry/natural and wet/washed processing systems and their consequent generation of different types and quantities of residues. The information obtained was synthesized to provide a comparative overview of the main residues generated in the two countries, as well as the opportunities and challenges associated with their sustainable utilization.

3. Coffee Market in Brazil

Coffee cultivation began in the 18th Century in Brazil in the Northern region, state of Pará, with a rapid spread to the Southeast region in the 19th Century, and the first coffee seeds introduced into Brazil belonged to the *C. arabica* species. During the Imperial period (1822–1889), coffee cultivation expanded with a workforce depended on the transatlantic slave trade; however, following the abolition of slavery in 1888, coffee production shifted toward western São Paulo. During the early Republican period (from 1889 onward), plantation owners increasingly relied on subsidized European immigrants recruited through the colonato system [18].

Brazil emerged as the central driver of 19th Century coffee expansion, generating around 80% of the century's total global growth. After accounting for over half of world coffee output by 1850, in 1906 Brazil was producing almost five times that of the entire rest of the world combined [19]. The rapid expansion of production resulted in recurrent oversupply and declining international prices. In response, the Brazilian government implemented coffee valorization policies beginning in 1906, intervening in the market to stabilize prices. These measures reflected new political and economic arrangements among regional elites while maintaining many structural characteristics inherited from the earlier slave-based agricultural economy [18].

By the beginning of the 20th century, Brazil accounted for nearly 75% of global coffee production, a substantial increase from approximately 50% in the mid-19th Century [19,20]. *C. canephora* was initially introduced to Brazil in the early 1900s, however its commercial cultivation was not significant until the 1960s, and only in the 1970s that the species established a market presence. Between 1984 and 2016, the coffee cultivation area in Brazil decreased by 20%, and production grew by 6%, resulting in a 33% gain in productivity. This progress was driven by technological innovations such as higher planting density, mechanization, new varieties, and irrigation [20–22].

As the world's largest producer and exporter of coffee, Brazil exerts an important role in the international market. Coffee farming is a key socioeconomic pillar for the country, encompassing hundreds of thousands of producing operations spread across various geographic regions. In 2026/27, it is estimated a production of 71.9 million 60-kg bags (Figure 1) in Brazil, and 70% of the coffee produced corresponds to *C. arabica*, while 30% corresponds to *C. canephora* [3–5].

Although *C. arabica* generally commands higher market value, *C. canephora* is considered a more rustic species, characterized by greater tolerance to climatic stress, reduced sensitivity to biennial bearing, and more stable productivity. Conilon and Robusta are the world's main cultivated botanical varieties of *C. canephora*. Robusta is the most widely cultivated variety worldwide, but in Brazil, the Conilon variety predominates, accounting for 67% of the total *C. canephora* production [21,23–25]. Globally, *C. canephora* is traded and marketed as Robusta; however, this is a simplification used by commodity markets to maintain uniformity in trading. Brazil is the only major global producer that strictly separates these two varieties of *C. canephora*. In Brazil, Conilon predominates in the Southeast, particularly in the state of Espírito Santo, while Robusta is the primary variety cultivated in the North, particularly in the state of Rondônia [23–26].

Although the geographical distribution of coffee production in Brazil is strongly associated with the climatic requirements and adaptation of each species and variety, the contribution of individual states to national production is not static and may vary considerably among harvest years. This temporal variability is influenced by the biennial bearing cycle of coffee, as well as by climatic stresses that affect flowering, fruit development, and grain filling. Frost events have historically affected coffee production in the South and Southeast regions, particularly in areas dominated by *C. arabica*, contributing to substantial fluctuations in regional production. Water availability is another important factor influencing coffee productivity, particularly in regions where *C. canephora* is cultivated. Prolonged water deficits and irregular rainfall have affected Conilon production in Espírito Santo in specific harvest years, while water deficit is also an important constraint to coffee production in Bahia [27,28]. Therefore, changes in the relative contribution of Brazilian states to national coffee production should be interpreted not only in terms of cultivated area and species or variety distribution, but also in the context of biennial bearing and interannual climatic variability [27–29].

According to Silva et al. [23], Conilon variety is characterized by smaller plants that are drought-tolerant but more susceptible to diseases, while Robusta has larger plants with bigger leaves and fruits, exhibiting lower tolerance to water deficit but greater resistance to pests and diseases.

C. arabica is also known for its smooth flavor profile and higher acidity, the state of Minas Gerais accounts for over 70% of the Brazilian output, followed by São Paulo (~12.90%) and Espírito Santo (~9.64%). Conversely, *C. canephora* is cultivated in warmer, lower-altitude climates, being known for its intense bitterness and higher caffeine and soluble solids contents. The state of Espírito Santo is the leader of Conilon production, generating nearly two-thirds of Brazilian *C. canephora* yield (~65%), followed by Bahia (~16.70%) and Rondônia (~13.24%) [26–28], as observed in Figure 3.

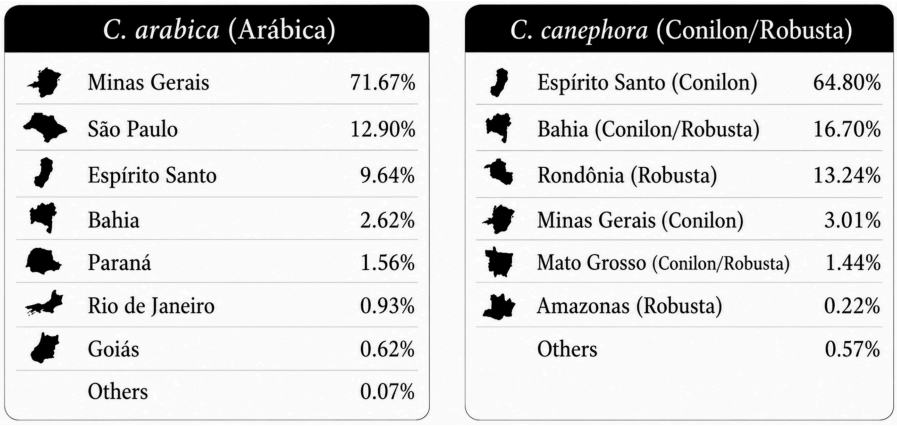


Figure 3. Estimated percentage share of Brazilian states in the total coffee production in Brazil in the 2026/27 crop year. Source: CONAB [26].

In addition to its world leadership in coffee production, the Brazilian coffee market has been directing efforts towards increasing the production of specialty coffees, with smaller-scale production and sustainability certifications. One of the main strategies for the consolidation of specialty coffees is the establishment of Geographical Indications (GIs), regulated by the INPI (National Institute of Industrial Property), including Denomination of Origin (DO) and Indication of Provenance (IP), ensuring product verification through an official seal, certifying the link between coffee origin and quality, favoring premium pricing, and protecting small producers [27–30]. Traditionally focused on the *C. arabica* species, Brazilian GIs also included *C. canephora* species in recent years (Table 1).

The global pioneering of this transition is manifested in the IP "Espírito Santo", focused on Conilon coffee, where the Espírito Santo production arrangement combines strong socioeconomic relevance with rigorous sensory analysis protocols. In parallel, the DO "Matas de Rondônia" recognized the Amazonian Robusta as the first sustainable *C. canephora* DO in the world, demonstrating that investment in post-harvest, sustainability, and traceability redefines the positioning of *C. canephora* coffees in the high-quality market [31–33].

Table 1 describes the 24 GIs registered at INPI until June 2026, highlighting the predominance of *C. arabica* and the importance of the states of Minas Gerais, São Paulo, and Espírito Santo within the Brazilian scenario of specialty coffees [33]. According to Cardoso et al. [33], GIs have been a potential strategy to facilitate smallholder family farmers' access to the coffee market, and they are considered key agents for sustainable development, as they promote the preservation of natural resources and cultural heritage in this sector.

In Brazil, the predominant postharvest processing method for coffee is the dry processing, in which whole cherries are dried with the pulp intact before hulling. Estimates suggest that dry processing accounts for 60–70% of Brazilian coffee, reflecting the country's

large scale of mechanized harvesting and favorable drying conditions in major producing states, such as Minas Gerais. However, a semidry method has also expanded, particularly in specialty coffee; recent surveys indicate that approximately 60–80% of Brazilian specialty coffee producers have adopted semidry processing, either exclusively or in combination with other methods [31,34,35].

Table 1. Geographical Indications registered at INPI (National Institute of Industrial Property) in Brazil [1].

Geographical Indication (GI)	State	Type of GI
C. canephora		
Espírito Santo (Conilon)	Espírito Santo	IP
Matas de Rondônia (Robusta)	Rondônia	DO
C. arabica		
Campos das Vertentes	Minas Gerais	IP
Canastra	Minas Gerais	DO
Caparaó	Minas Gerais/Espírito Santo	DO
Cerrado Mineiro	Minas Gerais	DO and IP
Chapada de Minas	Minas Gerais	IP
Mantiqueira de Minas	Minas Gerais	DO
Matas de Minas	Minas Gerais	IP
Sudoeste de Minas	Minas Gerais	IP
Alta Mogiana	Minas Gerais/São Paulo	IP
Circuito das Águas Paulista	São Paulo	IP
Nova Alta Paulista	São Paulo	IP
Região da Garça	São Paulo	IP
Região do Pinhal	São Paulo	IP
Torrinha	São Paulo	IP
Vale da Grama	São Paulo	IP
Montanhas do Espírito Santo	Espírito Santo	DO
Mandaguari	Paraná	DO
Norte Pioneiro do Paraná	Paraná	IP
Serra de Apucarana	Paraná	DO
Chapada Diamantina	Bahia	IP
Oeste da Bahia	Bahia	IP
Serra de Baturité	Ceará	IP

[1] Source: INPI [36].

4. Coffee Market in Colombia

Unlike Brazil, where both *C. arabica* and *C. canephora* are cultivated, the coffee marketed under the denomination "Colombian Coffee" consists exclusively of *C. arabica*. Colombian coffee farming is predominantly developed in small and medium-scale family production systems, established on mountainous terrain with steep slopes that limit the mechanization of agricultural work [37].

Coffee is grown in 22 of Colombia's 32 departments and in approximately 600 municipalities [38]. Production is concentrated mainly along the country's three Andean mountain ranges at elevations ranging from 1200 to 2100 m above sea level, although the optimum altitude for coffee cultivation is approximately 1575 m [39,40]. Within this altitudinal range, annual temperatures typically vary between 18 and 23 °C, with 1500 to 2100 h of sunshine per year, conditions considered optimal for the growth, flowering, and fruit filling of Arabica coffee [41]. Under these environmental conditions, coffee cherries develop more slowly, extending the ripening period and promoting a greater accumulation of sugars, organic acids, and aromatic compounds. Consequently, the beans exhibit superior physical

and sensory quality, producing a beverage with greater aromatic complexity, balanced acidity, and lower caffeine content [42,43].

For the 2026/27 crop year, the projected coffee production is about 13.4 million 60-kg bags (Figure 1), entirely corresponding to *C. arabica*. This positions Colombia as the world's second-largest producer of Arabica coffee, preceded only by Brazil, the world's largest producer, since in Vietnam 97% of the coffee produced corresponds to *C. canephora* [3]. Furthermore, Colombia is internationally recognized as the world's largest producer of washed Arabica coffee, and one of the leading exporters of premium coffee [44].

Colombia is characterized by having eight main coffee-growing regions, each with distinct profiles based on altitude, latitude, rainfall, and average temperature—factors that influence coffee production and varieties. The main coffee varieties grown in Colombia are: Castillo (approximately 45%), Colombia, Cenicafé, Caturra, Typica and Bourbon [45].

Colombia has consolidated its position as a key actor in the implementation of voluntary sustainability standards within the global coffee value chain. The adoption of governance mechanisms and certification schemes has enhanced the international competitiveness of Colombian coffee in markets that demand differentiated and certified products [46,47]. According to UN Comtrade data accessed through the World Bank's World Integrated Trade Solution, Colombia exported around 12 million 60-kg bags of green, unroasted, non-decaffeinated coffee (HS code 090111) in 2024, with a total export value of approximately USD 3.39 billion. The USA, Belgium, Canada, Germany, and Japan were the principal export destinations by reported export value [48]. USDA [3] identifies the USA as the leading destination for Colombian coffee exports, followed by the UE and Canada. The agency also reports that the recent recovery in Colombian coffee production was associated with favorable climatic conditions linked to El Niño, which accelerated coffee tree growth and promoted favorable soil moisture conditions for young production systems.

Coffee continues to be a strategic agricultural commodity in Colombia. During the first quarter of 2025, the value added generated by coffee cultivation increased by 31.3% year-on-year, making coffee one of the main contributors to the 7.1% growth recorded by Colombia's agriculture, livestock, forestry, and fishing sector during the period, according to official statistics from the National Administrative Department of Statistics (DANE) [49] and analyses by the Rural Agricultural Planning Unit (UPRA) [50].

Wet processing is the predominant postharvest processing method used for coffee in Colombia and represents a critical stage in obtaining high-quality coffee [51]. This process provides sensory attributes characteristic of Colombian coffee, such as: a clean cup, bright acidity, and a consistent sensory profile, characteristics that have historically positioned it in high-quality coffee markets [45]. Coffee traded globally from Colombia continues to be processed using traditional wet methods, reflecting both the existing infrastructure and practices established by generations of coffee growers, as well as the quality standards demanded by the industry and international buyers [45,52].

5. Postharvest Processing of Coffee and Solid Residues Generated Throughout the Production Chain

The coffee cherry consists of two beans at its core, surrounded by silverskin, parchment, mucilage, pulp, and an outer skin (Figure 4). For every ton of cherries, approximately 200 kg of green coffee beans are obtained [16]. The objective of coffee postharvest processing is to remove the external tissues and reduce the moisture content of the beans to approximately 10–12% (wet basis), which is considered suitable for safe storage, transport, and export as green coffee. After processing, the green coffee beans are roasted, ground, and brewed with hot water to extract soluble compounds, producing the coffee beverage consumed worldwide [35].

Coffee cherries undergo two main types of postharvest processing, dry and wet, and the semidry process has also been adopted mainly for the production of specialty coffees. The different processing methods result in beans with distinct quality characteristics. In addition to influencing coffee quality, types and quantity of residues, these processing techniques also differ in their environmental impacts, particularly regarding water consumption and the potential contamination of surrounding aquatic ecosystems. Therefore, a comparative evaluation of these processing methods is essential to better understand their effects on both coffee quality and environmental sustainability [34].

Although coffee processing strongly influences the physical, chemical, sensory, and economic value of the final product, current evidence does not demonstrate the consistent superiority of any single processing method. Instead, coffee quality is determined by the combined effects of postharvest practices, environmental conditions, technological resources, and production costs. Therefore, the choice of processing method should be based on local conditions and production objectives rather than on the expectation of universally superior quality [31].

In Figure 4, the coffee processing pathways and solid residues generation are presented. In the dry process (natural), the whole cherry goes to drying with its skin, pulp, and mucilage; there is a greater transfer of compounds from the pulp to the bean, resulting in more intense flavors and a higher risk of defects if drying management is not carried out very carefully. The wet process (washed/fully washed) is more complex and involves several operations, in which skin, pulp, and mucilage are removed before drying, and this produces cleaner coffees with more pronounced acidity and generally lighter body. The semidry process (pulped natural or honey) removes the skin and part of the pulp while retaining the mucilage to dry alongside the bean, and it offers an intermediate sensory profile, combining the higher sweetness and body of the natural process with greater clarity and acidity than the traditional dry process [53].

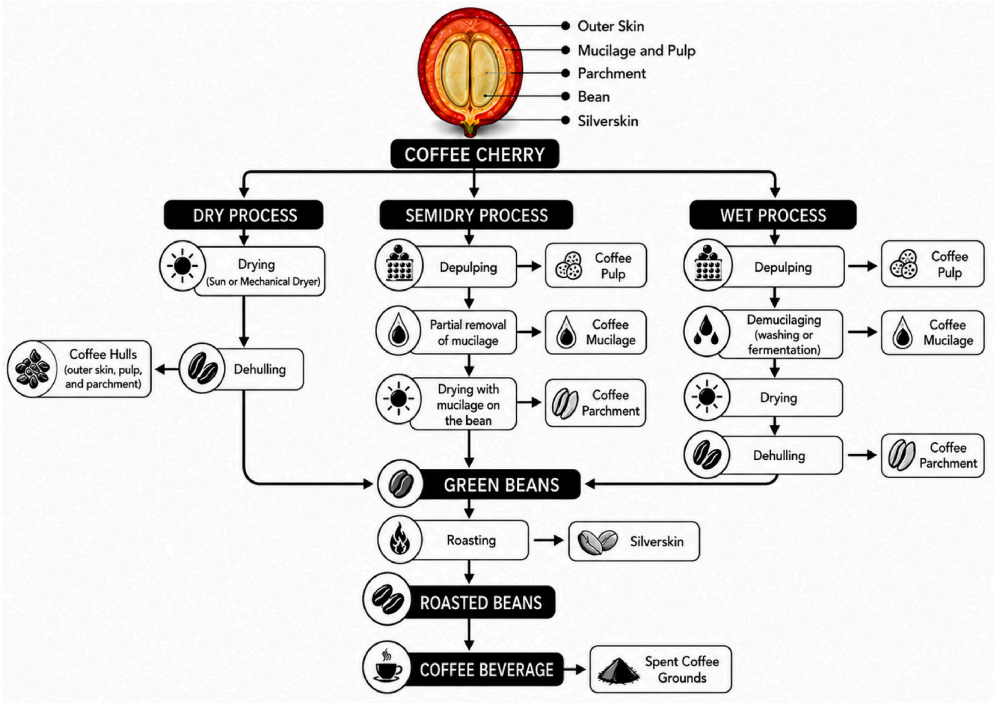


Figure 4. Schematic representation of coffee processing methods (dry, semidry, and wet) and the major solid residues generated throughout the production chain. Adapted from Refs. [16,35,54].

Table 2 provides a comparative overview of the three main coffee postharvest processing methods, highlighting the relationship between water consumption, residue generation,

organic pollution potential, and environmental risk. Approximately 40 million tons of biobased residues are generated annually by the global coffee industry. Despite their significant resource potential, these residues are frequently landfilled, incinerated, or diverted to animal feed. Their elevated caffeine and tannin contents, however, may adversely affect soil quality and contribute to the formation of potentially carcinogenic compounds when improperly incorporated into animal feed [55,56].

Table 2. Comparative overview of the three main coffee postharvest processing methods [1].

	Postharvesting Processing Methods		
	Dry	**Semidry**	**Wet**
Solid Residues	Coffee hulls	Pulp; mucilage retained on parchment	Pulp; mucilage; parchment
Estimated wastewater (m^3/ton)	0–0.3	1–5	5–20
Relative organic load	Low to moderate	High and concentrated	Very high
Water use	Very low	Low to moderate	High
Dominant characteristic	Large amount of dry lignocellulosic biomass	Lower water consumption than the wet process; however, the wastewater is often more concentrated	Greater generation of acidic wastewater rich in sugars and pectins

[1] Data adapted from [46,55,57–59].

Overall, the data (Table 2) indicate a clear trade-off between water use and the characteristics of the residues generated. The dry process is characterized by the lowest water consumption, generating coffee hulls, a dry lignocellulosic residue. Consequently, its relative organic load is classified as low to moderate, and its environmental risk is considered moderate if residues are not properly managed. Although this process produces a large volume of biomass, the residue is relatively stable and easier to store, transport, and valorize into biofuels, biochar, cellulose, phenolic compounds, and other biobased products.

In contrast, the wet process exhibits the highest environmental impact, especially regarding water use, producing large amounts of pulp, mucilage, and parchment, together with wastewater containing high concentrations of sugars and pectins. As a result, this process has a very high organic load and very high environmental risk when wastewater is discharged without treatment. These characteristics indicate that wastewater management is the major environmental challenge associated with wet coffee processing.

The semidry process represents an intermediate alternative between the dry and wet methods. Water consumption is substantially lower than in the wet process (Table 2). Although the wastewater volume is reduced, the remaining effluent is more concentrated, maintaining a high organic load and a high environmental risk if not adequately treated. Thus, reducing water use does not necessarily reduce pollution potential, since pollutant concentrations tend to increase.

5.1. Dry Processing

The dry process is the oldest and simplest post-harvest method used for coffee processing. One of its main advantages is that it requires little or no water, making it particularly attractive in regions where water resources are limited [35]. There are no official statistics on the use of dry processing for coffee processing in Colombia, but in Brazil is the main method used for coffee processing [31,34]. It can reduce processing costs; however, its

performance is highly dependent on weather conditions and seasonal variations. Careful monitoring is required to prevent bean overheating and cracking [35].

This process begins with freshly harvested coffee cherries spread out in thin layers (5–10 cm) on drying beds to be dried in the sun or by mechanical dryers (Figure 4) for approximately 2 to 4 weeks until the moisture content falls below 12%. The subsequent mechanical separation involves friction and impact between the beans, separating the bean from the hulls, pulp, mucilage, and parchment which together form a distinct fraction called coffee hull. This hull is the main residue from dry processing, resulting in 40–50% by mass of the dried fruit [54,60–63].

Residues from Dry Processing

Coffee hulls are the main solid byproduct generated during the dry processing method [64]. Chemically, this lignocellulosic residue consists mainly of cellulose (~25–31%), hemicellulose (~19%), lignin (~14–35%), and ash (~0.36%) [65]. Depending on the geographic origin, coffee variety, agricultural conditions, and specific hulling techniques, the chemical composition and physical properties of coffee hulls can vary significantly [14]. In addition, it contains 8–11% protein and 0.5–30% lipids [66].

Furthermore, coffee hulls possess anti-nutritional and phytotoxic compounds, particularly caffeine and tannins. When improperly disposed these compounds leach into surrounding soils and aquatic ecosystems, posing environmental contamination risks. In many producing regions, the lack of widespread industrial reuse leads to open burning in fields, generating toxic smoke and particulate pollution [67].

To address these environmental challenges, recent advances have highlighted coffee hulls as a valuable renewable source of biopolymers and functional compounds. For example, Paiva et al. [14] demonstrated an environmentally friendly, chlorine-free, single-step process using peracetic acid to extract a cellulose-rich material from raw coffee hulls, increasing the cellulose content from 31.5% to 71.6% and reducing the lignin content to 6.2%, with a view toward potential applications in hydrogels, food, and cosmetics. Chung et al. [68] developed coffee hulls biochar as a sustainable adsorbent for wastewater remediation, demonstrating high efficiency in the simultaneous removal of heavy metals.

5.2. Wet-Processing

In Brazil, there is no official recent statistic that states an exact percentage of coffee processed by wet method. In Colombia, almost 90% of all export-quality coffee continues to be processed by the wet processing method, with semidry processes representing only a small niche share. Wet processing in Colombia is characterized by the removal of mucilage through controlled fermentation (generally in fermentation tanks or vats) before washing (Figure 4). This reduces the sugar and fermentable compound load in the bean before drying, resulting in cleaner profiles with less variability. The process begins with the selection of ripe coffee cherries, identified by their bright red or yellow color depending on the variety; these hues indicate optimal ripeness and sugar concentration, the cherries are harvested directly from the coffee plants by the farmers; once harvested, they are transported to storage areas where they are sorted by flotation or sieving [45]. Following this, the exocarp (hull) and most of the mesocarp (pulp) of the selected fruits are mechanically removed using disc, cylinder, or cone pulpers. These processes allow the separation of the coffee bean from the solid residue, known as the pulping process [69] (Figure 4). After this process, the grain retains a layer of mucilage rich in sugars and pectins, which must be broken down before washing by the fermentation process carried out in tanks or vats by the action of native microorganisms, generally lactic bacteria, yeasts and

fungi, which enzymatically break down the mucilage. This process can last between 12 and 36 h, depending on the atmospheric conditions of the farm [70].

Once fermentation is complete, water is added until the coffee layer has cured to remove the remaining degraded mucilage. This process is usually carried out in washing tanks where the difference in density is used to classify the beans. At this stage, the coffee has a moisture content that can vary between 45% and 55%, and during this process, it can be reduced to 10% for subsequent storage and sale. Alternatively, solar drying is commonly used on raised beds or in solar tents; this process can last between 5 and 10 days. Mechanical drying using hot air dryers is also available, which takes between 12 and 24 h [71]. Once the drying process is complete, dry parchment coffee is obtained, which is sorted by size and packaged for grinding or export [72].

Residues from Wet Processing

According to Figure 4, the three main solid residues resulted from wet processing are coffee pulp, mucilage and parchment, and additionally a high-organic-load wastewater from pulping and washing operations. From a circular bioeconomy perspective, this process can be understood as a sequence of biomass fractionation operations, in which each stage separates specific fruit tissues with distinctive structural characteristics and physicochemical compositions. Wet processing in Colombia determines not only coffee quality but also the generation of multiple lignocellulosic and organic residues with distinctive physicochemical characteristics [73], and each of these fractions exhibits differentiated properties that determine its behavior during transformation processes and its valorization potential [45,74,75].

Understanding the origin and properties of these residues provides the basis for comparing Colombian and Brazilian coffee processing systems, whose contrasting technologies produce markedly different biomass streams and valorization opportunities. The wet processing system generates a heterogeneous biomass flow composed of both structural lignocellulosic residues and sugar-rich by-products, creating opportunities for integrated biorefinery approaches. The distribution of the different fractions of the coffee cherry varies according to variety, ripeness, growing conditions, and, particularly, the processing system employed. Studies conducted on Colombian coffee have reported that pulp represents approximately 40–50% of the fresh weight of the cherry, although this value may vary depending on fruit characteristics and processing conditions [76].

In a characterization of Colombian coffee residues, Arango-Agudelo et al. [77] analyzed different residues, showing that composition and valorization potential depend on the fraction considered. Therefore, it is not appropriate to establish a universal balance in which a fixed percentage of cherry weight is assigned to each residue fraction, particularly for wash water, whose volume depends directly on the processing technology and water consumption employed. The quantity and characteristics of these residues are highly dependent on processing conditions, technological configurations, and water use practices. In particular, wastewater generation exhibits substantial variability among processing systems. To provide a clearer overview of these differences, Table 3 presents the main residues identified in wet coffee processing, together with their process stages, reported proportions in the literature, and the main environmental challenges associated with each residue.

The nature of these residues is closely related to the biological function of the tissues that make up the fruit. The pulp obtained during pulping is one of the largest residues and corresponds mainly to the external tissues of the fruit, giving it a high proportion of structural compounds and secondary metabolites. On a dry basis, Pérez Calvo et al. [76] reported the following for the analyzed coffee pulp: 11 g of protein, 6 g of lipids, 46 g of carbohydrates, 10 g of ash, 36 g of crude fiber, and 2% caffeine per 100 g.

Table 3. Residual streams generated during wet coffee processing in Colombia [1].

Residue	Process Stage	Proportion Reported in Selected Studies	Main Issue
Pulp	Pulping	≈40–50% of fresh cherry weight	High organic load, odors from decomposition, and leachate generation
Mucilage	Mucilage removal/fermentation	≈6–15% in values reported for Colombian coffee	High concentration of sugars and pectic substances; significant contribution to the organic load of effluents
Parchment	Drying and dehulling	≈6% of cherry composition in reported characterizations	Solid lignocellulosic residue associated with the fruit endocarp
Wastewater	Fermentation and washing	Variable, depending on technology and water consumption	High chemical and biochemical oxygen demand, acidity, and organic matter

[1] Data adapted from [46,54,57–59,78].

The lignocellulosic composition of coffee pulp exhibits considerable variability among materials and origins, even when the same residual fraction is analyzed. In a characterization of Colombian coffee pulp from Jardín, Antioquia (Colombia), Arango-Agudelo et al. [77] determined, on a dry basis, 59 ± 2% cellulose, 5 ± 1.6% hemicellulose, 21 ± 3% lignin, in addition to 48 ± 2% water-soluble extractives and 0.48 ± 0.26% ash. In contrast, Malarat et al. [79] characterized coffee pulp from Thailand and reported 31% cellulose, 7% hemicellulose, 17% lignin, and 0.41% ash. The difference observed between these two characterizations, particularly in cellulose content, indicates that coffee pulp does not exhibit a single lignocellulosic profile. Nevertheless, these differences should not be attributed exclusively to geographical origin, as they may also be associated with the raw material, agroecological and processing conditions, and, importantly, the methodologies employed to quantify the different fractions.

Ballesteros et al. [80] reported values of 52% cellulose and 40% hemicellulose. Other studies have found different compositions; for example, Blandón-Castaño et al. [81], cited by Carvajal-Flórez and Oakley [82], reported 46% cellulose, 35% hemicellulose, and 9% lignin. This variability can be attributed to the origin, the variety, the growing conditions, the maturity, and the methodologies used to determine the lignocellulosic fractions.

Subsequently, during the removal of the mucilage through fermentation for 24 to 72 h, a matrix rich in soluble polysaccharides, mainly pectins and sugars, is released [60]. Studies on the composition of Colombian coffee byproducts have reported mucilage values close to 15%, although this proportion may vary depending on the characteristics of the fruit and the processing system. Its high concentration of pectic substances, with a high degree of esterification (≈84%), low methoxyl content (≈6%), and high galacturonic acid content, along with fermentable sugars (with low proportions of ribose, xylose, and glucose), makes this fraction an important source of organic matter and a material with potential for biotechnological valorization in the food industry [77,83,84].

Mucilage exhibits physicochemical behavior distinct from that of coffee pulp, mainly because of its high moisture content and the predominance of soluble compounds and pectic substances. Studies conducted on Colombian coffee mucilage have confirmed its highly hydrated nature and its content of potentially fermentable compounds. Orrego et al. [85] re-

ported values of approximately 84% water, 9% protein, 4% sugars, 0.91% pectic substances, and 0.70% ash. Complementarily, Oliveira et al. [86] reported approximately 84% moisture for this fraction and, on a dry basis, 30% pectic polysaccharides, 18% hemicelluloses, 17% proteins, and 8% cellulose.

Consistent with these compositions, a review of coffee fermentation compiled values for mucilage, on a dry basis, of approximately 35–35.8% total pectic substances, 30% reducing sugars, 20% non-reducing sugars, and approximately 17% cellulose [87]. Overall, the different sources consistently characterize mucilage as a fraction with high moisture content and a substantial proportion of soluble carbohydrates and pectic substances, distinguishing it from predominantly lignocellulosic fractions such as pulp and parchment.

Parchment exhibits a composition more closely associated with a lignocellulosic matrix. In the characterization of Colombian coffee residues conducted by Arango-Agudelo et al. [77], parchment contained, on a dry basis, 23 $\pm$ 0.81% cellulose, 4 $\pm$ 0.79% hemicellulose, 18 $\pm$ 1.02% lignin, 8 $\pm$ 0.80% water-soluble extractives, and 8 $\pm$ 0.02% ash. These results confirm the presence of a substantial lignocellulosic structural fraction, although they differ from ranges compiled in previous studies. For example, Mirón-Mérida et al. [88] described parchment as a lignocellulosic material containing approximately 40–49% cellulose, 25–32% hemicellulose, 33–35% lignin, and 0.5–1% ash. Comparison with the Colombian characterization consequently indicates substantial variability in the reported composition of coffee parchment and reinforces the need to consider both the source material and the analytical methodology when establishing its composition.

The wastewater generated during processing constitutes another environmentally significant stream. Its composition depends on the processing system, particularly the fermentation and washing operations, as well as the volume of water used. These effluents can have a high organic load, expressed through high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values, in addition to acidity and other soluble compounds derived from the pulp and mucilage. For this reason, wastewater requires proper management and treatment before final disposal. Rattan et al. [89] reviewed the characteristics, treatment, and valorization alternatives for coffee industry wastewater, highlighting its high organic load and the need for appropriate treatment technologies. In the Colombian context, Cenicafé has also developed anaerobic systems for the treatment of wastewater generated during coffee fermentation and washing. Therefore, it is not appropriate to assign a fixed percentage of the cherry's weight to wastewater, as its volume depends directly on the coffee cherry's weight.

Wastewater generated during pulping, fermentation, and washing operations constitutes a physicochemically distinct stream from the solid residues. Its characterization is primarily based on parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, and suspended solids, as well as other indicators that may include phenolic compounds and different forms of organic matter. Rattan et al. [89] compiled BOD values of up to 20,000 mg L^{-1}, COD values of up to 50,000 mg L^{-1}, and pH values below 4 for wastewater generated during coffee processing, evidencing its high organic load and acidic character.

Overall, the compositional differences among residual streams demonstrate that wet coffee processing by-products do not constitute a homogeneous biomass. Coffee pulp and parchment exhibit lignocellulosic matrices containing cellulose, hemicellulose, and lignin, although their proportions may vary widely among materials and analytical methods. Mucilage, in turn, is characterized by high moisture content and a greater presence of soluble sugars and pectic substances, whereas wastewater constitutes a liquid stream characterized primarily by its organic matter load and physicochemical properties. This differentiation is fundamental for defining specific valorization strategies and provides

a basis for integrating different transformation pathways within biorefinery and circular bioeconomy frameworks.

5.3. Semidry Processing

In the semidry, frequently referred to as the pulped natural or honey process, the outer skin (exocarp) and a portion of the pulp are mechanically depulped, similar to the wet method [87,90]. However, instead of undergoing full microbial fermentation to remove the mucilage, the beans are directly sun-dried with the remaining sticky, sugar-rich mucilage layer adhering to the parchment until reaching a target moisture content of approximately 10–12% [87,91].

The retention of varying mucilage amounts, combined with specific environmental drying conditions and turning frequencies, gives rise to distinct commercial processing styles, commonly categorized as yellow, red, and black honey coffees [91,92]. Visually and chemically, yellow honey retains the least mucilage (~25–50%) and dries the fastest, whereas black honey retains nearly all the mucilage (~100%) and undergoes prolonged, shaded drying, promoting controlled enzymatic reactions and organic acid concentration [91–93].

Sensorially, semidry processing generates a balanced, intermediate cup profile. It typically exhibits a lighter body than fully dry-processed (natural) coffees while delivering a cleaner, more defined acidity and pronounced sweet, fruity notes that closely resemble washed coffees [91,93]. From an environmental perspective, this hybrid approach significantly reduces water consumption and wastewater generation compared to traditional wet processing, positioning semidry processing as a sustainable alternative in modern coffee biorefineries [87,91].

Residues from Semidry Processing

During semidry coffee processing, mechanical pulping removes the outer skin and pulp, generating coffee pulp as the principal solid residue. However, unlike wet processing, the mucilage is not completely removed before drying. Instead, part or all of the mucilage may remain adhered to the parchment-covered beans and is subsequently dried together with the parchment. After drying, hulling removes the parchment, generating a lignocellulosic residue that may contain dried mucilage depending on the extent of mucilage removal. Thus, the relative amounts and physicochemical characteristics of the resulting residues depend on the degree of pulp and mucilage removal or retention, as well as on the specific processing conditions [34,87,90–92].

Wet and semidry processing generate related types of residues, but the main distinction is the treatment of the mucilage fraction. In wet processing, mucilage is removed before drying, whereas in semidry processing, part or all of the mucilage remains on the parchment-covered beans during drying. Consequently, coffee pulp and parchment with variable amounts of retained dried mucilage are the main solid residues associated with semidry processing (Table 2). Their composition may fall within ranges reported for the corresponding residues from wet processing; however, it can vary according to the extent of mucilage retention, processing conditions, and coffee characteristics.

6. Roasting Residue: Silverskin

During the roasting stage, the application of heat to green coffee beans triggers a series of complex physicochemical transformations responsible for the formation and degradation of various chemical compounds that determine the beverage's aroma, flavor, and other sensory characteristics. These changes are directly related to the roast level employed (light, medium, or dark), significantly influencing the coffee's sensory quality [60]. During this process, the beans undergo volumetric expansion due to heating, accompanied by

the detachment of the thin outer skin covering them, known as silverskin. This material constitutes the only solid residue generated during the roasting stage, corresponding to approximately 4–5% of the initial mass of the coffee beans [94–96].

Every year, approximately 200,000 t of silverskin are produced in Europe alone and discarded as waste [97]. Coffee silverskin must be distinguished from other coffee residues, such as pulp, hulls, and SCG, that originate at different stages of coffee processing [55]. Considering that silverskin accounts for approximately 4% to 5% of the total mass of processed coffee beans, major producing countries contribute substantially to this global byproduct stream. Using the 4–5% silverskin-to-coffee-bean mass ratio commonly reported in the literature [94–96], the estimated annual generation would range from approximately 172,560 to 215,700 t for Brazil and from 32,160 to 40,200 t for Colombia. In contrast, the ICO Coffee Development Report reports a silverskin yield equivalent to approximately 1.7% of green coffee bean consumption, which would result in lower estimates of approximately 73,338 t for Brazil and 13,668 t for Colombia when applied to the production volumes reported by the USDA and ICO. Therefore, these values should be considered approximate estimates, as the amount of silverskin generated depends on the production volume, processing and roasting conditions, and the silverskin yield factor adopted from the literature or statistical sources.

Its composition is characterized by high levels of dry matter (92.3–96.0%) and volatile solids (76.4–99.6%), indicating a predominance of organic compounds. It is notable for its high dietary fiber content (34.7–76.9%), composed primarily of cellulose (22.8%), hemicellulose (19.3%), and lignin (28.6–32.2%), which offers potential for use as a fiber-rich ingredient and as a raw material for obtaining value-added compounds. Furthermore, silverskin exhibits moderate protein levels (14.2–20.8%) and low lipid (1.6–3.7%) and ash (3.2–8.3%) contents. It also contains bioactive compounds, including phenolics (0.9%) and caffeine (0.1–1.0%), which may contribute to its antioxidant activity. The pH ranges from 5.3 to 8.5, and the calorific value ranges from 17.8 to 19.5 MJ/kg, highlighting its potential for food and functional applications as well as for energy recovery [98–101].

7. Post-Consumption Residue: Spent Coffee Grounds (SCG)

According to Silva et al. [9], preparation of coffee beverage involves extracting soluble constituents with hot water, producing a solid residue, the SCG. The growing global demand for coffee has intensified environmental concerns surrounding SCG disposal. It is estimated that about 6 million metric tons of SCG are produced annually worldwide, and of this total, approximately 50% is generated by small coffee shops, restaurants, and individual consumers [102,103]. Approximately 750,000 kg of SCG are produced daily through the espresso method, given that 50 million cups of espresso are consumed each day [104,105].

When discarded in landfills, this organic residue can contribute to methane and carbon dioxide emissions, thereby exacerbating global warming. Moreover, the presence of tannins, caffeine, chlorogenic acids, and phenolic compounds may create additional risks of environmental contamination. Despite being commonly treated as residue, SCG possess a complex and valuable composition. They contain insoluble dietary fiber, including cellulose, hemicellulose, and lignin, as well as proteins, lipids, and bioactive compounds such as chlorogenic acids, caffeine, melanoidins, and polyphenols, supporting their potential use as a raw material in food, cosmetic, pharmaceutical, and biorefinery applications [103–106]. Given these impacts, the importance of implementing practices associated with the circular economy is underscored through the development of strategies and technologies aimed at valorizing and transforming coffee farming waste, with the goal of mitigating the environmental liabilities generated throughout the supply chain [106,107].

SCG are characterized as a solid residue with a deep brown color and high moisture content; they exhibit phytochemical variations. It is characterized by a predominance of structural polymers, particularly cellulose and hemicellulose, and also contains significant amounts of lignin, proteins, and phenolic compounds [62,107–112], as observed in Table 4.

Table 4. Chemical composition of spent coffee grounds [1].

Components	Composition (Dry Basis)
Cellulose	12.4–24.0 g/100 g
Hemicellulose	31.1–39.1 g/100 g
Lignin	3.6–7.0 g/100 g
Lipids	2.0–13.0 g/100 g
Proteins	0.7–3.9 g/100 g
Ash	4.9–17.4 g/100 g
Insoluble dietary fiber	35.0–50.8 g/100 g
Soluble dietary fiber	8.0–9.7 g/100 g
Caffeine	280.0–660.0 mg/100 g
Chlorogenic acids	4.7–10.6 mg/g
Total phenolics	56.9–93.3 mg GAE/g

[1] Data adapted from [62,80,107–115].

8. Potential Applications

Coffee residues have diverse physicochemical characteristics and, consequently, different technological potentials for valorization. Coffee pulp, hulls, mucilage, parchment, wastewater, silverskin, and spent coffee grounds (SCG) can be directed toward different applications according to their composition, moisture content, availability, and processing history. These applications include biofuels, biofertilizers, biobased materials, functional food ingredients, bioactive compounds, and adsorbent materials, using thermochemical, biological, and extraction-based processes. The main technological pathways, together with their potential products, advantages, and limitations, are summarized in Table 5.

Table 5. Technological pathways for the valorization of coffee residues: advantages and limitations.

Residues	Valorization Routes	Advantages	Limitations	References
Coffee Hulls, Parchment, SCG and Silverskin	Thermochemical conversion (Pyrolysis, Gasification, Biochar)	High carbon retention, production of valuable coproducts (bio-oil, syngas, biochar), effective heavy metal adsorption, and stable energy output.	Generation of unwanted byproducts from the thermal process, high energy consumption, and high operating and capital costs.	[64,68,71]
Wastewater, Pulp, Mucilage and SCG	Anaerobic digestion e biogas production	Efficient mitigation of high organic loads (COD/BOD), production of renewable energy and biofertilizers.	Inhibition of microbial activity by toxic compounds (caffeine, polyphenols, tannins), low pH of effluents, and slow degradation rates of lignocellulose.	[34,55,63]

Table 5. *Cont.*

Residues	Valorization Routes	Advantages	Limitations	References
Mucilage, Pulp and SCG	Bioethanol and Biofuels	Utilizes high sugar/pectin content without extensive pretreatment and contributes to decarbonization of fuels	For some types of residues (SCG and cellulose), additional steps may be required to expose the lignocellulosic matrix; certain compounds (furfural and phenolic compounds) may reduce the yield of the fermentation process.	[85,100,104]
Pulp, SCG and Silverskin	Bioactive Compound Extraction	Permits the recovery of high-value antioxidants; possibility of using modern techniques (ultrasound, sonication); environmental appeal that adds market value	High solvent costs, potential thermal degradation of sensitive bioactives, complex purification steps, and seasonal feedstock degradation.	[11,61,77,94,109,113]
Hulls, parchment, pulp, SCG	Cellulose and Biocomposites	Modular reinforcing properties in biocomposites; a biodegradable alternative to synthetic polymers	High consumption of electricity, mechanical energy, and chemical products	[14,65,73,79]
Mucilage, pulp, silverskin, SCG	Functional Foods & Bakery Ingredients	A rich source of insoluble and soluble dietary fiber, low in calories, it improves the nutritional profile of baked goods and vegan products.	The presence of antinutritional factors and the possible formation of compounds during roasting that impart a bitter flavor, which require sensory optimization.	[76,86,94,97,105,110]

As discussed throughout the manuscript, coffee hulls and coffee pulp consist predominantly of complex lignocellulosic matrices containing cellulose, hemicellulose, and lignin, while coffee pulp also contains sugars and other carbohydrates and both residues may provide bioactive compounds, including phenolics. Their composition enables applications in several sectors, including cellulose and lignin recovery, extraction of bioactive compounds for food and nutraceutical formulations, composting and soil amendment, anaerobic digestion for biogas production, pyrolysis for biochar generation, bioethanol production, microbial fermentation, and the development of biobased composites [14,76,79,82,116]. Specific studies have demonstrated the potential of coffee pulp for functional food formulations and nanocellulose production, whereas coffee hulls have been investigated as a source of cellulose and as feedstock for pyrolysis and bioadsorbent or biochar production [14,64,67,68,76,79]. These alternatives demonstrate that coffee hulls and pulp can

function as multifunctional feedstocks for both material and energy recovery. Future research should focus on optimizing fractionation and conversion processes, improving product yields, and validating these routes at larger scales. Integrated valorization strategies that combine the recovery of high-value compounds, materials, and energy from the same residue stream may further enhance resource efficiency and support the development of circular coffee biorefineries [83,117,118].

Coffee mucilage represents another relevant residue for valorization because of its relatively high content of soluble sugars, pectin, and other organic compounds. These characteristics make mucilage particularly suitable for food-related applications and microbial fermentation. Previous studies have investigated coffee mucilage for incorporation into food formulations and as a substrate for fermentation processes, including the production of ethanol [85,86]. Its readily fermentable fraction also supports anaerobic digestion and other biological routes for energy recovery. However, the high moisture content of fresh mucilage and the presence of compounds such as phenolics, caffeine, and tannins may influence its processing, storage, and biological conversion, as indicated in Table 5. Further research should focus on improving the separation and recovery of valuable components, optimizing fermentation conditions, and integrating mucilage valorization into broader coffee biorefinery systems.

Coffee parchment and silverskin also offer relevant opportunities for valorization, although their applications remain less explored than those of coffee pulp, hulls, and spent coffee grounds. Coffee parchment has been investigated as a lignocellulosic source for the production of cellulose with potential use as reinforcement in composite materials, as well as a source of caffeine and phenolic compounds for the development of functional materials [65,88]. Coffee silverskin, in turn, contains bioactive compounds that support its potential use in functional food formulations, with studies demonstrating its incorporation into food products and the retention or bioaccessibility of relevant bioactive compounds [94,97]. Other approaches have explored the use of silverskin in biofuel production and vermicomposting, demonstrating its potential for both energy and agricultural applications [98,99]. Future research should focus on improving the recovery of valuable compounds from these residues, evaluating their safety and functionality in specific applications, and developing integrated valorization routes that combine material, food, energy, and agricultural uses within circular coffee biorefinery systems.

Mucilage and silverskin are therefore important components of the overall coffee-residue valorization framework and should not be considered secondary residues in the context of circular utilization. While mucilage is particularly relevant for biological conversion and food-related applications, silverskin has demonstrated potential as a source of bioactive compounds and functional food ingredients, in addition to energy and agricultural applications. The inclusion of these residues in Table 5 provides a more comprehensive synthesis of the technological pathways evaluated throughout this review.

SCG also represent a valuable lignocellulosic residue and retain components such as oils, fatty acids, sterols, and phenolic compounds with antioxidant potential. Their composition supports applications including the recovery of bioactive compounds, incorporation into functional foods and nutraceuticals, cosmetic formulations, fermentation processes, and the production of renewable fuels such as bioethanol, biodiesel, and biogas. In addition, SCG can be subjected to thermochemical conversion for biochar and bio-oil production and used in the development of biopolymers and biocomposites, as well as composting and soil amendment [107–116]. However, compositional variations associated with coffee species, processing and roasting conditions, together with concerns regarding contaminants, toxicological safety, and regulatory compliance, must be considered, particu-

larly for food and nutraceutical applications [118]. The main valorization alternatives for SCG and the associated technological characteristics are summarized in Table 5.

Despite the broad technological potential of coffee-residue valorization, the contribution of these pathways to a circular economy depends on their ability to effectively replace conventional raw materials, reduce waste disposal, recover resources, and generate products with sufficient technical, economic, and environmental performance [119,120]. Existing studies provide evidence that some coffee residues can already be incorporated into circular systems. For example, the use of coffee pulp as a fertilizer in coffee production was evaluated through life cycle assessment, life cycle costing, energy analysis, and eco-efficiency assessment. The authors reported reductions of 39–87% in cumulative energy demand and 49.69–72% in CO_2 emissions, together with a 6–26% increase in economic value added, demonstrating that residue valorization can generate simultaneous environmental and economic benefits when the recovered biomass is returned to the agricultural production system [121]. Similarly, spent coffee grounds (SCG) have been investigated as secondary raw materials for construction materials. Their incorporation into mortar formulations reduced the use of virgin aggregates and improved thermal insulation performance, while a multicriteria assessment indicated potential environmental and economic benefits compared with conventional alternatives [122]. These examples illustrate that circularity is not determined solely by the conversion of a residue into a new product, but also by the extent to which the resulting product substitutes virgin resources, avoids disposal impacts, and maintains its value within or beyond the coffee supply chain.

Techno-economic assessments have also demonstrated that the economic feasibility of coffee-residue valorization is highly dependent on process configuration, scale, feedstock logistics, product yields, and the number and value of products generated. For SCG biodiesel production, Kookos [123] reported that the process was economically unattractive at the evaluated scale, with a minimum selling price of approximately US$3.6 kg^{-1} of biodiesel, and concluded that economic performance could improve only at sufficiently large centralized production capacities. The study also indicated that the recovery of higher-value bioactive compounds could improve the economic attractiveness of the process. In a subsequent industrial-scale assessment, Thoppil and Zein [123] estimated an investment of approximately US$123 million for a biodiesel plant processing SCG and concluded that the baseline configuration was not profitable under the assumptions adopted, highlighting the importance of capital investment, feedstock availability, and product revenues in determining feasibility. More recently, Gu et al. [124] compared SCG transesterification and pyrolysis through process simulation, TEA, and LCA. The production costs of transesterification were 3.08 times higher than those of pyrolysis, while CO_2 emissions were 6.92 times higher under the evaluated conditions, mainly because of the additional pretreatment and separation requirements. These findings demonstrate that technically feasible conversion routes may present substantially different economic and environmental performances depending on process integration and operating conditions.

Evidence from integrated biorefinery systems further indicates that the simultaneous recovery of multiple products may improve the economic performance of coffee-residue valorization. A recent multiproduct SCG biorefinery based on hydrothermal carbonization evaluated four process configurations combining oil recovery, prebiotics, functionalized melanoidins, and hydrochar [125]. The baseline configuration was reported to be economically viable at a processing capacity of 10 t per batch (approximately 1.4 kt $year^{-1}$), with a net present value of US$108.2 million, an internal rate of return of 18.53%, and a payback period of 3.98 years under the market assumptions adopted. However, the environmental assessment showed that solvent- and steam-intensive operations were important contributors to environmental impacts, and simplified configurations presented lower impacts

across several categories. This evidence supports the potential advantage of integrated biorefineries, but also demonstrates that increasing the number of valorization steps does not automatically improve sustainability. Additional extraction, separation, and purification stages can increase capital and operating costs, energy and solvent consumption, and environmental burdens.

Life cycle assessment studies similarly show that the environmental benefits of coffee-residue valorization are strongly dependent on process configuration and the management pathway being replaced. Catalán et al. [126] evaluated the production of cellulase from coffee husks by solid-state fermentation and found that electricity consumption was a major contributor to environmental impacts, with the lyophilization step being particularly important during downstream processing. For anaerobic digestion of coffee husks, de Oliveira Fernandes et al. [127] compared landfilling with anaerobic digestion for energy generation, with and without hydrothermal pretreatment. The carbon footprint associated with landfilling was more than 13 times higher than that of the anaerobic digestion scenarios, while digestate management represented approximately 34% of the total emissions. The use of digestate as a substitute for chemical fertilizers improved the environmental performance, illustrating the importance of considering avoided products and coproduct utilization when evaluating circularity. In addition, recent LCA research on SCG pyrolysis has demonstrated that environmental performance is sensitive to operating temperature, energy requirements, electricity sources, and transportation distances [128]. Therefore, LCA results should be interpreted in relation to the functional unit, system boundaries, energy matrix, transportation requirements, allocation procedures, and substitution assumptions adopted in each study.

The available evidence indicates that coffee-residue valorization can contribute to circular economy strategies when it creates effective reverse flows of materials, substitutes virgin resources or conventional products, reduces waste-management impacts, and retains value through cascading or integrated use. However, the evidence is unevenly distributed among residues and applications. SCG is comparatively better represented in TEA and LCA studies, particularly for biofuel, biorefinery, and thermochemical pathways, whereas quantitative economic and environmental assessments remain more limited for coffee mucilage, parchment, and silverskin and for several food, material, and bioactive-compound recovery routes. Therefore, the main research gap is not the lack of proposed recovery pathways, but rather the limited availability of comparable quantitative evidence demonstrating whether these pathways can simultaneously achieve technical performance, economic viability, environmental improvement, and effective resource circularity on a larger scale. Future studies should consequently combine TEA, LCA, material-flow analysis, and process-scale validation to compare alternative coffee-residue valorization pathways using consistent system boundaries and functional units.

Overall, the available evidence indicates that the transition toward a circular coffee bioeconomy should be based on evidence of resource efficiency rather than on the number of potential applications identified for each residue. Coffee-residue valorization can provide environmental and economic benefits when recovered materials effectively substitute conventional resources, avoid disposal impacts, and generate products with sufficient market value. However, TEA and LCA results demonstrate that these benefits are highly dependent on process configuration, scale, energy and water requirements, transportation, product yields, and the management of residual streams. Consequently, the comparison of valorization pathways should consider technical, economic, and environmental indicators simultaneously. In this context, integrated biorefinery strategies remain relevant because they can enable cascading recovery of multiple products, but their advantages should be demonstrated through quantitative assessments rather than assumed from pro-

cess integration alone. Future research should therefore prioritize comparable TEA and LCA studies, material-flow analysis, and pilot- or demonstration-scale validation, particularly for mucilage, parchment, and silverskin, for which quantitative evidence remains comparatively limited.

9. Conclusions

This review demonstrates that coffee agro-industrial residues represent a substantial and still underexploited biomass resource in Brazil and Colombia. Although both countries occupy strategic positions in the global coffee sector, their contrasting production systems generate distinct residue streams, environmental pressures, and opportunities for valorization. Brazil, characterized by large-scale production of C. *arabica* and C. *canephora* and the predominance of dry processing, mainly generates coffee hulls, whereas Colombia's predominantly wet processing of C. *arabica* generates coffee pulp, mucilage, parchment, and wastewater. These differences highlight the importance of considering local production systems when designing residue management and valorization strategies.

The reviewed evidence also demonstrates that coffee residues should not be regarded as a homogeneous resource. Differences in physicochemical composition, moisture content, availability, and generation conditions determine their suitability for specific applications. Several routes, including the recovery of bioactive compounds and lignocellulosic fractions, production of biobased materials, bioenergy, biochar, fertilizers, and functional products, show promising technical potential. However, this potential should not be interpreted as evidence of industrial feasibility, as the technological maturity of the proposed approaches varies considerably and many remain primarily at laboratory or early development stages.

The transition from disposal-based practices toward a circular coffee bioeconomy therefore requires more than the identification of new applications. Technical limitations associated with residue variability, stabilization, processing, and scale-up must be considered alongside economic factors, such as processing costs, product yield, market value, and infrastructure requirements. In addition, the spatial distribution and seasonality of coffee production, together with the moisture and perishability of some residues, make collection, storage, and transportation important determinants of the feasibility of valorization systems. Safety and regulatory requirements are also particularly relevant for applications involving food, feed, agriculture, and nutraceutical products.

Regional regulatory frameworks should also be considered in the implementation and commercialization of coffee residue-derived products. In Brazil and Colombia, requirements vary according to the intended application, particularly for food, feed, and cosmetic products. These frameworks are especially relevant because coffee by-products may contain bioactive or potentially antinutritional compounds, such as caffeine and tannins, whose concentrations vary according to residue type and processing conditions. Therefore, future research should integrate regulatory and safety assessments with technological, economic, and environmental evaluations to support the safe and legally compliant commercialization of coffee residue-derived products.

Future research should consequently prioritize pilot- and demonstration-scale validation, standardized residue characterization, supply-chain and logistics optimization, and the integration of techno-economic analysis, life-cycle assessment, and technology readiness level evaluation. These approaches are essential to distinguish technically promising concepts from those with realistic potential for economic and environmental implementation. Greater attention should also be given to integrated biorefinery strategies adapted to regional conditions, in which different residue streams or fractions can be directed toward complementary applications to maximize resource recovery. Overall, the valorization of coffee residues represents a promising pathway toward a more circular coffee sector, but its

effective implementation will depend on demonstrating not only technical performance, but also economic viability, environmental benefits, technological maturity, and logistical feasibility at relevant scales.

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