processes
MDPI

Review

Upcycling Coffee Waste: Key Industrial Activities for Advancing Circular Economy and Overcoming Commercialization Challenges

Kanokthip Pongsiriyakul [1], Peerawat Wongsurakul [1,2], Worapon Kiatkittipong [1,3,*], Aerwadee Premashthira [4], Kulapa Kuldilok [4], Vesna Najdanovic-Visak [5], Sushil Adhikari [2,6], Patrick Cognet [7], Tetsuya Kida [3,8,9] and Suttichai Assabumrungrat [10,11]

[1] Department of Chemical Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University, Nakhon Pathom 73000, Thailand
[2] Department of Biosystems Engineering, Auburn University, Auburn, AL 36849, USA
[3] International Research Organization for Advanced Science and Technology (IROAST), Kumamoto University, Kumamoto 860-8655, Japan
[4] Department of Agricultural and Resource Economics, Faculty of Economics, Kasetsart University, Bangkok 10900, Thailand
[5] Chemical Engineering and Biotechnologies, Energy & Bioproducts Research Institute, Aston University, Birmingham B4 7ET, UK
[6] Center for Bioenergy and Bioproducts, 520 Devall Drive, Auburn University, Auburn, AL 36849, USA
[7] Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, 31062 Toulouse cedex 09, France
[8] Graduate School of Science and Technology, Department of Applied Chemistry and Biochemistry, Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto 860-8655, Japan
[9] Institute of Industrial Nanomaterials (IINa), Kumamoto University, Kumamoto 860-8555, Japan
[10] Center of Excellence in Catalysis and Catalytic Reaction Engineering, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand; suttichai.a@chula.ac.th
[11] Bio-Circular-Green-Economy Technology and Engineering Center (BCGeTEC), Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
* Correspondence: kiatkittipong_w@su.ac.th

Abstract: The valorization of coffee waste has gained traction due to its potential to generate valuable products, lessen its impact on the environment, and promote sustainability. This review examines the diverse range of coffee waste, including pulp, husk, mucilage, and parchment from the upstream processing of green beans, as well as silverskin (coffee chaff) and spent coffee grounds (SCGs) generated during roasting and brewing. These materials are identified as valuable raw inputs for biorefineries pursuing a bio-circular economy. Recent research has yielded several viable applications for these by-products, categorized into four main areas: (1) agriculture, (2) biofuels and bioenergy, (3) biochemicals and biomaterials, and (4) food ingredients and nutraceuticals. Despite significant advancements in research, the industrial application of coffee waste remains limited. This review summarizes the global commercialization landscape, highlighting that SCGs are particularly advantageous for large-scale upcycling, with applications spanning agriculture, biofuels, and biochemicals. In contrast, coffee husk is primarily utilized in food ingredients and nutraceuticals. The review also addresses the challenges and constraints that must be overcome to facilitate successful commercialization.

Keywords: food waste valorization; agriculture; functional food; renewable energy; biomaterial; active packaging; circular bio-economy; bio-based economy; perspective

check for updates

Citation: Pongsiriyakul, K.; Wongsurakul, P.; Kiatkittipong, W.; Premashthira, A.; Kuldilok, K.; Najdanovic-Visak, V.; Adhikari, S.; Cognet, P.; Kida, T.; Assabumrungrat, S. Upcycling Coffee Waste: Key Industrial Activities for Advancing Circular Economy and Overcoming Commercialization Challenges. *Processes* **2024**, *12*, 2851. https://doi.org/10.3390/pr12122851

Academic Editor: Antoni Sánchez

Received: 13 November 2024
Revised: 5 December 2024
Accepted: 10 December 2024
Published: 12 December 2024

1. Introduction

The world is currently facing a climate change crisis, commonly measured by the rise in the global average surface temperature. This phenomenon involves changes in weather patterns over the seasons, leading to the increased severity and frequency of extreme weather events, such as storms and heavy precipitation that cause widespread flooding, as well as prolonged heatwaves, multi-year droughts, and severe wildfires driven by shifts in climate conditions. Increasing greenhouse gas emissions significantly contributes to the rising global average temperature. More than 50 billion tons of greenhouse gas (CO_2 equivalents) are released into the atmosphere each year, with no sign of slowing down, which is mainly generated for energy production by burning fossil fuels such as coal, oil, and natural gas. To manage the climate crisis, the scientific community has examined environmentally friendly solutions to reduce greenhouse gas emissions, focusing on clean energy and chemical production from bioresources, for example, bioethanol [1], and biodiesel [2,3]. Typically, conventional biofuel has been produced from human food-based crops (i.e., corn, sugarcane, palm oil, etc.), which could negatively affect food supply chains. Accordingly, utilizing non-food biomass and municipal solid waste (MSW) to produce various products (foods, energies, chemicals, and medicines) has been increasingly investigated.

In 2016, the waste generation volume was globally estimated at 2.01 billion tons, and it is expected to reach 3.40 billion tons by 2050 under a business-as-usual scenario. Notably, a substantial portion of this waste comes primarily from the food and agricultural industries, accounting for 44% of total global waste generation [4]. The waste is mostly managed by disposing of it in landfills and open dumping; only 19% of the waste is recycled and composted, and some is burned. Regarding the global food industries, approximately 30% of food loss and waste have been generated during production, which amounts to 1.3 billion tons per year. Due to improper management, soil, water, and air could be polluted, which has a detrimental impact on the environment, human health, and animal life. To resolve the environmental issue, the trend toward the utilization of food and agricultural waste as a sustainable feedstock to produce various biorefinery products has gained increasing attention. Food wastes, in particular coffee waste, have been considered a high potential renewable resource due to their low price and high content of beneficial compounds such as lipids, carbohydrates, proteins, and bioactive compounds (i.e., polyphenols, carotenoids, dietary fiber, antioxidants, etc.) [5,6]. Consequently, searching for the efficient processing and utilization of food waste and by-products is becoming an indispensable challenge [7].

Coffee waste is one of the most promising renewable resources among food and agricultural waste generation. According to the International Coffee Organization report [8–10], coffee is one of the world's most popular beverages, with consumption increasing by approximately 10 million tons consumed every year since 2018.

Generally, coffee production involves multiple complicated procedures, beginning with the processing of coffee cherries to generate coffee beans, followed by roasting, grinding, and brewing to produce a coffee beverage. A significant volume of waste (approximately 40–45%) is generated throughout the coffee production process, including skin, pulp, mucilage, parchment, husk, and spent coffee grounds [11]. In this regard, a massive amount of waste, about 4 million tons, is generated each year, which could be harmful to the environment if disposed of without appropriate pretreatment due to the presence of naturally toxic compounds such as polyphenols, caffeine, and tannins [12,13]. Therefore, effective waste management is required.

Fortunately, a significant concentration of polyphenols, tannin, and caffeine in coffee waste are biologically active substances that could benefit the human body. Extracted tannin, for example, has been investigated as an active compound in food ingredients (for energy drinks and energy bars) [14], whereas polyphenols, an antioxidant source, could promote human health [15]. Furthermore, some bioactive compounds discovered in coffee waste have been proposed to be utilized as a dietary fiber source and functional component in bakery items and beverages [16,17], cosmetic and personal care products [18,19], as well as pharmaceutical applications [20,21]. Other compounds (starch, lipids, proteins, cellulose, enzymes, and pigments) found in coffee waste have been proposed for conversion into various products, such as biodiesel [22], bioethanol [23], biochar [24], biosorbents for heavy metal removal [25,26], bio-sources in polymers [27,28], supercapacitors [29], and dye applications [30].

The valorization of coffee waste can be accomplished using various processes, including physical, chemical, and biotechnological processes such as anaerobic digestion, composting, pyrolysis, extraction, etc. Various techniques have been investigated and developed in recent years to fractionate potentially high-value compounds from coffee waste and convert them into value-added products. Each approach has its advantages and limitations, and the possibility of a valorization approach depends on the desired component and its application.

Research studies for the utilization and valorization of coffee waste have continuously gained increasing attention due to their potential to generate biofuels, chemicals, and other products. However, most of the studies are conducted on a laboratory- and pilot-scale. The purpose of this work is to provide an overview of the coffee component and processing; subsequently, a review of the current state of research on the utilization and valorization of coffee waste is provided, with emphasis on their potential applications in different industries. In addition, this review provides a first-time summary of recent global commercial projects, focused on value-added products derived from coffee waste. The review also highlights the challenges and constraints that need to be addressed to navigate the path to successful commercialization.

2. Coffee Processing and Its Composition

Coffee beverages are produced from a fruit called the coffee cherry, which is composed of several parts, as shown in Figure 1. The cherry seed, also known as the green coffee bean, is a commercially valuable commodity that can be extracted from the cherry through many different methods. However, these processing techniques can be classified into three major categories: wet-, dry-, and semi-dry processing [31,32].

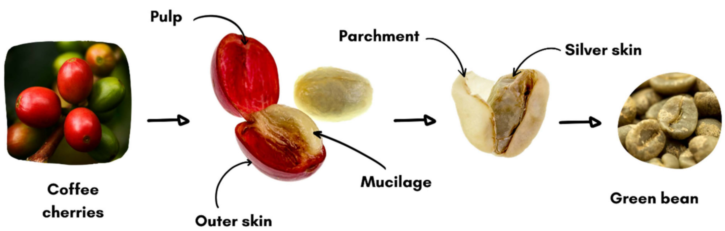

Figure 1. Coffee cherry structure.

Dry processing, also known as natural processing, is a simple technique in which freshly picked cherries are naturally dried under the sun or using a mechanical dryer. This process can take several weeks, during which the cherries are repeatedly raked and turned to ensure uniform drying and to lower the moisture content by 10–11%. Subsequently, the dried cherries are dehulled to remove the outer layers, which include skin, pulp, mucilage, and parchment, known as a coffee husk (CH) [33–35].

Conversely, wet processing (washed method) is a more intricate method compared to the drying method, involving several essential steps. Firstly, the freshly picked coffee cherries are cleaned and sorted (size and density) by immersing the cherries in water, and then the skin and pulp are removed by a pulper machine. Subsequently, the beans are subjected to fermentation, followed by thorough washing to eliminate any remaining fermented mucilage. Finally, the washed coffee beans are dried and dehulled, in which the parchment layer is removed [36,37].

Semi-dry processing, also known as the pulp natural, semi-washed, or honey method, is a hybrid approach that combines wet and dry processes. The technique begins with the same cleaning and sorting as wet processing, followed by depulping. The distinction between semi and wet processing concerns the treatment step of the mucilage layer. There are two techniques to demucilage coffee cherries for semi-processing: one is by directly drying with the mucilage layer attached, and the other is via the mechanical demucilage method, whereas wet processing involves fermentation (Figure 2) [38–40].

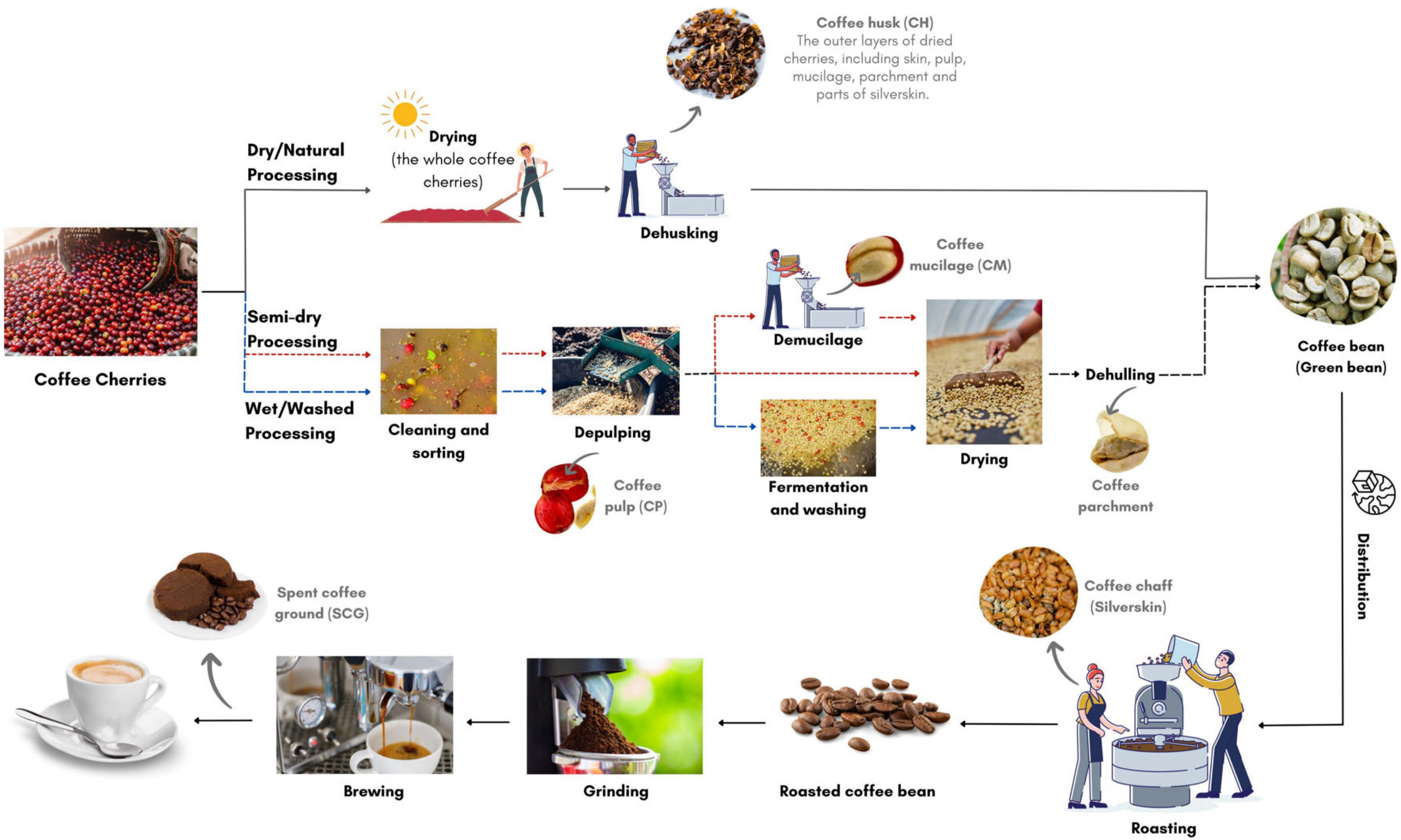

Figure 2. Coffee processing and its wastes.

Green bean coffee is obtained and disseminated globally after the separation of the coffee cherry and seed. Once the green bean coffee has been roasted and ground, the roasted ground coffee is then brewed using various techniques to make a coffee beverage. During the roasting and brewing processes, coffee waste such as silverskin (coffee chaff) and spent coffee grounds are produced.

3. Coffee Waste Composition

As demonstrated in Figure 2, brewing a cup of coffee can result in a variety of wastes, depending on the coffee processing method. During the process from farm to cup, a large amount of coffee waste, mainly coffee pulp, husk, mucilage, parchment, silverskin, and spent coffee grounds, is generated, estimated at more than 10–15 million tons per year [41,42]. Typically, the coffee waste could be divided into two categories based on its origin:

- Primary waste obtained by coffee processing (to derive green beans)—coffee pulp, husk, mucilage, and parchment.
- Secondary waste obtained by coffee beverage preparation—silverskin and spent coffee grounds.

Each part of the coffee waste has variable characteristics and chemical compositions, particularly coffee pulp, husk, mucilage, and parchment, which are significantly affected by several factors such as coffee species, processing method, geographic location, climate, and soil conditions. Understanding their compositions and characteristics is crucial for developing sustainable approaches for their utilization in diverse industries and simultaneously reducing their detrimental effects [34,43,44].

3.1. Coffee Husk (CH) and Coffee Pulp (CP)

Coffee husk (CH) and coffee pulp (CP) are major forms of waste generated during coffee processing. Although both CH and CP originate from the outer layers of the coffee cherry, their composition varies depending on the processing techniques employed. Coffee husk is produced through dry processing, where the dried outer skin, pulp, mucilage, and parchment are all combined into a single fraction, representing about 12% of the coffee cherry on a dry-weight basis. On the other hand, coffee pulp is the outer skin and pulp obtained during the depulping stage of the wet-processing method, accounting for 37–43% of the weight of the coffee cherry [45].

According to the chemical composition displayed in Table 1, coffee husk and pulp have similar characteristics, which mainly consist of carbohydrates and lignocellulosic compounds (i.e., cellulose, hemicellulose, and lignin). Furthermore, they contain proteins, caffeine, tannins, and phenolic compounds. However, coffee pulp shows a higher moisture content (ca. 85 wt%) due to its processing technique, as well as a higher concentration of total phenolic content (1.5 wt%). Moreover, coffee pulp shows relatively high amounts of total fiber and minerals when compared to coffee husk.

Table 1. Chemical composition of coffee waste (wt%).

Component	Husk	Pulp	Mucilage	Parchment	Silverskin	Spent Coffee Grounds
Processing	**Dry**	**Wet**	**Wet**	**Semi-Dry/Wet**	**Roasting**	**Brewing**
Yield	kg/100 kg of coffee cherry				kg/100 kg of coffee bean	
	12–18	37–45	11.8	5.8–6.1	4.2	65
Moisture	7–18	75–90	80–94	4–9	5–7	50–85
Carbohydrates	58–85	35–89	5–46	0.4	44	54–82
Celluloses	16–43	18–63	8	35–54	10–24	7–23
Hemicelluloses	4–30	2–29	18	20–38	4–22	15–42

Table 1. *Cont.*

Component	Husk	Pulp	Mucilage	Parchment	Silverskin	Spent Coffee Grounds
Processing	**Dry**	**Wet**	**Wet**	**Semi-Dry/Wet**	**Roasting**	**Brewing**
Lignin	6–24	14–26	-	27–35	18–31	0–26
Proteins	3–13	4–14	0.5–12	0.4–3	15–23	10–18
Lipids	2–7	1–5	0.12	0.3–0.9	2–6	2–24
mineral	3–7	6–10				
Pectins	2–12	5.5–12.4	0.6–2.6	-	1	0.01
Total fiber	18–30	18–64	-	89–91	56–72	21–59
Ash	6	0.3–8.9	0.4	0.5–1	4–8	1–3
References	[12,31,46]	[12,37,46]	[12,35]	[12,35]	[12,31,35]	[12,31,35,47]

3.2. Coffee Mucilage (CM)

Coffee mucilage (CM) is a gelatinous or sticky layer found between the coffee pulp and parchment. In the wet-processing method, CM is typically eliminated through fermentation, although it is occasionally taken along with the pulp during the depulping stage and then usually disposed of in the environment. Additionally, the dry-processing method employs mechanical techniques, such as friction, to remove the mucilage, which accounts for approximately 11.8 wt% of the coffee cherry [42,45]. Recently, mechanical demucilaging through friction has gained interest since it is more sustainable and environmentally friendly than fermentation. This method reduces water consumption and lowers power requirements and processing costs [48].

The compositions of coffee mucilage are mainly water, protein, and sugar, of which the majority are reducing sugar (63 wt%) and small amounts of lignin and pectin [49]. Regarding chemical compositions, CM has been examined for its potential in various applications such as biopolymers [49,50], bioethanol [42,51], biohydrogen [52,53], and food products [54,55].

3.3. Coffee Parchment (CPm)

Coffee parchment (CPm) is a protective layer covering the epidermis (silverskin) and green beans, which is found beneath the mucilage. It plays a crucial role during the drying process by aiding moisture removal and maintaining the quality of the coffee. This layer can only be obtained through the wet-processing method. On the other hand, in the dry-processing method, the coffee parchment (CPm) is removed along with other components and obtained as a coffee husk.

Despite being produced through the wet-processing method, CPm contains only 9 wt% moisture since it is generated during the milling process after the demucilaging and drying stage. In terms of the composition, CPm accounts for approximately 5.8–6.1 wt% of the coffee cherry [42,45,46] and primarily consists of lignocellulosic materials. Furthermore, CPm contains valuable antioxidants, particularly caffeine and phenolic compounds like gallic acid, chlorogenic acid, *p*-coumaric acid, and sinapic acid, as shown in Table 2. It is worth noting that CPm possesses relatively high cellulose and total fiber content among other coffee waste (see Table 1).

3.4. Coffee Silverskin (CS)

Coffee silverskin (CS), also known as coffee chaff, is a thin and papery layer covering coffee green beans. It is produced during the coffee beverage preparation by the roasting process. CS accounts for approximately 1.2 wt% of the coffee cherry [45] or 4.2 wt% of the coffee bean [46].

The chemical compositions in CS are relatively similar to those of CPm, which are mainly lignocellulosic materials. CS is also rich in dietary fiber (50–72%), including 7–15% of soluble dietary fiber and 49–85% of insoluble dietary fiber [56–58]. In comparison to CPm, the CS contains relatively high amounts of proteins and lipids, as shown in Table 1.

Like other coffee wastes, CS contains noticeable amounts of antioxidants such as caffeine, tannins, polyphenols, and melanoidins (Table 2) [46]. CS is also a source of minerals, particularly rich in potassium, calcium, magnesium, sulfur, phosphorus, and iron. In addition, aluminum, copper, manganese, and zinc can be found in CS [59].

Table 2. Bioactive compounds of coffee waste.

Compound	Coffee Waste				
	Pulp	**Husk**	**Parchment**	**Silverskin**	**SCGs**
Caffeine (mg/g)	2.05–31	1.33–9.82	0.10–58.20	0.70–53.30	0.03–76.90
Tannins (mg/g)	1.80–60	18–93	17	2.50–7.66	0.99 mg CE/g
Trigonelline (mg/g)	-	1.56–5.43	1.20–13.60	36.50	0.40–2.40
Melanoidins (mg/g)	-	1.50	-	1.70–2.30	-
Phenolic acid and polyphenols					
Chlorogenic acids (mg/g)	1.80–3.40	1.21–132.50	0.05–9.40	0.04–21.40	1.40–85
5-Caffeoylquinic acid (mg/g)	1.74–22.80	0.20–1.90	6.10	0.40–89	1.40–37
4-Caffeoylquinic acid (mg/g)	0.14–0.43	0.01–0.12	-	0.18–23.80	1.36–16.20
3-Caffeoylquinic acid (mg/g)	0.06–0.26	0.02–0.05	-	0.94–17.90	0.02–15
Dicaffeoylquinic acids (mg/g)	-	-	-	-	3.31–5.79
3,4-Dicaffeoylquinic acids (mg/g)	0.29–4.50	-	-	10.43	2.89
3,5-Dicaffeoylquinic acids (mg/g)	0.20–1.13	-	-	0.44–9.97	1.04
4,5-Dicaffeoylquinic acids (mg/g)	0.24–1.22	-	-	10.56	1.65
Caffeic acid (mg/g)	0.09–4.29	0.06–28.20	0.004–0.007	0.08–0.54	0.004–6.10
Ferulic acid (mg/g)	0.05–4.30	0.01	0.001–0.003	0.004–0.230	0.01–0.03
5-, and 4-Feruloylquinic acid (mg/g)	0.01–0.20	0.07–0.19	-	1.22	-
p-Coumaric acid (µg/g)	2–160	0.10–8.70	6.70–34	1–18	4.42–500
5-Coumaroylquinic acid (mg/100 g)	-	3.50–6.20	-	5.70	-
3-Coumaroylquinic acid (mg/100 g)	-	-	-	2.40	-
Sinapic acid (mg/g)	-	-	-	0.18	0.01
Gallic acid (µg/g)	4.30	1.90–87	3–97	15.80–31.10	32.50
3-*O*-Metylgallic acid (µg/g)	-	-	2.30–5.30	-	-
4-Hydroxybenzoic acid (µg/g)	-	13.40	1.60–2.40	3.40	885–1813
Protocatechuic acid (µg/g)	85–4700	37–488	9.20–14.10	44	5.77–530
Gentistic acid (µg/g)	-	27–77	-	-	0.26
Syringic acid (µg/g)	0.06	-	3.50–8.60	39–78	3.41
Salicylic acid (µg/g)	-	3.1	0.70–1.00	2.30	7.61
Vanillic acid (µg/g)	7	23	15.90–42.80	30–345	340–1103
Flavonoid					
Quercetin (µg/g)	-	-	-	1.53–3.56	3.20–3.76
Quercitrin (µg/g)	-	-	-	0.12–0.59	0.13–0.83
Quercetin-3-O-rutinoside (rutin) (µg/g)	90–700	9.85–114.95	-	1.25–10.65	2.36–9.65
Quercetin-3-O-glucoside (µg/g)	-	57–69.90	-	-	-
Quercetin-3-O-galactoside (µg/g)	-	55	-	-	-
Catechin (µg/g)	60–630	0.82–1.70	-	10.20	14.55
Epicatechin (µg/g)	630–4360	8–25	-	151.10	10.08
Naringin (µg/g)	-	-	-	0.32–0.45	86.94
Naringenin (µg/g)	-	1.32–1.94	-	-	-

Table 2. *Cont.*

Compound	Coffee Waste				
	Pulp	Husk	Parchment	Silverskin	SCGs
Kaemferol (µg/g)	-	-	-	0.76–1.66	-
Kaempferol-3-O-galactoside (µg/g)	-	123	-	-	-
Anthocyanidins (mg/g)	40–50	-	-	-	-
Procyanidins (µg/g)	1200–8500	1.3–534	-	-	-
Total flavonoids (mg QE/g)	21.80–58.80	0.071–15.70	0.80 mg CE/g	2.73	2.11–8.29
Total phenolic content (mg GAE/g)	2.55–442	1.85–4.55	2.28–2.84	2.60–36	3.33–273.30
Antioxidant capacity (µmol TE/g)	51–92	3136.40	14.50	21.35	20.04
References	[43,60–68]	[62,63,65,66,69–77]	[38,62,63,65,72,73,75,78–80]	[46,62,63,65,66,73,75,76,78,79,81–83]	[46,62,65,66,74,78,81,83–87]

GAE, gallic acid equivalent; QE, quercetin equivalent; CE, catechin equivalent; TE, Trolox equivalent.

3.5. Spent Coffee Grounds (SCGs)

Spent coffee grounds are the most abundant waste generated in secondary coffee processing, which could be annually produced in an amount as high as about 15 million tons worldwide [88,89]. It is obtained by the coffee brewing process, which is from domestic use (including household, restaurant, coffee shop) and industrial use for instant coffee production. On average, for every kilogram of ground coffee, about 0.91 kg of spent coffee grounds are generated [90], while the production of one kilogram of instant coffee yields around 2 kg of coffee sludge or wet spent coffee grounds [47,90].

The chemical composition of SCGs varies slightly depending on the composition of the roasted coffee beans and the extraction techniques used in domestic (e.g., drip, espresso, infusion, French press) or industrial production. Nevertheless, SCGs are mainly composed of polysaccharides, specifically cellulose and hemicellulose, which account for almost 50% of its composition. The other most abundant compounds are lignin and protein, comprising approximately 20 wt%. SCGs also contain a significant amount of lipids (over 15 wt%), primarily consisting of linoleic acid (45%) and palmitic acid (38%) [91,92]. In addition, SCGs contain significant amounts of phenolic compounds, which have antioxidant activity and some mineral content [93].

4. Valorization of Coffee Wastes

As mentioned in Section 3, the waste obtained from coffee processing is rich in lignocellulosic materials and contains other crucial organic and bioactive components that have the potential to be used as alternative raw materials for several applications including agriculture, animal feed, and livestock nutrition, food processing, pharmaceuticals, cosmetics, energy, and other biomaterials.

The valorization of coffee waste transforms what was once considered waste into valuable resources, addressing environmental concerns and creating economic opportunities. This section explores the application of coffee waste across the food supply chain, as shown in Figure 3, beginning from farms to obtain raw feedstock, then passing through food processing and transportation, subsequently obtaining high nutritional value products, and distributing them to customers.

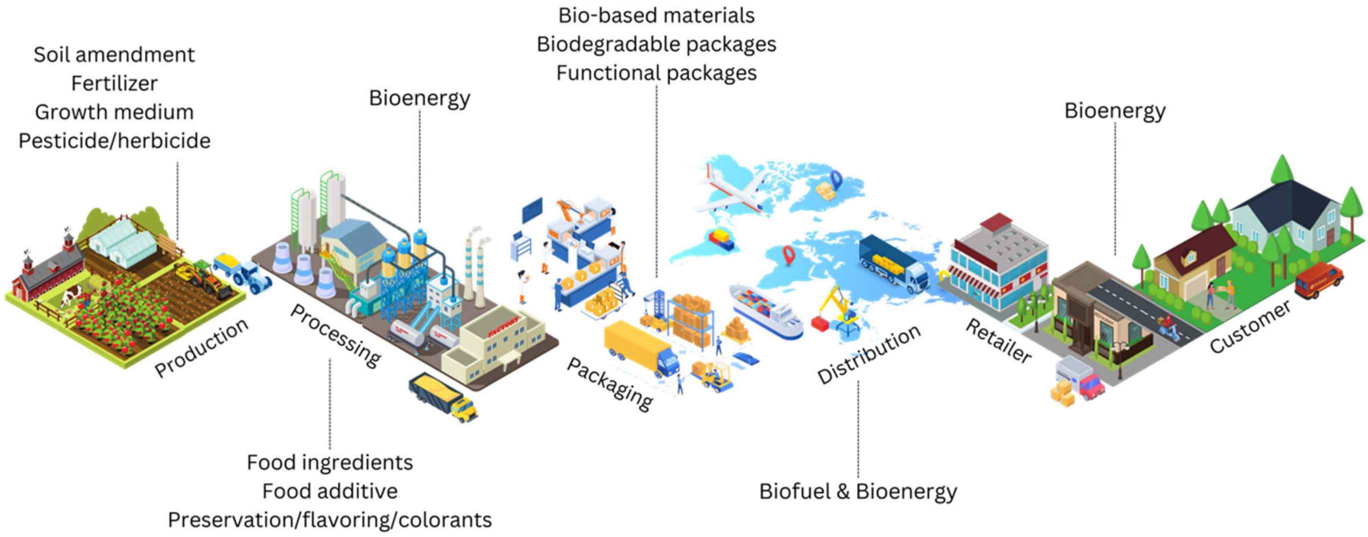

Figure 3. Utilization of coffee waste in the food supply chain.

4.1. Agricultural Applications

4.1.1. Soil Amendment and Fertilizer

The use of coffee waste for agricultural applications, such as soil amendment, compost, or fertilizer, is the most popular and simple way to recover and reuse the nutrients in organic waste. This idea has gained traction among farmers, leading to notable improvements in crop yields and soil health. The coffee wastes, rich in organic matter and nutrients, provide an eco-friendly alternative to synthetic fertilizers. However, there are toxic compounds contained in coffee waste, especially in spent coffee grounds, such as caffeine, tannins, and chlorogenic acid, which have deleterious effects on soil microorganisms and the growth of plants [94–96], and also a contaminant of soil and water [97].

Hardgrove et al. [96] studied the effect of directly applying fresh SCGs (untreated) on horticultural plant growth. An improvement in the soil structure was observed, and the soil water-holding capacity was increased, corresponding to increases in the SCG amendment. However, all horticultural plant growth was suppressed, which could be due to phytotoxic effects. The reduction in plant germination and growth was also observed in the field experiment when untreated SCGs were applied, which was possibly related to the presence of caffeine [98–100]. In addition, other phytotoxins including tannins and polyphenols in untreated SCGs have been reported to have a negative effect on plant growth [101–103].

Composting

As mentioned earlier, coffee waste contains bioactive compounds that have been evidenced to cause plant phytotoxicity. Therefore, the proper pretreatment stage should be applied to eliminate or decrease the substances, especially when using the SCG amendment. Regarding that, composting has been considered an effective way of detoxification.

Composting coffee waste not only aids in waste management but also produces a valuable soil conditioner. The composting process involves the aerobic decomposition of organic matter with bacteria, fungi, worms, or other organisms, resulting in a nutrient-rich humus [104–107]. In addition, the composting process can significantly reduce the level of phenolic compounds, caffeine, and tannins, making it safer for soil application [12,102,108]. Bernal et al. [109] emphasized that the primary requirement for compost to be safely applied to soil is its stability or maturity. This indicates that the compost should have a stable organic matter content and be free from phytotoxic substances as well as plant or animal pathogens.

Among coffee wastes, CH, CP, and SCGs have been intensively investigated in this application area. Several studies revealed that CP, CH, and SCGs were successfully composted alone or co-composted with other organic wastes such as animal manure, biomass wastes, and municipal solid waste in different ratios.

Kasongo et al. [110] studied the effectiveness of using coffee waste (mixed CP and CH) as an alternative fertilizer in improving the properties of sandy soils in humid tropical conditions. The study has shown that coffee waste can help reduce the acidity of sandy soil with a pH higher than 5.5 and immobilize Mn, also significantly reducing the level of phytotoxic Al, which is a non-essential metal for plant growth [111]. Additionally, the CP and CH notably increased the concentrations of essential nutrients, including N, P, K, Ca, and Mg in the treated soil, and also improved its water-holding capacity [112].

The composting of coffee husks with cow manure and phosphate fertilizer was investigated in the growth of coffee plants in rural areas in Vietnam. The compost was supplemented by 0.1% effective microorganisms and composted for 3 months before use. The compost enriched soil fertility and enhanced nutrients in coffee leaves, as well as increased coffee's growth rate and yield up to 14% in comparison with using a pure chemical fertilizer. Furthermore, during 3 years of study, composted coffee husk could reduce 20–30% of the chemical fertilizer applied in coffee fields [113].

Additionally, Dadi et al. [114] studied the efficacy of coffee husk and pulp composted alone and co-composted with source-separated municipal solid waste (SSMSW). They revealed that all final samples are mature, stable, and sanitary compost, with a C/N ratio of less than 25:1. The results indicated that co-composted coffee waste could yield a higher head weight of cabbage when combined with the local soil, due to the higher concentration of total nitrogen in the co-compost sample. Beneficial attributes in crop growth from soil treated with composted coffee pulp and coffee husk have been reported. Topsoil mixed with 20% coffee pulp compost improved soil physiochemical and biological properties of poor soils in Ethiopia, resulting in enhancing the yield of chickpeas [115].

Jibril and Bekele [116] conducted a field experiment in Ethiopia to study the effects of different proportions of coffee husk compost and blended NPSB fertilizer on the physiochemical properties of soil in a potato field with a 50% clay content. They discovered that coffee husk compost alone had a positive impact on soil properties. Yet, when combined with NPSB fertilizer, it yielded superior outcomes by increasing soil pH, total organic carbon, and nitrogen; improving available phosphorus and sulfur; lowering exchangeable acidity; and boosting cation exchange capacity and exchangeable bases, which in turn enhanced potato production and productivity.

This result is consistent with the findings of Nduka et al. [117]. They found that the combined application of inorganic fertilizer and coffee husk compost significantly improved soil physicochemical properties and crop yield over using them separately. The application of coffee husk/pulp is advantageous for raising soil pH [117], while solely using inorganic fertilizers tends to increase soil acidity [118]. Although integrating coffee waste with inorganic fertilizer or other organic wastes offers better improvement than using them independently, finding the proper mixture ratio is crucial for optimizing soil fertility and enhancing plant growth.

Additionally, spent coffee grounds (SCGs) have been thoroughly researched for their potential use in agronomy as an alternative soil improvement material. Several studies indicate that SCGs enrich soil with nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, etc. [89,99,100,119], increase all organic matter fraction [96,103], and enhance the presence of plant-growth-promoting bacteria (PGPB) along with the diversity, richness, and evenness of bacterial community structures [120]. Furthermore, the addition of SCGs significantly improved the physical properties of the soil by increasing the soil aggregate size and total porosity, which consequently decreased soil bulk density [121–123]. SCGs also facilitate an increase in the water-holding capacity [123,124].

Santos et al. [102] found that the mixture of spent coffee grounds (SCGs), wheat straw, and *Acacia* debris was successfully composted and significantly decreased total phenolics and total tannins. The resulting compost exhibited maturity and stability. A higher germination of radish seeds (14–34%) was observed when the co-composting of SCGs (78–85%) with poultry manure (15–20%) was applied, implying that the compost highly provided useful nutrients and exhibited low toxicity for plant growth. In addition, the compost enhanced microbial community diversity, boosted antioxidant activity (scavenging of DPPH radical), and decreased the phenolic content in pepper fruit, compared to commercial fertilizer, resulting in raising the value of the commercial crops [125].

Furthermore, coffee silverskin (CS) is the primary coffee waste generated from the roasting process. It contains relatively high amounts of nitrogen (N) and potassium (K), which are essential nutrients for plant growth, making CS a valuable material for generating nutrient-rich composts [33]. However, as observed in other coffee wastes, phytotoxic compounds, mainly polyphenol, and chlorogenic acid, are also found in raw CS, which negatively impact plant growth and germination. Additionally, the characteristics of CS itself can be problematic for the final compost quality and soil application if no attentive management is provided, including acidic properties and high salinity. Moreover, CS can easily compact together due to the low bulk density and water-holding capacity, leading to pile compaction and risk of anaerobic conditions during composting, resulting in nitrogen loss and a reduction in overall nutrient content.

To overcome these limitations, Picca et al. [126] investigated co-composting CS with pruning waste and biochar with different ratios. The final composts had improved their physicochemical properties, containing high essential plant nutrients which are rich in N and K; water-holding capacities were also increased, and no phytotoxic effect was observed in the germination test, which makes it safe for use as a soil amendment. This nutrient-rich compost can reduce the dependency on mineral fertilizers and support sustainable agriculture. Furthermore, these researchers showed the benefit of combining biochar during the compost. As aforementioned, CS has some limitations due to its characteristics. The addition of biochar increased the free spaces between particles, preventing the compaction of the heap, and promoting aeration, which reduces heat loss and provides a favorable environment for the proliferation and activity of microorganisms. The presence of biochar in the composting also increased the stability of the final compost.

Finally, the authors showed that if all of the CS produced in Europe could be composted, 2420–3481 tons of N and 1873 tons of K would be recovered, leading to the reduction in mineral fertilizer demand. They also pointed out that further studies should determine whether composting CS could be used as a peat for horticulture and gardening purposes, aiming to reduce the reliance on finite resources and fragile ecosystems such as peat bogs [126].

Peat has been the predominant component of growing media in horticulture due to its extremely suitable physical and chemical properties. It has high porosity, structural stability, and low bulk density, which provides good aeration and a high water-retention capacity [127,128]. Rising demand for peat increases the environmental impact and sustainability issues because peat is a non-renewable resource and extracting peat can destroy the peatland and its biodiversity system [129]. Thus, exploring alternative growing media is necessary to overcome the adverse environmental effects associated with peat extraction and use.

Composted SCGs have been evidently revealed as a potential alternative component of growing media for potting plants. Mixing SCG compost in commercial peat improved the physicochemical of the growing media by increasing pH values (6.1–7.6) and soil salinity (electrical conductivity values of 2.02–3.53 dS/m), which are greater than those values provided by conventional fertilizer. The mixture of moderate SCG compost (40%) and commercial peat showed the best results for tomato and basil development and were almost similar to those results obtained from conventional fertilized peat media. This indicates that SCG compost is effectively a partial substitution for commercial peat and conventional fertilizer in the production of horticultural crops [130].

This finding is in agreement with Picca et al. [131], who found that co-composting SCGs with biochar is a promising alternative peat substitution, which could effectively replace up to 50% of peat. All the growing media mixtures revealed a germination index greater than 80%, implying that there are no phytotoxic effects. Also, fruit production had significantly improved. However, the growth in the seedling development stage was retarded, which probably impacts the fruit yield and its quality due to the high levels of electrical conductivity (EC) of the medium, indicating a high soluble salt concentration, which led to increasing osmotic pressure and interrupting nutrient uptake [129,132]. Therefore, optimizing ratios of the substrate in the growing medium is necessary to balance the nutrient supply without causing salinity issues.

Vermicomposting

Vermicomposting is a bio-oxidative process that produces nutrient-rich, well-aerated, and more stable compost through the biodegradation of organic waste using earthworms as bionatural reactors. This process involves the cooperation between earthworms and microorganisms [133]. Earthworms play a crucial role in this process, as they are capable of breaking down organic matter, mixing, fragmenting, enzymatically digesting substances, and accelerating microbial degradation through their intestine [134–136].

Cervera-Mata et al. [103] demonstrated the effective ability of vermicomposting and biocharization to detoxify phytotoxic compounds. They compared amendments derived from different treatments of spent coffee grounds (SCGs), including fresh SCGs, compost, vermicompost, biochar, ethanol/water-washed SCGs, and hydrolyzed SCGs. Vermicomposting and biocharization at 400 °C completely eliminated polyphenols, thus alleviating the limitation on lettuce growth. However, the Zn, Cu, and Fe concentrations in lettuce decreased compared to the compost with a high polyphenol content, likely due to the reduction in chelating properties (polyphenols) that facilitate the uptake of elements in plants [137]. Hence, the authors suggested that mixing fresh SCGs or compost with inorganic fertilizer could simultaneously improve lettuce productivity and nutritional value; however, the appropriate mixture ratio should be developed [103].

The vermicomposting of the mixture of SCGs and coffee silverskin with horse manure in different proportions has been evaluated. The growth rate of earthworms and cocoon production decreased significantly when coffee waste was used alone, especially coffee silverskin, probably due to the release of toxic substances. Earthworms are highly sensitive to nitrogen content in feedstock, and the relatively high ammonia detected in coffee silverskin caused earthworm mortality. The best combination for the recent work involved 25% or 50% of coffee silverskin and 25% of SCG with horse manure, which showed high biomass gain, growth rate, and cocoon production with no toxic effects on seed germination [138]. A similar finding was also observed in another study [139]. Vermicomposting with SCGs only reduced earthworm survival compared to the lowest SCG proportion mixed with straw pellets, due to unsuitable conditions (lower carbon content, lesser aeration, and higher bulk density) and toxic substances. Caffeine levels were reduced in all experiments, with vermicomposting showing 38 times lower caffeine levels compared to treatments without earthworms under the same conditions [139].

Meanwhile, the potential of using coffee pulp as a raw material for vermicomposting has been reported [140]. Applying the highest rate (15 t/ha) of vermicomposting coffee pulp (75%) and cow dung (25%) with *Eisenia fetida* revealed the highest total yield of hot pepper (97.86%) compared to the control treatment, due to the availability of micro- and macronutrients (organic carbon, N, P, K, Ca, Mg) to the plant root rhizosphere, along with essential enzyme and growth hormones produced by earthworms, enhancing plant growth and yield. In addition, the physicochemical composition of the vermicompost varied depending on the natural ability of worm species utilized in the process [141].

Biochar

Biochar is a solid carbon-rich material produced through a thermal conversion of organic material. Typically, pyrolysis is the preferred method, in which biomass is treated in a limited concentration or absence of oxygen at an elevated temperature (T = 300–700 °C) [142]. Meanwhile, biochar can also be obtained as a by-product in gasification and hydrothermal liquefaction (HTL) for the production of syngas and bio-oils, respectively [142–144]. For agricultural applications, biochar has been reported for its potential as a sustainable soil amendment to enhance fertility and sequester carbon. However, nutrient compositions, physical and chemical properties of biochar, as well as the amendment rate are influenced by feedstocks' properties, pyrolysis conditions, soil type, and its environmental conditions, leading to different soil improvement performance [145,146]. Therefore, several studies have extensively investigated the influence of the pyrolysis temperature and feedstocks' properties on the biochar characteristics [147–149].

For example, Lataf et al. [150] investigated the effect of pyrolysis temperatures (450, 600, and 750 °C) and eight different feedstocks on the agronomic properties and potentially toxic elements of biochar through slow pyrolysis in a rotary kiln reactor. They found that the pyrolysis temperature and feedstocks' properties significantly impact biochar yield, composition, toxicity, and agronomic properties including pH, acid-buffering capacity, electrical conductivity (EC), cation exchange capacity (CEC), water-holding capacity, and stability. The biochar yield was reduced at higher temperatures due to the decomposition of volatile compounds, while the stability and pH of biochar improved at higher temperatures. In addition, the water-holding capacity is a crucial factor for retaining moisture in soils, particularly in arid regions. At higher temperatures, biochar has greater porosity, resulting in an increased water-holding capacity. Nevertheless, the pore structure might collapse at excessively high temperatures, decreasing the water-holding capacity [146]. The study also emphasizes the potential toxicity of biochar; biochar produced at the highest pyrolysis temperature at 750 °C exhibited a relatively high concentration of some potentially toxic elements (PTEs) including Zn, Cr, and Cu, and polycyclic aromatic hydrocarbons (PAHs), potentially contaminating the soil, which negatively impact soil health and plants. Therefore, this study recommends that the proper pyrolysis temperature should not exceed 600 °C for beneficial of agronomic properties and minimized potential toxic behaviors, depending on the feedstock used.

These results are also observed by Domingues et al. [151]. They investigated the performance of biochar derived from nutrient-rich biomass and woody biomass by varying pyrolysis temperatures. The result revealed that biochar produced from chicken manure had a relatively low carbon content compared to that from woody feedstock, and its concentration decreased with an increase in pyrolysis temperature, indicating that the organic compounds found in chicken manure are more labile. Meanwhile, the greater H/C and O/C ratios of woody biochar were observed at high temperatures due to a high degree of polymerization. As a result, woody biochar has greater carbon stability, which is suitable for increasing C storage in soils and has environmental benefits by reducing CO_2 emissions [146].

In addition, nutrient-rich feedstock such as chicken manure and coffee husk, containing N, P, K, Ca, and Mg, resulted in higher liming values of biochar compared to woody biochar. The higher pyrolysis temperature resulted in a higher pH value for all biochar. Furthermore, the CEC value is inversely correlated with the temperature. At low temperatures, all biochar exhibited a relatively high CEC value due to the exposure of essential functional groups at the biochar's surface, such as carboxylic, ketone, aldehyde, and phenolic groups [151–153]. However, the CEC value not only depends on temperature but also on the type of feedstock used [150]. Regarding the study, the author concluded that biochar produced from nutrient-rich biomass has high agronomic potential, which can be considered for use as a slow-release fertilizer, improving soil quality and further crop productivity.

Typically, biochar has a high surface area and porous structure, which can help to improve the soil structure. It can provide abundant space for soil, leading to increasing soil aeration, and water-holding capacity, and reducing soil compaction, which can limit root growth [154]. In addition, biochar generally exhibits an alkaline pH, which can adjust the pH of the soil, particularly beneficial for acidic soils common in many tropical and subtropical regions [155–157]. By increasing soil pH cooperatively with its high porous structure, applying biochar can increase the cation exchange capacity (CEC). As a result, the soil has an improved ability to retain and exchange nutrients like calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and ammonium (NH_4^+) [158,159], also preventing nutrient leaching and improving fertilizer use efficiency [160,161].

Ngalani et al. [157] revealed biochar produced from coffee husk and cocoa pod biochar could act as a source of P for soil fertility and facilitate P desorption to the soil solution, thereby increasing P availability for plant uptake, particularly at a high amendment rate and about 550 °C of pyrolyzed biochar. Additionally, a field experiment investigated the performance of coffee husk biochar combined with inorganic NP fertilizer on soil properties and potato cultivation in Ethiopia. Using pure inorganic NP fertilizer shows significant increases in total nitrogen and available P, while the fertilizer combined with biochar revealed a greater response for not only total N and available P level but also for soil organic matter, leading to enhanced potato production [162], demonstrating the economic benefits of this combined application [163].

Furthermore, the high surface area and porosity of biochar can serve as a proper habitat for beneficial soil microorganisms, leading to the high abundance and diversity of fungi and microbes in soils [164,165]. Consequently, soils have been improved and further enhance plant growth and productivity.

Lima et al. [166] revealed that applying biochar to sandy soil significantly improved its properties, particularly coffee husk biochar, by increasing soil pH, nutrient availability, and water retention. As a result, the water use efficiency was increased, leading to improved maize yields even under conditions of water scarcity, which is particularly important in semi-arid regions. The nutrient (N, P) and C use efficiency were also improved, reducing the leaching of the nutrients and boosting their availability to plants, compared to the mineral fertilizer (NPK). Biochar produced from coffee husk has a relatively high specific surface area (SSA) compared to coffee ground biochar, which makes it more effective in improving soil properties.

A similar result was found in this study [167], which exhibited the influence of coffee husk and coffee ground biochar on microbial biomass carbon, and enzymatic activity in sandy soils. The application of coffee ground biochar resulted in greater enhanced microbial biomass and activities of enzymes like β-glucosidase and fluorescein diacetate (FDA) compared to coffee husk biochar, which is important for carbon cycling and soil fertility. This is because the coffee grounds have a relatively high availability of organic nitrogen and carbon compounds, which are more easily metabolized by microbes, further conducive to microbial colonization and activity. Another study exhibited that coffee husk biochar application positively affects root colonization by arbuscular mycorrhizal fungi (AMF). The improvement of soil conditions can provide a favorable habitat for microbes, allowing AMF to thrive, and leading to improved nitrogen fixation and higher crop yields [168].

As aforementioned, the porosity and surface area of the biochar are significant physical properties that influence their potential for soil improvement. As noted by another study [169], hydrothermal carbonization (HTC) shows a favorable performance in producing biochar (called hydrochar) with a larger specific surface area (SSA), higher porosity, and rich functional groups on the surface compared to slow pyrolysis. The SSA and porosity size of biochar are in the order of hydrothermal carbonization (HTC) (210 °C) > torrefaction (270 °C) > hydrothermal liquefaction (HTL) (270 °C) > slow pyrolysis (500 °C). At a temperature above 400 °C, the pore structure can be destroyed, resulting in a decrease in surface area [170]. Regarding the properties of hydrochar, it is beneficial for enhancing water and nutrient retention, promoting microbial colonization and diversity, and effective for environmental application by water/soil remediation.

Unfortunately, phytotoxic compounds were highly found in hydrochar produced at mild temperatures (175–215 °C), probably due to polyphenol compounds' favorable accumulation at lower reaction temperatures [171,172]. Also, the volatile compounds could be condensed and absorbed into hydrochar during the hydrothermal treatment as it was a closed system [172]. Nevertheless, the phenolic fraction and caffeine were evidently eliminated from hydrochar at elevated treatment temperatures (260–275 °C) [142,173].

The same result was also observed on torrefied biochar [174]. The greater phytotoxic compounds were detected at 250 °C, even higher than that of compounds in untreated spent coffee grounds. This could be due to the incomplete breakdown of toxic compounds, and certain toxic substances may remain in the biochar. Furthermore, a new toxic intermediate compound could be formed at this temperature, leading to inhibit plant growth more severely than the untreated SCG.

As previously noted, pyrolysis biochar is considerably suitable for agronomical applications due to its neutral to slightly basic pH, high nutrient content, and stability in the soil, making it more versatile and beneficial across a broader range of agricultural applications. Ultimately, the choice of the process depends on the purpose of biochar application, type of feedstock, particularly, the specific soil conditions and crop requirements.

Remarkably, utilizing coffee waste as biochar not only benefits agriculture but also contributes to environmental sustainability. The process of converting coffee waste into biochar sequesters carbon, thereby reducing greenhouse gas emissions [175]. Additionally, biochar application has been shown to decrease soil emissions of nitrous oxide, a potent greenhouse gas, by enhancing soil microbial processes [176,177]. Coffee waste biochar has a high capacity for immobilizing heavy metals, reducing their bioavailability and preventing their uptake by plants, which aids in the remediation of contaminated soils [178–180].

4.1.2. Mushroom Cultivation

The application of coffee waste for mushroom cultivation is another approach to utilize its valuable organic compounds, promote sustainable agriculture, and solve the environmental issue from waste management simultaneously, particularly, in coffee producer countries like Colombia [181], Brazil [182], Mexico [183], and El Salvador [184]. A separate discussion of mushroom cultivation from soil amendment and fertilizers is helpful because it distinctly uses coffee waste as a specialized substrate that supports fungal growth. This process not only recycles waste but also produces a high-value product, highlighting the unique role of coffee waste in sustainable agricultural practices.

Edible mushrooms, macro-fungi that can be safely consumed, significantly contain a variety of beneficial nutrients for human health, including carbohydrates, proteins (with a good distribution of essential amino acids), vitamins (especially vitamins B, C, D, and E), minerals (such as K, Cu Fe, Mn, and Zn), and also high dietary fiber with lower lipids and calories [185–187]. Moreover, edible mushrooms are considered a crucial source for therapeutic purposes due to the presence of various bioactive compounds that have medicinal properties such as antioxidant [188], antiviral [189], antibacterial [190], anticarcinogenic [191], antithrombotic [192], anti-inflammatory [193], antidiabetic [194], antitumor [190], hepatoprotective [195], hypocholesterolemic [196], and immune-modulatory effects [197]. As such, edible mushrooms are considered global functional foods that contribute to overall health and disease prevention.

Mushroom productivity, yield, and nutrient composition significantly depend on the cultivation process, which includes environmental conditions, substrates, and cultivation practices. The type of substrate significantly results in various levels of nutrient contents, which directly affect the development of mushrooms and their concentration of bioactive compounds [198,199].

For example, the oyster mushroom cultivated on nutrient-rich substrates such as corncob and sugarcane bagasse has evidently improved its fruiting body and yield, and also enhanced protein, fiber, and mineral (Ca, K, Mg, Mn, and Zn) contents compared to those obtained from sawdust cultivation [200]. Meanwhile, using lignocellulose/fiber-rich material as a substrate can provide a good environment for the mycelial growth rate, which refers to the root-like network of fungal spreads over the substrate over a specific period. Because the mycelia favorably grow on carbon-rich material [201], additionally, the porous structure of lignocellulosic material can provide high aeration and water-retention properties, which are an effective factor in mycelial development [202].

Coffee waste, containing significant amounts of several beneficial components including lignocellulose, nutrients, and minerals, is considered a potential substrate for mushroom cultivation. The use of coffee waste has been reported to have a positive effect on the yield and quality of edible mushrooms [203,204]. Fan et al. [205] investigated the feasibility of using coffee waste, i.e., coffee husk, coffee leaves, and spent coffee grounds as a substrate for different strains of *Pleurotus* species cultivation through solid-state fermentation (SSF). Among the tested substrates, coffee husk showed the best result for *P. ostreatus* cultivation by achieving the highest biological efficiency (BE) with the shortest duration for the first mushroom formation. The biological efficiency (BE) refers to the weight of fresh mushrooms produced per the weight of dry substrate used, which is an indicator reflecting the ability to utilize the substrate of the mushroom strain for its development into harvestable mushrooms [205]. Additionally, caffeine and tannins in coffee husk were significantly decreased after 60 days of fermentation. A small amount of caffeine (0.157%) was found in the fruiting body with no tannin content, indicating that the fungal has the capability of degrading phenolic compounds in the coffee husk, making it suitable for mushroom cultivation without pretreatment, further enhancing the safety and utility of the spent substrate.

Dissasa [203] used composted and non-composted coffee parchment and coffee husk for substrate supplementation with cow dung (18%) and gypsum (2%) for the cultivation of four different oyster mushroom species (*Pleurotus* species). Each *Pleurotus* species required a different time for the development of the fruiting body and pinhead. Among four species, *P. ostreatus* has required the shortest fruiting period, leading to the highest mushroom yield. Composted coffee waste showed a higher efficiency in promoting mushroom growth compared to the non-composted one. In a comparison of the two substrates, coffee husk showed a superior effect on mushroom growth compared to coffee parchment, which produced 6–10% more biological efficiency on average. This is probably due to the different characteristics of the two substrates, including their chemical composition, C/N ratio, and structure.

Coffee pulp is a suitable substrate for the cultivation of the edible mushrooms Pleurotus [206], Lentinula, and Auricularia [183]. It showed a good result on the mycelial growth rate and biological efficiency of Pleurotus species, leading to an increased yield and fruiting body size [207]. Moreover, the use of coffee pulp as a substrate can provide a high protein content of Pleurotus pulmonarius product of 17.8%, which is comparable to the value found in eggs (14%) and peas (19.4%). This is due to the high nitrogen content in the coffee pulp substrate, which is an essential nutrient for protein formation [181].

Additionally, the presence of some phenolic compounds in coffee pulp could promote fruiting body formation [208], leading to shortening the duration of the cultivation cycle to enhance the efficiency of commercial production [207]. This was also observed by Fan et al. [209], who found that low amounts of tannins (<100 mg/L) in the coffee husk substrate can stimulate mycelial growth.

Similarly, Gasecka et al. [210] used 25% of spent coffee grounds (SCGs) as an additive in the substrate (beech sawdust + wheat bran) for *P. eryngii* cultivation. The result showed an effect for improving the fruiting yield and enhancing the levels of phenolic acids in fruiting bodies (particularly ferulic and *p*-coumaric acids), leading to higher antioxidant activity. The supplementation of higher amounts of SCGs (50%) on the original substrate resulted in a higher total phenolic content and antioxidant potential; however, the fruiting yield was detected inversely.

Another study [204] found a negative effect of the incorporation of SCGs in the organic substrate for the production of *P. salmoneo-stramineus*, in which the yield drastically decreased by 85%, with a smaller mushroom size, lower total protein content, and high total sugar content compared to the original substrate. *P. citrinopileatus*, on the other hand, has no significant effect on its production yield, which achieved a maximum value of

25.1%. Furthermore, this study emphasized the biological properties of the mushroom extracts, which exhibited the potential of its activities, especially in terms of antioxidant and prebiotic activities.

The detrimental effect of phenolic compounds in coffee waste substrates on mushroom productivity has been further reported. The high amount of phenolic content (such as caffeine, and tannins) can cause an inhibition of mycelial growth of *Lentinula edodes* (shiitake) on coffee pulp, further affecting the shiitake fruiting body growth, as the incomplete development of primordia was observed (the initial stage of mushroom fruiting body formation) [211]. Similarly, a negative impact of SCGs was observed on the production of *P. ostreatus*. The incomplete colonization of the mycelium was found when using a sole SCG substrate, which may be due to the high level of caffeine content in SCGs, resulting in inhibited mycelial growth [212]. According to the study of Gąsecka et al. [210] and Carrasco-Cabrera et al. [212], a ratio of SCGs in the mixed substrates below 50% is recommended.

Despite the inhibitory effects, *P. ostreatus* surprisingly shows its capability to partially degrade caffeine into xanthine through sequential N-demethylation produced mainly by theophylline and 3-methylxanthine. Additionally, other metabolites such as paraxanthine and theobromine were observed, which were detected in both the substrate and fruiting bodies of the mushroom. However, the levels of caffeine in the fruiting bodies have no significant effect on human health. From the study, the authors highlighted that *P. ostreatus* and other species in this genus may have the potential for the detoxification of coffee waste, which is beneficial for environmental management [212]. In addition, the mycelial growth rate also depends on the substrates' chemical composition and C/N ratio. The mycelial growth rate improved when the strain was cultivated on a substrate with a high C/N ratio and high cellulose and hemicellulose compositions. This is because cellulose and hemicellulose supply energy for fungi and are more easily degraded into simple sugars compared to lignin, making these compounds readily absorbed and metabolized by the mycelium. Eventually, the mycelium rapidly grows, which further affects the yield and nutrient profile of fruit bodies [211,213].

Conclusively, many parts of coffee waste revealed the feasibility of growing mushrooms and enriching nutrients. It is necessary to emphasize the appropriate selection of the substrate and its combination, as well as preparation and sterilization techniques directly affecting the mushroom's quality and productivity. The substrate that meets the specific needs of mushroom species results in a positive effect on their quality and productivity [203,211].

4.1.3. Pesticides and Herbicides

The increasing demand for food has driven a surge in pesticide and herbicide use within the agricultural sector. Over the past five decades, the application of these chemicals has significantly boosted crop yields and improved product quality [214]. However, these practices have introduced various negative impacts on food safety, the environment, and human health, including soil quality degradation, nutrient cycling disruption, and water pollution [215].

To address the drawbacks associated with conventional pesticides and herbicides, the adoption of bio-based alternatives is essential. Bio-based pesticides and herbicides present a promising solution, mitigating the adverse effects seen with traditional chemical counterparts. These eco-friendly options offer high selectivity towards target pests, ensuring minimal impact on non-target organisms and the surrounding environment [216,217].

Biopesticides

Spent coffee grounds (SCGs) can be utilized to produce biopesticides. The methanolic extract derived from SCGs includes caffeine, an alkaloid, along with fourteen different phenolic acids and five flavonoids [217]. Phenolic compounds are well-known for their roles as antifeedants, digestibility reducers, and insect toxins [218]. A study conducted by Chowdhury et al. [217] demonstrated that this phenol- and flavonoid-rich extract showed insecticidal effects and reduced oviposition rates against the main pests of green beans (*Phaseolus vulgaris*).

In addition to the methanolic extraction method, SCGs can also be used to produce bio-oil via fast pyrolysis. This bio-oil exhibits insecticidal and bactericidal characteristics [219]. Bio-oils produced at temperatures of 500 °C and 550 °C exhibited superior antibacterial activity against *S. scabies* and *C. michiganensis*, while those produced at 400 °C and 550 °C demonstrated the most pronounced bioactivity against the Colorado potato beetle.

Despite their diminutive stature, mosquitoes rank among the most perilous insects worldwide. As vectors for numerous severe diseases, mosquitoes contribute to over 700,000 global deaths annually [220]. Poopathi and Mani [221] explored the use of coffee husk waste (CHW) as a nutrient source to cultivate *Bacillus sphaericus* (Bs) and *Bacillus thuringiensis* subspecies *israelensis* (Bti) for the production of mosquitocidal toxins. The results indicated that the toxins produced using CHW were biochemically similar and equally effective in killing mosquito larvae as those produced in a conventional medium (NYSM).

Bioherbicides

Weed management in agriculture is highly challenging, as weeds compete with crops for essential resources such as nutrients, water, and space, significantly reducing both crop yield and quality [222]. Various weed management strategies are employed, including cultural, mechanical, chemical, and biological control methods [223].

Among these, chemical herbicides offer a convenient, cost-effective, and efficient solution, enabling reduced tillage and earlier planting dates in fields [224]. However, chemical herbicides can harm the environment by reducing insect pollinator populations, endangering species, and altering soil biodiversity, while also posing risks to human health, including skin, eye, and nervous system issues, and cancer. Ecologically, they can lead to weed resistance and affect crop resistance to pests and diseases [225].

An effective method for producing bio-based herbicides involves utilizing spent coffee grounds as feedstock. Sant'Anna et al. [226] conducted a study on the antimicrobial, antioxidant, and herbicide activities of an aqueous extract of coffee grounds. The results showed that the spent ground coffee extract exhibited allelopathic activity, inhibiting lettuce seed germination and reducing seed germination parameters and the germination speed index. The results suggest that the aqueous extract of coffee grounds may serve as a natural organic herbicide for crops.

4.2. Biofuels and Bioenergy

The ethanol production from agricultural waste offers an innovative solution to numerous environmental and economic challenges we face today. A particularly noteworthy example is the conversion of coffee waste, such as coffee husks, pulp, and SCGs, into ethanol. As one of the most consumed beverages worldwide, coffee generates substantial amounts of waste. Rather than discarding these SCGs, they can be transformed into biofuels, addressing significant waste management issues while providing a renewable energy source. This environmentally friendly alternative to fossil fuels has the potential to reduce our reliance on non-renewable resources significantly.

SCGs are rich in organic compounds and contain significant amounts of lignocellulosic material, making them an excellent feedstock for biofuel production such as biodiesel, bioethanol, biogas, and bio-oil. They generally have a high calorific value and boast various beneficial components such as oils, carbohydrates, and proteins.

Utilizing SCGs for energy production can significantly reduce waste, lower greenhouse gas emissions, and create new revenue streams for coffee producers and processors, promoting the use of renewable and sustainable energy sources.

4.2.1. Bioethanol Production

Coffee waste, particularly spent coffee grounds (SCGs), has been found to contain a significant amount of sugar, which exhibits the potential for conversion into bioethanol [227,228].

The production of bioethanol from coffee waste encompasses four primary stages: (1) pretreatment, (2) hydrolysis, (3) fermentation, and (4) ethanol recovery.

Pretreatment

In bioethanol production from coffee waste, pretreatment is a crucial step for breaking down the complex structure of lignocelluloses into a form that is easier to hydrolyze and ferment. Pretreatment can enhance the interaction between lignocellulose-degrading enzymes and the cell wall, significantly improving sugar recovery [229].

There are many approaches to coffee waste pretreatment. Many of them focus on environmentally friendly methods. One of them is using ethanol in the pretreatment step. Nguyen et al. [230] demonstrated that ethanol pretreatment at high temperatures is effective. Using ethanol is considered an organosolv pretreatment, which is a promising "green" method, allowing biomass fractionation with minimal or non-toxic by-products, using recoverable solvents, and being straightforward [231]. Another approach, described by Choi et al. [228], involves using a popping machine to pretreat coffee residue waste or spent coffee grounds. The pretreatment is conducted at a pressure of 1.47 MPa for 10 min to enhance enzymatic hydrolysis. Employing this technique resulted in hydrolysis and fermentation efficiencies of 85.6% and 87.2%, respectively [228]. Another approach is using steam explosion. Chiyanzy et al. [232] demonstrated that steam explosion at 210 °C for 15 min produced a substrate more suitable for enzymatic activity, necessitating lower enzyme dosages for subsequent hydrolysis relative to untreated SCGs.

Hydrolysis

The hydrolysis step is crucial in extracting sugar from coffee waste. Hydrolysis can be performed using either enzymes or strong acids [233]. Each method presents distinct advantages and disadvantages. Chemical extraction is less favorable owing to the risk of contamination by chemical extractants, whereas biological transformation is characterized by a notably low efficiency. Many types of enzymes can be used, such as pectinase and cellulolytic enzymes (cellulase and β-glucosidase) [230,233]. Among these enzymes, cellulases are especially important for breaking down cellulose, which is the most abundant component of lignocellulosic biomass, into glucose, which can be fermented into ethanol [234]. Submerged fermentation (SmF) is frequently employed for large-scale enzyme production due to its ease of control and scalability. However, the high energy demands associated with mixing and aeration make it a more costly option [235]. In contrast, solid-state fermentation (SSF) is considered a more cost-effective and industrially viable method, though it presents challenges in maintaining consistent process control and scalability [236].

Selvam et al. [237] optimized the production of cellulase, an enzyme that breaks down cellulose, using a newly isolated bacterial strain, *Acinetobacter* sp. TSK-MASC, in the SSF system. The researchers explored using a novel combination of coffee pulp waste and pineapple waste as the substrate for fermentation. The results showed that TSK-MASC achieved high enzyme yields (888 U/mL) at a pH of 7.0 after 60 h of incubation, using 3.0 g/L of coffee pulp and pineapple waste. Catalán et al. [238] performed a life cycle assessment (LCA) to evaluate the environmental impacts associated with cellulase production from coffee husks using SSF. The study examined the entire production process, covering everything from raw material acquisition to enzyme purification and including downstream steps such as extraction, filtration, ultrafiltration, and lyophilization. The results showed that electricity consumption was the main contributor to the environmental impacts in several categories, with the lyophilization process being the most energy-intensive. Marín et al. [239] enhanced the downstream processing of cellulases produced from coffee husk through SSF. A combination of compost, coffee husk, and wood chips served as the fermentation feedstock. The findings showed a maximum activity recovery of 108 ± 30% during extraction with a 1:5 solid-to-solvent ratio, using static mode and distilled water. This recovery rate, exceeding 100% compared to standard extraction methods, indicates the exceptional efficiency of these specific extraction conditions. Additionally, no activity loss was detected after lyophilization for at least 50 days, as recovery values stayed around 100% throughout the storage period.

In addition, sulfuric acid can be utilized in the acid hydrolysis method. However, when using acid hydrolysis, the resulting hydrolysate must be neutralized with an alkaline substance like potassium hydroxide and peroxide [233,240]. Sometimes, a combined approach of acid hydrolysis and enzymatic hydrolysis is employed. Morales-Martínez et al. [240] reported that they used dilute acid hydrolysis (DAH) to remove hemicellulose, followed by peroxide alkaline pretreatment (PAT) to remove lignin. Glucose was then extracted from enzymatic hydrolysis using the Cellic CTec3 enzyme. The results indicated that optimizing the pretreatments in coffee husk waste enhanced cellulose production and facilitated the enzymatic process, leading to a high concentration of glucose. However, the acid hydrolysis process not only releases sugars from the raw material structures but also leads to the formation and release of several compounds, such as acetic acid, furfural, hydroxymethylfurfural (HMF), and phenolic compounds. These substances can be toxic to microbial metabolism, depending on their concentration in the fermentation medium [241].

Fermentation

In their study on fermentation, Nguyen et al. [230] developed an innovative approach to simultaneously produce ethanol and D-mannose, addressing the limited supply of D-mannose despite its extensive applications in biological research, pharmaceuticals, and the food and feed industries. The main aspects of their process involve optimizing the fermentation step to enable bioethanol-producing yeasts to consume nearly all the glucose and galactose for ethanol production, while preserving significant amounts of D-mannose in the fermented mixture. After the fermentation step, colored compounds and other impurities in the broth were removed, and ethanol and D-mannose were separated using the pervaporation technique. This innovative approach not only enhances the efficiency of ethanol production but also provides a valuable source of D-mannose, expanding its availability for various industrial applications.

The different parts of coffee waste have also been studied. Gouvea et al. [242] investigated the potential for producing ethanol through the fermentation of coffee husks using *Saccharomyces cerevisiae*. They conducted batch fermentation experiments using whole coffee husks, ground coffee husks, and an aqueous extract of ground coffee husks. The study found that higher yeast concentrations led to lower fermentation yields. The optimal conditions identified were whole coffee husks, a yeast concentration of 3 g per liter of substrate, and a temperature of 30 °C.

Mussatto et al. [243] investigated ethanol production from three different yeast strains—*Saccharomyces cerevisiae*, *Pichia stipitis*, and *Kluyveromyces fragilis*—when cultivated in sugar-rich hydrolysates derived from the acid hydrolysis of coffee silverskin (CS) and SCGs. The fermentation of CS hydrolysate yielded minimal ethanol production, likely due to the low concentration of sugars present. In contrast, *S. cerevisiae* exhibited the highest ethanol production from SCG hydrolysate, achieving 11.7 g/L with an efficiency of 50.2%.

Ethanol Recovery

Typically, distillation is the conventional method used for ethanol purification, and it is known for its ability to achieve very high bioethanol recovery. However, distillation presents some disadvantages in the purification of lignocellulosic bioethanol, such as operating in batch mode and requiring high energy [244]. In contrast, Dadi et al. [233] demonstrated that pervaporation membranes can effectively purify fermented broth. Their study revealed that pervaporation achieved a bioethanol yield of 132.2 $\pm$ 40 g/L from coffee husk under optimal conditions. The sugar yield after hydrolysis and the ethanol concentration after fermentation/pervaporation, yield, and productivity from various studies in the literature, are presented in Table 3.

Table 3. Comparison of ethanol production methods from different feedstocks.

Feedstock	Hydrolysis Method	Sugar Yield	Ethanol Concentration	Yield and Productivity	Ref.
Spent coffee grounds	Dilute acid pretreatment	Glucose: 192 mg/g SCG	19.0 g/L	Ethanol yield: 0.50 g/g Productivity:1.90 g/L·h	[245]
Coffee husk	Dilute acid hydrolysis followed by peroxide alkaline pretreatment, then Enzymatic Hydrolysis	Glucose: 115.6 g/L	48.19 g/L	Ethanol yield: 0.41 g/g Productivity: 2.4 g/L·h	[240]
Coffee husk	Acid hydrolysis and enzymatic hydrolysis	Glucose: 11.5 g/L Xylose: 7.4 g/L	After fermentation: 36.6 ± 0. 2 g/L After pervaporation: 132.2 ± 40 g/L	Productivity: 3.05 g/L·h	[233]
Spent coffee grounds	Acid hydrolysis and enzymatic hydrolysis	Glucose: 16.0 g/L Xylose: 15.6 g/L	After fermentation: 47.9 ± 0.06 g/L After pervaporation: 51.7 ± 7.4 g/L	Productivity: 4.00 g/L·h	[233]
Spent coffee grounds	Ethanol pretreatment at high temperature, then enzymatic hydrolysis	Glucose: 17.5 g/L Galactose: 8.0 g/L Mannose: 31.7 g/L	After fermentation: 16.4 g/L After pervaporation: 11.3 g DW of ethanol from 150 g DW of ethanol-pretreated CRW	Productivity: 0.23 g/L·h	[230]
Spent coffee grounds	Popping pretreatment followed by enzymatic pretreatment	Fermentable sugar: 40.2 g/L	15.3 g/L (45.9 g of ethanol per 300 g of CRW)	Productivity: 0.15 g/L·h	[228]
Spent coffee grounds	Acid hydrolysis followed by peroxide alkaline pretreatment	Sugar concentration: ~50 g/L	11.7 g/L	Ethanol yield = 0.26 g/g Productivity= 0.49 g/L·h	[243]

4.2.2. Biodiesel Production

The oil content in coffee grounds ranges from 11% to 20% of their weight, depending on the type of coffee beans utilized. The typical oil extraction rate from used coffee grounds is approximately 15% [246]. Various solvents have been analyzed to assess their effectiveness in extracting this oil, and hexane is frequently used. Other solvents that have been recorded include ethanol, methanol, acetone, butanol, petroleum ether, and dimethyl ether [246–249]. A recent study by Veitía-de-Armas et al. [250] demonstrated the potential use of environmentally friendly solvents such as ethyl acetate, ethyl butyrate, and ethyl propionate for extracting oil from discarded coffee grounds. The researchers successfully attained an oil recovery rate of 16.4% by employing ethyl propionate.

Fatty acids are the primary chemical constituents of extracted coffee oil [251]. Following the extraction process, the oil is frequently treated with an esterification treatment. Typically, this procedure entails the use of methanol and a catalyst. Notable progress has been achieved in the transformation of coffee oil into biodiesel. These methods encompass the utilization of acid–base catalysts [246], solid catalysts derived from discarded eggshells [252], and supercritical methanol [253].

In the conventional process, biodiesel production from SCGs is typically accomplished through transesterification, using SCG oil extracted using an n-hexane solvent [254]. However, biodiesel production from SCGs via conventional processes requires a lot of SCGs. To overcome this advantage, in situ transesterification has been invented, and this process has been successfully used with canola, soybean, palm fruit, algae, cottonseed, and castor seed. The difference between these two processes is shown in Figure 4.

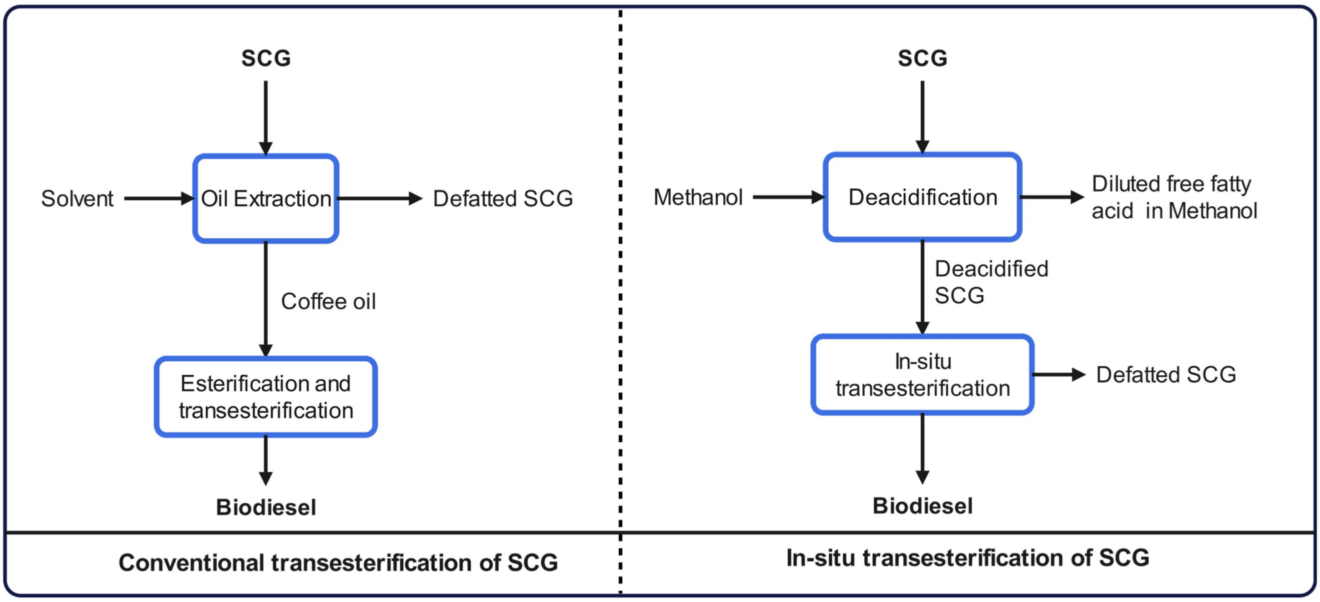

Figure 4. Comparison of conventional and in situ transesterification of spent coffee grounds.

For the in situ transesterification technique, Tuntiwiwattanapun et al. [254] found that methanol and an alkaline catalyst can be employed as both a reactant and an extraction solvent for biodiesel in the in situ transesterification process. This approach simplifies the production system and reduces its size. The process starts by deacidifying the SCGs using methanol washing, since the high acid value of the feedstock would deactivate the alkaline catalyst used in the in situ transesterification, reducing the biodiesel product. Following the deacidification process, the SCGs undergo in situ transesterification, producing biodiesel. The residual product of this integrated procedure is the defatted SCGs, which are left over after biodiesel extraction. The in situ transesterification process is one of the strategies for enhancing biodiesel production. Najdanovic-Visak et al. [255] improved the in situ transesterification of spent coffee grounds by utilizing sodium hydroxide as a catalyst. The highest yield obtained from the in situ transesterification was 96.0% under the following specified reaction conditions: a 400 methanol to oil mole ratio, a temperature of 333 K, a catalyst concentration of 0.2 mol/L, and a duration of 90 min.

Due to the high water content in SCGs, which can hinder traditional transesterification processes, many studies have focused on the in situ transesterification of wet SCGs [22,253,256,257]. Tarigan et al. [22] reported the method for directly producing biodiesel from wet SCGs utilizing a Soxhlet extractor comprising two primary sections: an extraction chamber and a reaction chamber. At first, SCGs are placed in a small metal container called a thimble, which is put inside the extraction chamber. A solution comprising methanol, hexane, and a catalyst is introduced into the reaction chamber. The solvent mixture becomes hot during the reaction, evaporates, and condenses. This process repeatedly occurs, causing the solvent to flow over the biomass in the extraction chamber. This flow helps to carry out the in situ transesterification process. After the extraction, the biodiesel that has dissolved in hexane is separated and subjected to several washes with distilled water to eliminate contaminants. The hexane is subsequently evaporated to acquire the refined biodiesel.

However, to avoid concerns regarding the free fatty acid content and reduce issues related to water content in SCG oil during ester-based biodiesel production, advancements in bio-hydrotreated diesel—also known as bio-hydrogenated diesel (BHD), hydrotreated vegetable oil (HVO), green diesel, or hydrogenated esters and fatty acids (HEFA)—have been explored. Instead of methanol, pressurized hydrogen was employed for heteroatom (mainly oxygen) removal from lipid molecules [258]. As oxygen is removed, the resulting hydrocarbon products resemble fossil fuel, providing higher heating values and an improved oxidation stability [259].

Combined Processes for Producing Biodiesel and Bioethanol

SCGs can be used as feedstock to produce both ethanol and biodiesel, while the residual solid waste is appropriate for composting or fuel pellets, simultaneously addressing waste management and energy generation.

Passadis et al. [260] experimentally investigated the possibility of producing biodiesel and bioethanol from SCGs. The researchers employed the Soxhlet extraction method, utilizing methanol and hexane as solvents. Their results indicated that hexane exhibited greater effectiveness as a solvent, achieving oil extraction yields of 73.15% to 97.21%. The highest saccharification yield obtained during enzymatic hydrolysis was 44.20% for ethanol production. This yield was achieved using a 0.3 M NaOH solution and a CellicCTec2 concentration of 75 μL/g cellulose. Their findings proposed that producing approximately 10.0 kg of biodiesel and 2.5 L of bioethanol from 100 kg of SCG is technically feasible.

Kwon et al. [261] developed a sequential process for producing biodiesel and bioethanol from spent coffee grounds, which proved more efficient than direct bioethanol conversion. Direct ethanol conversion was deemed less effective due to slow enzymatic saccharification, which was hindered by triglycerides and free fatty acids (FFAs) in the raw materials. They found that the acid/enzyme hydrolysates from spent coffee grounds after lipid extraction contained a higher concentration of total sugars (66 g/L) than those from raw spent coffee grounds (58.4 g/L). This difference highlights the inhibitory effect of lipids on sugar extraction.

The sequential method starts by extracting lipids, which removes the inhibitory effects on ethanol-producing enzymes and allows for a non-catalytic transesterification process that is suitable for handling a high FFA content in biodiesel production. Using this method, Kwon et al. [261] achieved a 97.5% biodiesel yield. After lipid removal, the remaining material, rich in carbohydrates, becomes a more optimal feedstock for ethanol production. Using this method, they achieved an ethanol yield of 0.46 g/g of consumed sugar.

4.2.3. Bio-Oil Production

As mentioned earlier, using coffee waste for biodiesel production requires extracting fat from the coffee waste. However, after lipid extraction, the remaining part, the defatted coffee grounds, can produce bio-oil and biochar.

Vardon et al. [262] reported that the production of bio-oil from coffee waste involves several key steps. Initially, 100 g of dry coffee waste is prepared as the feedstock. This feedstock undergoes slow pyrolysis in a tube furnace, where it is heated to 450 °C at a rate of 50 °C per minute, with a retention time of two hours under a nitrogen sweep gas. Volatile products generated during this process are collected using an ice-chilled collection vessel, while the remaining solids in the furnace, known as biochar, are weighed. The collected liquids are then separated using solvent extraction into a bio-oil (solvent-soluble phase) and an aqueous phase containing organics. The solvent is then removed from the bio-oil phase through evaporation.

4.2.4. Biogas Production

Anaerobic digestion is a biochemical process in which microorganisms decompose organic matter in the absence of oxygen, resulting in the production of biogas. Spent coffee grounds (SCGs) are particularly suitable for this method due to their balanced composition of proteins, carbohydrates, and minerals, providing essential nutrients for digestion. In a study by Czekala et al. [263], the feasibility of using coffee production and consumption waste in anaerobic digestion was assessed, highlighting SCGs' potential to enhance biogas generation. The experiment conducted under anaerobic digestion conditions revealed that coffee husks had a total solid content of 93.37% and an organic matter content of 93.34%. The efficiency of biogas production, measured in terms of fresh matter, was 329.50 m^3/Mg.

However, some work proved that using SCGs as the sole feedstock can cause challenges, such as the lack of sufficient nutrients and trace elements necessary for the anaerobic digester (AD) process. SCGs contain high levels of lignocellulosic materials, which are complex plant materials that microorganisms find difficult to break down. These materials are poorly bioavailable, meaning they are not easily accessible to the microbes involved in the AD process [264]. The co-digestion of SCGs with other waste, such as cow and pig manure, spent tea waste, food waste, or sewage sludge, can solve these problems.

Kim et al. [265] investigated varying ratios of spent coffee grounds (SCGs) to food waste (FW) from 1:100 to 1:10 to utilize the spare capacity of existing digesters for SCG treatment. This co-digestion approach enhanced methane production compared to digesting food waste alone while maintaining process stability. However, increasing the SCG ratio beyond 4% did not improve methane yield further.

4.2.5. Biorefinery Concept of Coffee Waste Variolization into Biofuels and Bioenergy

Coffee waste consists of various parts, each exhibiting a distinct chemical composition. Within the biorefinery framework for transforming coffee waste, it is crucial to consider the appropriate processes for each component to optimize the conversion and utilization of the waste effectively.

Coffee waste materials, including the skin, pulp, and parchment (husk), are rich in chemical compounds, like phenolic compounds, carotenoids, flavonoids, and antioxidants, that have potential applications as bioactive compounds. In terms of energy production, coffee husk is a good source of sugars that can be fermented by *Saccharomyces cerevisiae* to produce bioethanol [242]. Both coffee husk and pulp have a high organic matter content, making them suitable substrates for biogas production through anaerobic digestion [263,266]. The mucilage, which contains polysaccharides, can be effectively utilized in fermentation processes [45]. Co-digesting mucilage with other organic materials, such as glycerin and animal manure, through co-digestion, not only improves biogas yield but also enhances the economic viability of biogas production [266].

However, among different parts of coffee waste, SCGs have attracted significant interest in the biorefinery context for producing biofuels [93,267]. Rich in organic compounds, SCGs contain substantial amounts of polysaccharides, lipids, proteins, and bioactive compounds [268], making them an excellent feedstock for producing biofuels such as biodiesel, bioethanol, biogas, and bio-oil. Additionally, they have a high calorific value, typically exceeding 20 MJ/kg [174]. The biorefinery approach to coffee waste valorization for energy production employs a variety of processes to convert SCGs into valuable energy products and other useful by-products. Among the frequently explored sustainable solutions are biofuels, such as biodiesel and bioethanol. SCGs can serve as a valuable resource in this regard. Lipids extracted from SCGs can be utilized for biodiesel production, while sugars in the residual biomass can be fermented to produce bioethanol. Additionally, glycerol, a by-product of biodiesel production from SCG-derived oil, can be further transformed into biohydrogen. Solid residues from SCGs can be used to produce fuel pellets or generate biogas through anaerobic digestion. Furthermore, SCGs can be directly converted into bio-oil and biochar through processes like pyrolysis. These applications not only provide renewable energy alternatives but also promote a more sustainable waste management strategy. Moreover, by-products like biochar can enhance soil quality, adding further value to these processes. Figure 5 illustrates the biorefinery concept for converting spent coffee grounds into energy.

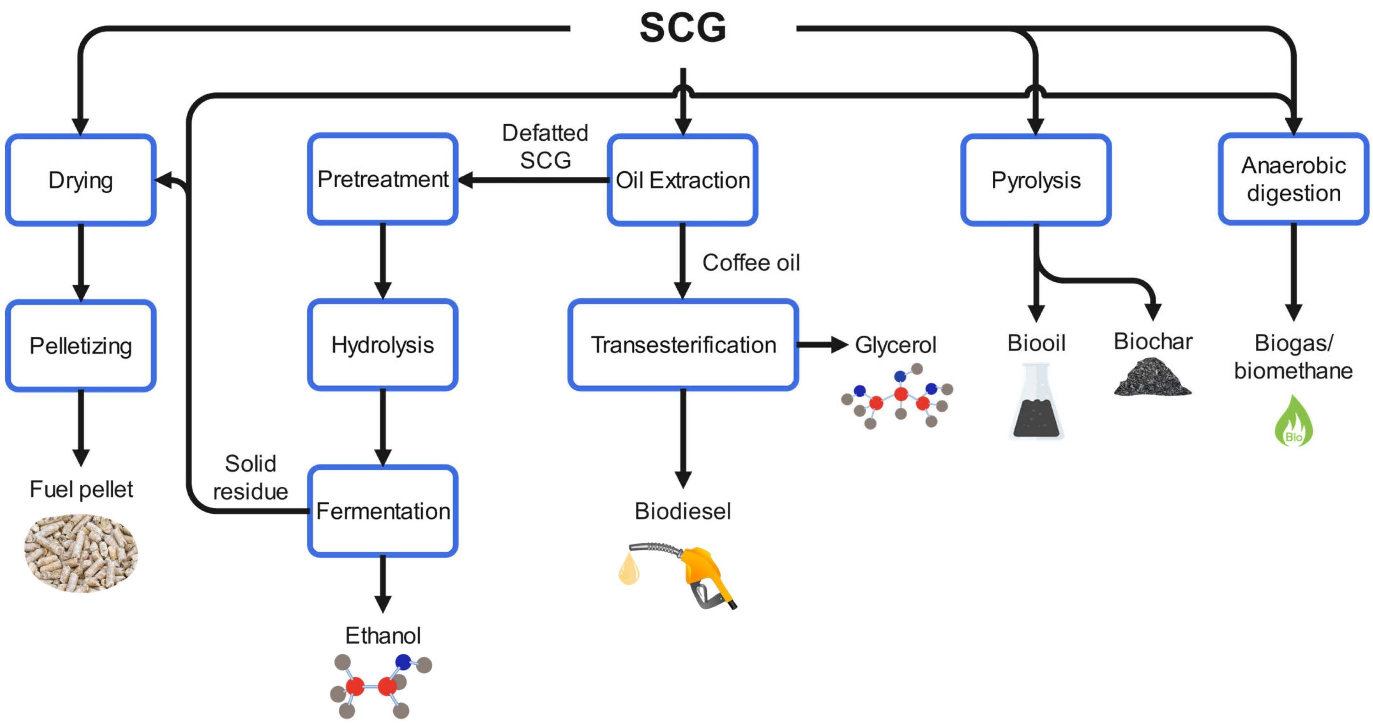

Figure 5. Biorefinery concept of spent coffee grounds valorization into energy.

4.3. Food Ingredients and Nutraceuticals

The food industry is increasingly recognizing the potential of coffee waste and by-products as valuable resources. Coffee waste contains beneficial components such as proteins, dietary fibers, antioxidants, and other bioactive compounds, which can enrich food nutrition and provide additional health benefits for humans. This makes coffee waste a promising source for a wide range of applications in food production and other related fields.

4.3.1. Bakery Production

In bakery production, coffee waste has been widely used as a functional ingredient not only to enhance nutrition, making bakery goods healthier, but also to improve the sensory and shelf life.

Bread

Coffee silverskin (CS) has been reported to have a high potential to be used as a functional food ingredient with multiple health-promoting properties. The extract of CS and CH was obtained by water extraction at 100 °C for 10 min, as described in the patent WO/2013/004873 [269]. Gluten-free bread formulations enriched with these two extracts have shown increased dietary fiber content and antioxidant activity. Total protein values and total phenolic compounds significantly increased, particularly in bread in which the CS extract was applied. Furthermore, the CS and CH extracts revealed the capability to inhibit alpha-glucosidase activity, which is a health benefit for people with the particular requirement of regulating postprandial glucose levels [270].

Coffee pulp can be processed into flour and used as a functional ingredient in gluten-free bread products. Rios et al. [271] revealed novel gluten-free bread labeled as "high in dietary fiber" and a "source of protein", which was obtained by a coffee cascara flour substitution of 3–4.5%. In the present study, coffee cascara was pretreated by water extraction [269], then dried and milled to obtain flour. This flour was incorporated into gluten-free bread formulations enriched in dietary fiber (~11%) and protein (~10%) with relatively high glutamic acid and other essential amino acids. In addition, the total starch content was reduced with increases in the coffee cascara flour content, due to the starch being eliminated during the coffee cascara water extraction process, leading to a low caloric content, and potentially decreasing the glycemic index of the bread. The author emphasized that incorporating coffee cascara flour (with pretreatment) in gluten-free bread contributes to a healthier possibility for people who have celiac disease and/or gluten intolerance and require glycemic control.

Another study by Rivas-Vela et al. [272] investigated the properties of coffee pulp flour prepared by an extrusion process for bread formulations. They found that the extrusion temperature and feeding moisture are crucial factors for the increase in the water adsorption index and water solubility index of the CP flour. The technique also significantly affects the phenolic and caffeine content by an increase of up to 60% and 30%, respectively, compared to the control, which may be because of the effect of shear, temperature, and pressure during the process. The author highlighted the potential of using CP flour in wheat-based and gluten-free bread formulations, which could be substituted in amounts of up to 15% of CP flour, with no significant effect on its sensory characteristics. Additionally, the bread formulated from this study provided good nutrition, including protein, caffeine, phenolic compounds, and dietary fiber, which are comparable with these compounds in protein bars for athletes.

Cookies, Cake, Biscuits

The potential for the nutritional enrichment of CS was also observed in cookies [273] and cake [274] formulations. The results showed that as the CS level increased in bakery formulations, the protein, fiber, phenolic compound, and antioxidant values increased. The bioaccessibility of phenolics and antioxidants was examined using an in vitro enzymatic digestion system [275]. The values increased up to 85% when a CS value of 7.5% was added into cookie formulations [273].

Moreover, applying CS significantly affects both cookies' and cake's sensory and textural attributes by increasing moisture and making the goods darker and more bitter compared to the control sample. The bitter test of the baked goods is related to the high caffeine content in CS [274].

Ateş and Elmaci [276] reported that using water-treated CS (up to 30%) in cake provided favorable sensations (no bitterness), texture, and moisture content, which is comparable to cake without the CS addition. They also suggested that water-treated CS has more efficiency as a fat replacer, as it provided a lower fat content in cake products with no significant effect on sensations and texture compared to the control sample.

Similarly, Koay et al. [277] revealed the potential of spent coffee grounds as a fat replacer. A similar fat content and oiliness were observed between SCG-enriched shortbread and the control sample. In addition, the incorporation of SCGs improved the properties and enriched the nutritional composition in shortbread biscuits, including higher moisture, fiber, protein, and total phenolic content, leading to higher antioxidant activity, with lower carbohydrates and calorie content. The shortbread with 10% SCGs exhibited the most preferable aroma and a softer texture, as well as greater shelf-life stability, which is related to a high total phenolic compound content and high antioxidant activity, which could slow lipid oxidation during the storage period.

Another study by Martnez-Saez et al. [16] found that the incorporation of 4% of SCGs in biscuit formulations contributed to high nutritional and sensorial qualities. In this study, SCGs were applied directly with stevia, maltitol, and oligofructose. SCGs were detected as having a high amount of antioxidant dietary fiber, essential amino acids, and notable amounts of proteins, caffeine, and chlorogenic acids, with low glycemic sugar. The study emphasized the potential of combining SCGs with a sucrose replacement to reduce Maillard reaction products (MRPs) and decrease the formulation of advanced glycation end products (AGEs), which is related to various chronic diseases such as diabetes and obesity. Eventually, the author suggested that these innovative biscuit formulations probably benefit people with reduced energy intake and particular requirements.

Martnez-Saez et al. [278] further investigated the potential of innovative biscuits on human health benefits by simulating biscuit digestion in in vitro oral gastrointestinal human digestion conditions. After digestion, galactomannan was found in coffee fiber biscuits, and a higher amount of antioxidants were released compared to the original biscuits, providing benefits to weight management by reducing weight gain, adiposity, liver fat, and blood glucose levels [279].

In addition, coffee fiber biscuits exhibited a significant inhibitory effect on α-glucosidase activity, aiding in reducing postprandial glucose levels. This effect is probably associated with phenolic compounds being released (particularly chlorogenic acid), which could act as α-glucosidase inhibitors [280,281]. A novel finding was that serotonin and glucagon-like peptide-1 (GLP-1) were significantly released by increasing their secretion by 335% and 273%, respectively, compared to the basal level during the digestion of antioxidant coffee fiber biscuits. Both hormones play an important role in reducing appetite suppression by stimulating satiety signals [282] and improving glycemic control [283].

Consequently, these results imply that consuming coffee fiber biscuits can regulate food intake and aid in weight management, further contributing to reducing the risk of chronic diseases such as obesity and type 2 diabetes.

4.3.2. Yogurt

Apart from baked goods and beverages, coffee waste has been studied in the dairy production context, specifically for yogurt, in order to create a healthier food with high nutrition and satisfactory sensation. Whole milk-generated yogurt was supplemented with arabica and robusta coffee silverskin (CS) at 2%, 4%, and 6% [284]. The presence of CS significantly influenced the physicochemical properties of the yogurt, with higher CS levels causing greater syneresis (whey separation), pH, and firmness values. The addition of CS increased the nutraceutical value of yogurt, improving its dietary fiber and total phenolic content. Furthermore, to analyze the bioaccessibility of bioactive compounds and antioxidant activity after ingestion, in vitro simulated gastrointestinal digestion (SGD) was performed as described by Minekus et al. [285]. This study highlighted that bioactive compounds, including phenolic compounds, caffeine, and chlorogenic acid in CS-added yogurt, are bioaccessible after digestion, leading to the significantly increased antioxidant potential of yogurt, particularly using arabica CS, while robusta CS contributed a greater caffeine content. As such, this CS-fortified yogurt may help reduce oxidative stress, which causes chronic diseases such as cancer, cardiovascular disease, type 2 diabetes, and neurodegenerative disorders (e.g., Alzheimer's, Parkinson's) [286–288], as well as improve physical and cognitive performance [289].

In addition, yogurt containing a coffee cascara extract and inulin revealed the possibility of regulating carbohydrate metabolism, providing benefits in blood sugar control due to the glucosidase inhibitory effect of the cascara extract [290]. In this study, a high inulin value of 13% further increased the prebiotic fiber content, promoting gut health; however, it was associated with gastrointestinal discomfort (such as abdominal cramps, bloating, flatulence, and gastrointestinal rumbling), probably due to its indigestible fiber.

4.3.3. Innovative Beverages

Although coffee waste has been extensively investigated as an ingredient in food and bakery products for human health benefits, its utilization in beverages has been rarely found. One study exhibited that antioxidant beverages developed from a coffee silverskin (CS) extract can be used for body fat reduction and body weight control. The CS extract enriched bioactive compounds in the beverage, including chlorogenic acids (CGAs), caffeine, and melanoidins, which were found to have a significant effect on antioxidant capacity and fat body reduction through an in vivo analysis with nematodes (*C. elegans*). The fat body reduction in the beverage could be enhanced by the synergic effect of the food matrix, in which complex molecules such as dietary fiber, proteins, and melanoidins could influence the bioaccessibility and bioavailability of CGAs and caffeine. In particular, the Robusta CS extract beverage showed a significant effect on lipid oxidation and its metabolism, comparable to a commercial dietary supplement. Additionally, the presence of melanoidins in the beverage contributed to significant antioxidant activity and sensory attributes, such as flavor and color [291].

Cascara tea, another antioxidant beverage, was developed from coffee cherry pulp. The result showed the that bourbon variety coffee pulp from Congo has the highest caffeine and total phenolic compound content, dominantly including protocatechuic acid and chlorogenic acid, and notable amounts of rutin and gallic acid, leading to the highest antioxidant capacity. The beverage brewed from this coffee pulp variety contained significant amounts of caffeine of 226 mg/L, which is comparable to coffee brew, while the total polyphenols content was lower than that found in coffee brew [43].

Another study highlighted the potential of coffee pulp (CP) in developing functional probiotic beverages using kefir cultures. Prior to the beverage formulation, CP was prepared with different pretreatment methods (steam and viscozyme) followed by aqueous extraction (5 g pulp + 50 mL distilled water 90 °C, 10 min). The result showed that the steam pretreatment had a maximum value of polyphenols, flavonoids, anthocyanins, chlorogenic acid, and caffeine, leading to high antioxidant activity with no cytotoxicity. In addition, the extracted CP revealed the capability to manage the hyperglycemia-induced disorder, significantly inhibiting alpha-amylase and alpha-glucosidase activities, probably due to the presence of anthocyanins [292]. CP probiotic beverages have been shown to be beneficial not only in enhancing the nutritional profile and physicochemical properties, but also in improving sensory attributes and shelf life, with probiotic organisms surviving up to 30 days [293].

An alcoholic beverage is another application for which coffee wastes were utilized. Coffee pulp and mucilage waste obtained from wet processing, which are rich in sugars, have been used to successfully create alcoholic beverages by fermentation, which contain significant levels of alcohol content [54]. Superior sensory qualities were obtained from an alcoholic beverage fermented from coffee pulp compared to pure mucilage and mucilage with beans. This result could be attributed to the concentration of phenolic compounds in the beverage, as chlorogenic acid has been reported to relate to the coffee fragrance and flavor [294]. Greater amounts of ester, tannin, and polyphenol contents in coffee pulp-derived alcoholic beverages could positively influence the aroma, taste, and aftertaste, providing more satisfactory sensory attributes. However, the appearance of the coffee pulp-derived alcoholic beverage is reddish, like red wine, which correlates with the coffee skin pigment.

Similarly, new distillate beverages developed from coffee pulp and coffee wastewater fermentation with a sucrose addition lead to a high-quality spirit with an ethanol content of 38%. Several volatile compounds, particularly ethyl esters and terpenes, contributed to floral, sweet, and fruity aromas in the beverage. Comparatively, the coffee pulp-derived spirit provided more impressive sensory attributes (taste and aroma) compared to a sugarcane spirit [295].

The other two studies explored the potential of using the extraction of spent coffee grounds to create sustainable beverages. For spirit preparation, the bioactive compounds in SCGs were extracted through hydrothermal [296] or microwave-assisted processes [297]; then, the SCG extract was supplemented with sucrose and potassium metabisulfite before fermentation with the yeast *Saccharomyces cerevisiae*, followed by distillation to produce spirits with an ethanol content of 38–40%. According to the chemical compositions, the spirits showed a remarkable taste and aroma, which is reminiscent of coffee. The sensory profile of the SCG-derived alcohol changes significantly based on their production by fermentation and distillation processes. The final spirits exhibited superior sensory qualities compared to the fermented beverages, which appeared as clear and brilliant, and had complex profiles, including coffee, toasted beans, alcohol, and frankly, aromas with astringent and pungent tastes, which gave panelists a feeling of elegance and finesse. Additionally, caramel and vanilla aromas were observed in the spirit [297].

For the further development of coffee-based alcoholic beverages, Liu et al. [298] studied the effect of using non-*Saccharomyces* wine yeast on SCG alcoholic production. In this study, SCGs were defatted and hydrolyzed before fermentation using *T. delbrueckii* Biodiva and *P. kluyveri* FrootZen. They found that the beverages obtained from these two non-*Saccharomyces* produced a lower ethanol content compared to the beverages from *Saccharomyces*; however, the addition of yeast extracts in the fermentation enhanced the growth of yeast, leading to high ethanol production [299], particularly *P. kluyveri*. In addition, the supplementation of yeast extracts in the SCG fermentation process increased the production of volatile compounds, such as alcohols and esters, leading to more sensory complexity. Significant amounts of glycerol and ethyl ester were detected in the beverages prepared from these two non-*Saccharomyces*, which contributed to the mouthfeel, smoothness, and sweet tastes [300], and fruity and floral aromas, respectively. Regarding the findings in this study, yeast extracts help improve the fermentation process, leading to achieving a more balanced flavor profile and enhancing the overall sensory quality of the alcoholic beverages derived from SCGs. The utilization of coffee waste as a functional ingredient in food production is summarized in Table 4.

Table 4. The utilization of coffee waste as a functional ingredient in food production. (CP: coffee pulp; CH: coffee husk; CM: coffee mucilage; CPm: coffee parchment; CS: coffee silverskin; SCGs: spent coffee grounds).

Food Products	Coffee Waste	Process	Functions	Ref.
Bread	CP powder	Baking	• Substitution of wheat flour. • Fiber enrichment increased by 89% of dietary fiber.	[301]
	CP flour	Extrusion/Baking	• Multipurpose flour. • Extrusion increases phenolic compounds and caffeine. • Reducing phytic acid content. • Providing good nutrition and antioxidants (phenolic compounds, caffeine, protein, and dietary fiber).	[272]
	Coffee cascara isolated fiber	Water extraction/Baking	• High dietary fiber of 11%, comparable to whole-grain bread.	[271]
	CPm ground	Baking	• Enriches dietary fiber and the antioxidant capacity in gluten-free bakery products. • Decreasing oxidative stability and lowering the presence of HMF.	[302]
	CS powder	Alkaline hydrogen peroxide pretreatment/Baking	• Increased water retention. • Low caloric density and high dietary fiber.	[303]
	CH and CS extracts	Water extraction/Baking	• Antioxidant capacity and α-glucosidase activity (chlorogenic acid and phenolic compounds). • Reducing the risk of chronic disease related to blood-glucose levels. • Natural coloring.	[270]
Biscuits	SCG powder	Baking	• High moisture, protein, fiber, phenolic compounds, and antioxidant activity. • Lower carbohydrates and calorie content. • Delaying lipid rancidity and increasing the shelf-life stability.	[277]
	CS fiber/SCG powder/dietary fiber extracts	Extraction/Baking	• Natural coloring. • Rich in insoluble dietary fiber and amino acids. • High levels of antioxidant activity with low calories. • Low levels of aerobic microorganisms, acrylamide, and hydroxymethylfurfural (HMF). • Inhibitory effect of the α-glucosidase.	[16,20,278,304]

Table 4. *Cont.*

Food Products	Coffee Waste	Process	Functions	Ref.
Brownies	SCG extracts	Isopropanol extraction/Baking	• Phenolic compounds and flavonoids content. • Antifungal, antibacterial, antimycotic, and anti-ochratoxigenic properties. • Moderate cytotoxic effects against liver cancer cells (Hep-G2) • Significantly reduced ochratoxin A levels during dough incubation.	[305]
Cake	CS powder	Water treatment/Baking	• Increased antioxidant activity and fiber of CS-added cake. • Improves moisture, oiliness, and sweetness. • Used as a fat replacer up to 30% in cake formulations.	[274,276]
Cereal	CS grounds	Extrusion and Baking	• Provided high dietary fiber, protein, and bioactive compounds such as chlorogenic acid.	[306]
Cookies	coffee flour	Baking	• High dietary fiber and antioxidant activity. • High amounts of coffee flour made the cookies harder, darker, and bitter.	[307]
	CPm powder	Ultrasound treatment/Baking	• Low fat, high fiber, and antioxidant content.	[308]
	CS powder	Baking	• 60% of phenolic compounds of 60%. • High antioxidant bioaccessibility of 85%. • More bitterness at high amounts of CS incorporation.	[273]
	SCG powder	Baking	• High total phenolic and flavonoid contents and high antioxidant activity. • Nitrite scavenging activities and lipase inhibitory activities.	[309]
	SCG powder	Baking	• High fiber and phenolic compounds with high antioxidant activity. • High hardness at high SCG content.	[310]
	SCG powder	Baking	• Increasing fiber, fat, and total phenolic content. • Reducing moisture and protein content with higher SCG content. • Decreasing antioxidant activity at 25% of SCGs	[311]
	SCG oil	Ethanol extraction/Baking	• Alternative to butter as a healthier ingredient in bakery products. • 20% of SCG oil substituted in cookies enhances antioxidant properties.	[312]
French Meringue	Coffee fresh skin extract	Ethanol extraction	• Natural coloring. • Anthocyanins (mainly cyanidin 3-glucoside). • Providing color close to synthetic pigments.	[313]

Table 4. *Cont.*

Food Products	Coffee Waste	Process	Functions	Ref.
Muffins	SCG powder	Baking	• Increased total phenolic compounds, fiber, and antioxidant activity. • Light-roasted SCG has greater amounts of caffeine, trigonelline, chlorogenic acid, total phenolic compounds, and antioxidant activity.	[314,315]
Yogurt	Cascara extracts	Water extraction/Inoculated fermentation	• Glucosidase inhibitor and a source of dietary fiber. • Inulin improves digestive health and the texture of the yogurt. • Help modulate hunger and fullness.	[290]
	CS powder	Inoculated fermentation	• Increased dietary fiber (mainly insoluble fiber), phenolic compounds (chlorogenic acid), and caffeine. • Increased whey separation (syneresis) over storage.	[284]
Antioxidant Beverage	CS extracts	Extraction and/Infusion	• Low glucose, high total fiber, and high water-soluble proteins. • High total antioxidant capacity (melanoidins and chlorogenic acid) and caffeine. • Promoting weight control.	[291]
Instant Cascara (IC)	CH extract powder	Extraction-Freeze dried/Infusion	• High nutrition with low caffeine and acrylamide levels. • Low fat, low sugar, and high fiber, potassium, magnesium, and vitamin C. • High levels of melanoidins and total phenolic compounds (Chlorogenic acid).	[316]
Cascara Beverage	CP powder	Milled/Infusion	• Rich in phenolic compounds (chlorogenic acid, protocatechuic acid, gallic acid, and rutin). • Coffee variety and type of processing significantly affect the content of phenolic compounds and caffeine.	[43]
Cascara Kombucha	Dried whole CH	Steeping/Fermentation	• High total polyphenol and flavonoid content, and high antioxidant activity. • Antibacterial against pathogenic bacteria. • Prebiotic potential by promoting the growth of probiotic strains.	[317]
Probiotic Beverage	Dried whole CP	Viscozyme or steam pretreatment/Infusion/ Inoculated Fermentation	• Significant amounts of protein, fiber, potassium, and calcium. • High antioxidant activity, Chlorogenic acid, caffeine, and total flavonoids (anthocyanins). • α-amylase and α-glucosidase inhibitory effects, indicating antidiabetic potential.	[293]
Distilled Beverage	Wet or dried CP in coffee wastewater	Fermentation/Distillation	• High ethanol. • Coffee-like aromas, floral, and fruity flavors, due to the presence of ethyl ester and terpenes.	[295]

Table 4. *Cont.*

Food Products	Coffee Waste	Process	Functions	Ref.
Alcoholic Beverage	Wet CP and CM	Fermentation	• High alcohol content (8.86% ABV) with great antioxidant capacity. • Reddish color and fruity aroma like red wine, contribute to flavonoid (anthocyanins), chlorogenic acids, and ester content, respectively.	[54]
SCG Spirit	SCG extract	Hydrothermal extraction/Fermentation/ Distillation	• Coffee aroma and acceptable organoleptic qualities. • Alcohol and esters (e.g., ethyl acetate) are the major volatile compounds, contributing to the aroma and flavor of the spirit.	[296]
Alcoholic Beverage	SCG hydrolysate	Acidic-enzymatic hydrolysis/Fermentation	• Different yeast types affect aroma and flavor. • More complex aroma and flavor with ester and alcohol. • Yeast extract improves fermentation efficiency and flavor outcomes. • Enriching the fruity and floral notes.	[298]
Coffee-Flavored Liquor	SCG hydroalcoholic solution	Ethanol extraction	• Create coffee-flavored liquor with designable sensory qualities. • Matched sensory expectations.	[318]

4.3.4. Food Preservatives

Coffee waste contains several essential bioactive compounds, leading to high antioxidant activity, which could be used as natural food preservatives. Antioxidant properties of coffee waste could contribute the preventive food spoilage by inhibiting micro-organism (e.g., molds., yeast, bacteria) activity and/or chemical reactions (e.g., oxidation), leading to extended shelf life and preserved qualities of food (including texture, color, order, and taste).

As such, using a coffee waste extract as a preservative for whiteleg shrimp has been reported. The fraction of the coffee extract exhibited a high potential for antioxidant activity and anti-tyrosinase, which plays a crucial role in preserving the qualities of shrimp and is associated with the presence of high phenolic compounds, especially flavonoids. High tyrosinase activity can accelerate the formation of black spots (Melanosis) in shrimp, resulting in deterioration and shortened shelf life during refrigerated storage. Commonly, sulfites and their derivatives, anti-browning agents, have been applied for the prevention of melanosis in the food industry; however, they cause negative clinical effects for sensitive people, including urticaria, flushing, dermatitis, hypotension, diarrhea, abdominal pain, and asthmatic reactions. Treating whiteleg shrimp with coffee waste extracts also inhibited the growth of aerobic microorganisms and Enterobacteriaceae, which can cause food spoilage and a wide range of illnesses. Therefore, coffee waste extracts can effectively be used as shrimp preservatives and alternatives for sulfite agents [319]. Moreover, recent studies have highlighted the ability of antioxidants in coffee waste for raw, cooked, and frozen meat preservation, such as beef [320], pork [321], and chicken [322].

Lipid and protein oxidation is recognized as a major cause of meat product deterioration, which can negatively affect the flavor, color, texture, nutritional quality, and shelf life [323,324]. To overcome these issues, synthetic antioxidants such as butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), propyl gallate (PG), and tert-bytylhydroquinone (TBHQ) are commonly used; however, these synthetic agents have been reported to have carcinogenic effects, resulting in health concerns [325].

Due to health concerns about synthetic antioxidants, natural antioxidants have been examined. For example, rosemary extracts have been widely reported as effective inhibitors of meat lipid oxidation [326–328], which are commercially used in the meat industry. Coffee wastes, rich in natural antioxidants, have been considered as a promising candidate. Several reports revealed the ability of spent coffee grounds to inhibit lipid oxidation, similar to the effects of rosemary. Dark-roasted SCGs were found to have the greatest antioxidant effect on raw beef, which significantly reduced thiobarbituric acid reactive substances (TBARSs) and aldehyde (especially pentanal and hexanal), which are associated with lipid oxidation and rancidity, respectively [329]. This effect was comparable to the rosemary effect, which had a greater effect when incorporated with sodium chloride. However, treating beef with rosemary led to a higher redness quality than beef treated with SCGs, which is an important factor that influences customers' buying decisions [320]. Similar results have been reported in the works of Hashimoto et al. [321] and Jully et al. [330]. They explored the antioxidant effects of various coffee forms (ground, lyophilized brew, and spent coffee grounds) on pork, focusing on raw, cooked, and frozen pork patties. The studies showed the potential of dark-roasted coffee in different forms (especially lyophilized coffee) to inhibit lipid oxidation in cooked and raw pork without inhibiting protein oxidation. The antioxidant effects of this coffee treatment were comparable to rosemary extracts. In terms of sensory qualities, the added coffee had a slight effect on the flavor changes on the third day; however, it did not affect the participants' acceptability.

Another study evaluated the antioxidant activity of SCGs extracted by ethanol and water as a preservative for chicken fillets over 15 days. The ethanol extracts showed a higher total phenolic compound content, total flavonoid content, and antioxidant activity compared to those obtained from water extracts, leading to effectiveness in preventing lipid oxidation in chicken fillets, which is similar to or greater than synthetic antioxidants (BHT). Surprisingly, added SCG ethanol extracts exhibited the ability to inhibit several food-borne bacteria strains (such as *Bacillus cereus*, *Staphylococcus aureus*, *Streptococcus faecalis*, *Pseudomonas aeruginosa*, *Salmonella* sp., and coliform) and fungal strains (mold and yeast). The values of total bacterial count (TBC) were in the range of acceptable limits for fresh meat according to the International Commission on Microbiological Specifications for Foods (ICMSF), while the meat treated with BHT was over the acceptable limits after 12 days [322].

Kim et al. [325] also observed the potential of SCG antioxidant activity extracted by ethanol over the aqueous extraction. The result showed effectiveness in preventing lipid oxidation in oil emulsions and raw meat. Nevertheless, the effectiveness was reduced in cooked chicken patties after 3 days of refrigeration. Results similar to those reported by Marques et al. [331] were obtained; TBARS values (an indicator of lipid oxidation) for raw chicken burgers were found to be higher than the values of grilled burgers, but these two values were still higher than the meat without coffee husk extracts. These results could be attributed to the levels of antioxidant activity of treated meat, which is associated with the concentration of bioactive compounds in the extracts. Furthermore, during the cooking process, the meat matrix would be destroyed by heating and exposure to oxygen, releasing phospholipids which would interact with pro-oxidants. Hence, pre-cooking before storage tends to increase oxidation activity, making cooked meat deteriorate more quickly compared to raw meat [332].

Overall, the studies collectively demonstrate that coffee waste can serve as a natural antioxidant in various meat products. Its use not only reduces lipid oxidation and antimicrobial effects that cause food spoilage, but also maintains the sensory qualities and extent of shelf life. The future of food preservation could see more widespread use of coffee as a natural, sustainable additive in a variety of food products.

4.4. Biochemicals and Biomaterials

Coffee waste contains large amounts of crucial compounds, as shown in Tables 1 and 2, which can be converted into valuable chemicals and materials, with potential for transformation into a variety of commercial products. For example, spent coffee grounds (SCGs) have a high lipid content, which can be used in applications such as biodiesel production [91,254,262], food additives [312], cosmetics [333,334], and poly-(-3-hydroxybutryate) (PHBs) production [32]. Additionally, coffee waste is rich in polysaccharides, which can be incorporated into polymer matrices such as high-density polyethylene (HDPE), polypropylene (PP), polyethylene (PE), polylactic acid (PLA), etc., to create functional and eco-friendly bioplastics and biocomposites. The utilization of coffee waste in polymer production has been extensively reviewed [7,46].

Additionally, several bioactive compounds (Table 2) and organic acids such as citric acid [335], gibberellic acid [336], lactic acid [337], succinic acid [338,339], and levulinic acid [340] can be derived from coffee waste, serving as essential ingredients for the food and pharmaceutical industries, as well as in monomeric production [341,342].

In food applications, coffee wastes show significant potential, being rich in bioactive compounds and polysaccharides, which can be used to develop colorants [313] and active packaging materials [343,344]. These materials not only provide antioxidant and antimicrobial properties, but also maintain sensory and nutritional quality.

4.4.1. Natural Colorants

Regarding the colorant capability of coffee waste, coffee husk and coffee silverskin have been reported to promote a darker color in coffee-added gluten-free bread, which provides the typical color of whole-meal bread [270].

Similarly, it was reported that as coffee waste incorporation levels increased, the bakery products were darker but they had subtle differences. For example, in comparison with the control sample, the incorporation of cascara (pulp+husk) resulted in a redder and more yellow color of bread [271], while SCGs led to a lower red and yellow color [314]. The distinct color appearance of various coffee wastes significantly depends on their chemical compounds, which are further influenced by extraction methods [274,276].

Natural pigment compounds are typically classified into four groups, including betalains, chlorophyll, anthocyanins, and carotenoids, which are obtained from many parts of plants, including, leaves, flowers, and fruit [345]. Focusing on the pigment of coffee waste, anthocyanin is the majority compound found in coffee waste, particularly coffee pulp and husk [346,347], which is related to the red color appearance in the bakery products mentioned earlier. In addition, carotenoids (beta-carotene, lutein, and astaxanthin) are highly found in coffee husk and pulp [64,348], while coffee silverskin and spent coffee grounds have significant amounts of melanoidins, which are brown pigments obtained from the Maillard reaction during the coffee-roasting process [349].

Melanoidins are high-molecular-weight compounds formed during the heat treatment of food and during beverage processing through the Maillard reaction between reducing sugars and amino acids. In coffee, melanoidins are found to have phenolic compounds, particularly chlorogenic acids (CGAs), incorporated into their structure [350,351]. In the incorporation of coffee waste in food production, melanoidins are strongly responsible for the dark brown color of the products. One study on instant cascara beverages examined the formation of melanoidins during the coffee cascara sun-drying process, indicating that they play a significant role in the beverage's color and flavor profile. As the concentration of coffee cascara increased, the color of the beverage became darker, which was confirmed by the similar UV-visible absorbance spectra to the caramel standard (E-150d). However, the color significantly changed to a lighter and lower red tonality when the beverages were exposed to a temperature over 40 °C and light for 72 h simultaneously; thus, a cooler temperature and dark conditions seemed to be the best conditions to preserve the qualities of the beverages [316].

Anthocyanins are responsible for a wide range of colors, from red to purple, which have been developed in various food productions such as dairy products [352], drinks [353], bakery items [313], confectionery items [313], etc. However, the utilization of anthocyanins in food production is challenging due to their high sensitivity to all changes during food production including the pH, temperature, light, the presence of other phenolic compounds, solvents, proteins, oxygen, sugars, enzymes, sulfites, and metal ions [354–356].

For instance, the reaction between anthocyanins and phenols can generate a brown color in prune juice [357]. Remarkably, among all, pH variations significantly influence the anthocyanins' structure changes, resulting in forming other compounds with a different color appearance, including red (at pH below 2), colorless (at 3–6), purple (at neutral), blue (at pH 7–8), and yellow (chalcone) (at 8–9) [354,358,359]. As such, anthocyanins have been reported to have favorable stability conditions at a low pH and temperature (<40 °C) [358,360].

Parra-Campos and Ordóñez-Santos [313] studied the utilization of coffee peel as a natural pigment (anthocyanins) in French meringue. They found that the intenseness of the color increased as the concentration of anthocyanins increased. Nevertheless, high concentrations of anthocyanins resulted in high acidity, which negatively affected the qualities of the meringue (shape, texture, and taste), because extremely acidic conditions can cause the irreversible denaturation of protein, leading to a lower stability of egg white foam.

Carotenoids have been reported to have poor stability during processing and storage [359,361]. On the contrary, carotenoids favor stability at a high pH and moderate heat, but are highly sensitive to oxygen, light, peroxide, acid, heat metal ions, and enzymes, which cause oxidation and isomerization [355,362].

To overcome this issue, encapsulation techniques have been evaluated to increase the stability of natural color compounds and protect these pigments [363–365]. Therefore, prior to applying anthocyanins and carotenoids as natural pigments in food or dietary supplement products, a stabilization process is required.

Using these natural compounds as alternative colorants not only contributes to promoting food quality but tends to increase health benefits due to their antioxidant, antimicrobial, anti-inflammatory, antihypertensive, or prebiotic activity, compared to synthetic coloring agents [62,363,366].

4.4.2. Active Food Packaging

Food packaging, another food-associated application, is used for protecting food from environmental contamination, further damage, and decaying during storage and transportation. In terms of active packaging, some additional functions have been designed to meet the requirements of food, preserving freshness, improving quality and safety, and extending the shelf life. This type of packaging typically works by absorbing or releasing a substrate that is associated with food property changes, including oxygen, water, ethylene, carbon dioxide, and antimicrobial and antioxidant agents [367,368].

Coffee wastes are rich in polysaccharides, which are considered as natural polymers, and antioxidants (phenolic compounds and caffeine), resulting in several beneficial properties, which make them a promising substance for incorporation into biopolymer matrices for active food packaging. To utilize coffee waste in food packaging, it can be applied in a raw form with or without modification, and as extracts into several biopolymers such as polylactic acid (PLA), polybutylene adipate-co-terephthalate (PBAT), starch, and carrageenan, among others.

Using raw coffee waste without modification has advantages, as it is simple to process, with a reinforcing ability. The coffee waste is dried, then milled into powder, and passed through a sieve before being incorporated into polymer matrices. For example, coffee silverskin (CS) powder has been applied in polylactic acid (PLA) and PLA/Polybutylene succinate (PBS) composites. The addition of CS could improve the elastic modulus, crystallinity, and biodegradability of the composites. However, at higher amounts of CS, a reduction in the tensile strength and a 7% decrease in the water contact angle was observed, indicating that CS slightly increases the hydrophilicity in the polymer matrix [369].

Similar results were observed when spent coffee grounds (SCGs) were used as a filler in polybutylene adipate-co-terephthalate (PBAT) composites. Compared to coffee silverskin, SCGs showed more hydrophilic behavior, with a higher 50% decrease in the tensile strength and 30% reduction in the water contact angle at the same amounts of coffee silverskin added. This indicates that SCGs significantly decrease the hydrophobicity of PBAT composites. To address this issue, the author added PEG as a plasticizer, which had a positive effect by improving mechanical properties and thermal stability. This improvement was attributed to the enhanced SCG dispersion and compatibility in PBAT composites [370].

As aforementioned, the compatibility of substances in the polymer matrix is a crucial factor for the improvement in mechanical properties of biocomposites. Several pretreatment processes have been proposed to improve interfacial adhesion between coffee waste filler and the polymer matrix, resulting in better mechanical properties. For example, the salinization of coffee silverskin before incorporation into polybutylene adipate-*co*-terephthalate (PBAT)/Poly-3-hydroxybutyrate-*co*-3-hydroxyvalerate (PHBV) composites exhibited enhanced interface compatibility between CS and biopolymers, resulting in a high tensile strength and ductility [371].

The torrefaction of spent coffee grounds (SCGs) at 250 °C and 270 °C) can improve SCG hydrophobicity by degrading water-attracting functional groups. During heating treatment, less stable compounds such as hemicellulose and some parts of cellulose were broken down, leading to reduced hydroxyl (-OH) and carbonyl (C=O) groups, which can enhance moisture resistance in the composites. The incorporation of torrefied SCGs into PBAT composites enhanced SCG dispersion in the PBAT matrix, leading to improved mechanical properties and thermal stability. Although the tensile strength of the composites increased with 10 wt% of torrefied SCGs, the values decreased with an increasing SCG content [372]. This result is associated with the interfacial adhesion between the fiber and polymer matrix [371]. At a higher fiber content, it can cause an agglomeration effect within the polymer matrix, leading to non-uniform dispersion and the discontinuity of the polymer matrix, resulting in a lower tensile strength [373,374].

The development of functional composites is another possible application of coffee wastes, as these materials contain antioxidants. Typically, coffee waste extracts have been applied as a source of phenolic compounds in a polymer matrix. The ethanol extraction of coffee parchment (CPm) yields significant amounts of phenolic compounds, including gallic, chlorogenic, *p*-coumaric, and sinapic acid, along with caffeine, which is a major component of the extracts. The addition of the CPm extracts into gellan gum films demonstrated antifungal properties, which are related to the presence of antioxidants and caffeine. The resultant films showed the significant inhibition of fungal growth against *Fusarium* sp., *C. gloeosporioides*, and *F. verticillioides*. In addition, the presence of CPm extracts increased film thickness, while decreasing the humidity and water activity of the film [79].

Coffee cascara extracts combined with gelatin and glycerol yield a dark yellowish edible film, with significant antioxidant activity that retained strong activity (>45%) even after tenfold dilution. The film showed good water vapor and oxygen barrier properties, which can be varied depending on the concentration of glycerol and gelatin content due to the hydrophilic properties of substances. Coating roasted hazelnuts with the cascara film effectively maintains their quality and potentially doubles their shelf life compared to uncoated hazelnuts, due to the film's efficient inhibition of lipid oxidation. However, the color and taste of the cascara-based coatings need to be developed to meet the consumer's satisfaction [375].

Phenolic extracts and cellulose fibers from coffee husk (CH) showed a positive effect on thermoplastic starch films, which provided significant antioxidant and antibacterial activity against *L. innocua* and *E. coli.* In addition to the active extracts, the water vapor permeability (WVP) and oxygen permeability (OP) were reduced by 30% and 50–85%, respectively, depending on the extract's concentration. CH fiber has no effect on barrier properties but improves mechanical properties [376]. Similarly to the incorporation of CH extracts and CH-derived carbon dots (CDs) into carboxymethyl cellulose (CMC), the resultant film exhibited high water and gas barrier properties, high antioxidant activity with 95.1% DPPH, and antibacterial efficiency against *L. monocytogenes* (51.2%) and *E. coli* (46.6%), which are bacteria that causes foodborne illness. Moreover, the developed films displayed a brownish hue, which significantly changes depending on the concentration of coffee husk incorporated. The films also exhibited the capability to block UV light (especially in a range of 200–400 nm). According to the findings, these formulations are suitable for active food packaging, which is confirmed by preservative testing of fresh-cut apples. Fresh-cut apples commonly have a short shelf life due to exposure to air, moisture, and microbial contamination; using the resultant films can slow down its browning and weight loss, and prevent bacterial growth, resulting in extending the shelf life up to 7 days at 4 °C [377]. The effect of phenolic-rich coffee extracts on UV light absorption was reported by [373,377].

SCG extracts exhibited greater UV light barrier properties when incorporated into whey protein edible films compared to the control sample, which has the capability to block UV light (at 280–350 nm). The extracts also resulted in increased antioxidant activity of the films up to 73.2%, which retains a high of 60.9% after 12 months of storage. However, the SCG extract tends to increase the water vapor permeability of the films, probably due to increasing hydrophilic characteristics from phenolic compounds in the extracts. This implies that the films have a lower moisture prevention ability when incorporated with SCG extracts [378].

On the contrary, incorporating oil extracted from SCGs resulted in a decreasing tensile strength and water content of the edible κ-carrageenan film, due to the hydrophobic property of SCG oil. The low water content of the edible film is an advantage for preserving food quality, because the high water content in the package or film can ingress into food and accelerate food deterioration [379].

Isolated cellulose nanocrystals (CNCs) fractionated from coffee husk demonstrate significantly improved properties of corn starch/PLA blend films, compared to cellulose fiber (CF). When combined with CNCs, the films exhibited a 148% increase in elastic modulus and a 45% improvement in tensile strength, resulting in significantly enhanced stiffness and strength. However, the effectiveness of CNCs as a reinforcement depended on the method of incorporation, with better results achieved when CNCs were directly applied at the starch phase. Moreover, the water vapor permeability (WVP) and oxygen permeability (OP) in CNC-reinforced films decreased by 28% and 42%, respectively, while the OP of CF-incorporated films increased by 40% [380]. All these findings are associated with the crystalline structure of the blended films, since the nanoscale of CNCs leads to good dispersion and strong interaction with the polymer matrix, forming stronger and more durable films. Simultaneously, a tortuous path within the matrix was promoted during the formation of a hydrogen-bonded structure and percolation network, which impeded the penetration of H_2O, O_2, and CO_2 through the films. This effect significantly improves the blended films' mechanical, thermal, and barrier properties [380].

In a similar study [381], it was discovered that the properties of PLA nanocomposite films significantly improved with the addition of cellulose nanocrystals (CNCs) extracted from coffee silverskin (CS). However, the tensile strength decreased at higher concentrations of CS-CNC (e.g., 5%). This reduction could be attributed to the agglomeration of CNCs, leading to poor dispersion and weaker interfacial bonding. As a result, the study recommended an optimal CS-CNC content of 3%.

In a related study, Yang et al. [377] observed a similar trend to a previous study on CMC-based composite films. They found that an optimal concentration of nano carbon dots (CDs) at 3% significantly enhanced the tensile strength and elasticity modulus, greatly improving the film's mechanical durability. The film's tensile strength increased by 130% compared to the pure CMC film but showed a tendency to decrease at higher CD concentrations.

Consequently, the addition of coffee waste to these polymers can enhance not only mechanical properties such as tensile strength and flexibility, but also functional properties including antioxidant and antimicrobial activities, and the barrier effect. These enhancements make them suitable for active food packaging. The specific reinforcement functions in final products can be determined by material selection and incorporating methods.

5. Navigating the Path to Commercialization: Current Status and Key Challenges

5.1. Present Commercialization Situation

According to the literature review, coffee wastes are generated in high amounts annually and have been commonly discarded in landfills [40,108]. Remarkably, there are several essential compounds found in coffee waste such as proteins, fibers, lipids, antioxidants, and bioactive compounds that have potential benefits in various applications such as agriculture, energy, food, pharmaceuticals, personal care products, and plastics, among others. Utilizing coffee waste into valuable products has gained significant attention in recent decades, since they are not only reducing environmental impacts and costs related to waste management but also creating new revenue streams for coffee farmers and coffee-related processors.

Integrating coffee waste into the food supply chain could help increase consumer demand for sustainable products, since consumers become more aware of their ecological footprint, and the appeal of upcycled, waste-reducing products increases. Coffee waste has been particularly appealing in the eco-conscious market, where both environmental and health benefits influence purchasing decisions.

Recently, several startups and established companies have been creating novel products, offering products ranging from coffee cultivation to products in the processing sector, such as fertilizers, biofuels, food ingredients, beverages, food preservation items, and packaging items, as shown in Table 5. Spent coffee grounds (SCGs) are more favorable for large-scale upcycling compared to other coffee wastes due to their high content of bioactive compounds that can be used as raw materials in various industries, as mentioned earlier. Additionally, SCGs are the biggest form of waste generated from coffee beverage production annually worldwide [382], particularly in developed countries that have advanced processing technologies and higher investment capabilities for upcycling [383,384].

For instance, Nestlé, the world's largest company in the coffee market [385], produces over 800,000 tons of coffee products annually [383]. Considering the substantial waste generated from coffee production, Nestlé has converted this waste into alternative energy, which aims to use SCGs as fuel in all Nescafé factories. This approach allows Nestlé to reduce waste and energy consumption by approximately 20% per ton of production, while also decreasing CO_2 emissions by more than 48,000 tons per year [386]. Similarly, small to mid-sized companies such as Bio-bean, Caffee Inc., Coffeefrom, Ecobean, Kaffee Bueno, and Kaffeeform have established strategies to transform coffee waste into valuable products. In the case of Bio-bean, spent coffee grounds collected from coffee-related businesses in the UK have been converted into products including coffee logs, biodiesel, and other coffee-based materials. However, the drying of SCGs leads to high production costs due to high energy requirements. Despite its innovative efforts, Bio-bean collapsed in 2022 due to a major equipment fire and financial challenges related to reconstruction costs and inflation [387–389].

In contrast, other types of coffee waste such as coffee pulp, coffee husk, and coffee parchment are not frequently upcycled on a large scale. These waste materials generally remain in coffee-producing countries, which are predominantly in developing regions with limited access to information, infrastructure, technologies, and investments. The lack of these resources leads to fewer innovations and scale-up opportunities for the utilization of coffee waste. Furthermore, using coffee waste in food products requires strict testing and regulation to ensure food safety, as coffee pulp and mucilage are more susceptible to microbial contamination, necessitating significant handling and treatment processes. Therefore, laboratory analyses and food safety guarantees are essential, which increases the difficulty of developing scalable and cost-effective solutions [390].

Collaboration with large companies in developed countries could help to overcome these challenges. For example, companies like Nestlé, Starbucks, and The Cherry Coffee co. are partnering with coffee farmers to upcycle coffee waste such as coffee pulp and husk, creating new valuable products, helping farmers manage coffee waste, and generating additional revenue streams.

Table 5. Current landscape of coffee waste commercialization.

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Agriculture	Substrate for growing mushroom	SCGs	PermaFungi	Brussels, Belgium	• Profit in 2023 of EUR 87,000 (USD 95,000). • Gross margin of EUR 483,000 (USD 530,000).	• Growing high-quality oyster mushrooms and chicory in SCGs combined with fruit peeling and straws. • Harvesting over 1000 kg of mushroom and chicory monthly. • Recycling over 61 tons of SCGs since 2014.	[391–394]
	Compost	Coffee silverskin (Chaff)	Imbibe coffee roasters	Dublin, Ireland	N/A	• A small Irish coffee roasting business that delivers wholesale roasted coffee to over 80 cafés and restaurants. • Providing high nitrogen content coffee chaff to improve soil health for free.	[395]
	Compost	SCGs	Nestle	Switzerland	FY2023 • Total organic growth reached 7.2%, a decrease of 1.5%. • The trading operating profit (TOP) margin was 15.6%. • Total sale revenue CHF 93 billion (USD 108 billion). • Nearly 27% of this revenue came from the Powdered and Liquid Beverages category including coffee, cocoa, and malt beverages [385,396].	• Using SCGs to make compost and fertilizers by local winemakers.	[397,398]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Agriculture	Compost	SCGs	Starbuck	USA	FY2023 • Total net revenue of USD 36 billion, increased by 12% compared to FY2022. • Cash and investments were USD 4.2 billion. • International operating margin of 16.4% [399].	• Creating the program "Grounds for Your Garden" to encourage customers to recycle their coffee grounds. • Providing free SCGs for interested customers to enrich soil and plants, as well as to repel common garden pests (ants and slugs). • Noting that SCGs are provided in some stores in the USA, Canada, and Thailand. • Aiming to reduce carbon, water, and waste by 50% by 2030.	[400,401]
Biofuels and Bioenergy	Biomass pellet, Fire log, Biodiesel	SCGs	Bio-bean	Cambridgeshire, UK	Total equity funding is approximately USD 7.3 M in 7 rounds (2014–2022).	• Collecting and processing approximately 50,000 tons of SCGs annually. • Reducing 6.8 tons of CO_2 emissions for every ton recycled. • Providing various products such as coffee logs, biomass pellets, biodiesel, and bio-based raw materials for other applications (bioplastic). • The processing involves sifting and drying SCGs before organic solvent extraction to remove any remnants of coffee odor and oil that are processed to biodiesel. • The solid remaining is filtered and pressed into pellets. • The company collapsed in March 2023 due to factory fire and monetary inflation. • The drying SCGs process requires high energy and bespoke machinery, leading to high production costs. • The company's assets were acquired by Envar Composting Ltd. (UK) in July 2023.	[387–389,402]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Biofuels and Bioenergy	Biomass (for steam boiler)	SCGs	Nestle	Australia	As mentioned above in Nestlé company.	• Generating energy from SCGs and sawdust, more than 113,274 gigajoules in 2020 (about 60% of the energy used by the factory). • Providing steam power for the Nescafé factory in Gympie, Queensland. • Reducing waste transportation and disposal. • Investigating the potential utilization of coffee production by-products as components for bio-based packaging materials.	[403]
	Biogas	SCGs	Nestle	Switzerland		• Partnership with Groupe E Greenwatt. • Generating biogas from fermented SCGs and providing electricity for the HENNIEZ bottling plant and the Swiss power grid. • Using 3800 tons of SCGs per year for biogas plants (accounted for 13% of total organic co-substrates).	[397,398]
	Biomass (for steam boiler)	SCGs	Nestle	Spain		• 45,000 tons of coffee grounds are generated annually at Nestlé's Girona factory. • Aiming to generate steam from 80% of the SCG production. • Annually, 125,000 tons of steam will be generated, representing a 25% reduction in natural gas consumption.	[404,405]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Biofuels and Bioenergy	Biomass (for steam boiler)	SCG	Veolia	Netherlands	FY2023 • Sale revenue of EUR 45 billion (USD 49 billion), growth of +9% at constant scope and exchange rates. • Increasing current net income up +14.9% to EUR 1.3 billion (USD 1.5 billion).	• Partnering with Douwe Egberts Master Blenders (DEMB) to develop reusing SCGs and reduce the company's consumption of natural gas for instant coffee production. • Veolia is a developing service company that helps find solutions for partners. • Suppling SCGs in a boiler to generate steam for a drying and combustion system. • Using 33,000 tons/year of SCG. • Reducing 70% of CO_2 emissions (equivalent to 14,000 tons of CO_2/year).	[406–409]
Biochemicals and Biomaterials	Biochemicals, Colorants	SCGs	Caffeinc.nl	Amsterdam, Netherlands	Funding USD 4.4 million (EUR 4 million) by Amsterdam Climate and Energy Fund (ACEF) in 2022.	• Creating a network of partners to collect SCGs in the Netherlands. • Saving 400 kg CO_2 with every ton of processed SCGs. • Providing raw materials for personal care, biomaterials, and coffee colorants for eco-friendly dyes with a capacity of 850 tons/year.	[410–412]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Biochemicals and Biomaterials	Polymers	SCGs	Coffeefrom	Italy	Coffeefrom started with bootstrapping and secured seed investment in 2023 through the Terra Next accelerator program.	• Developing SCG-incorporated thermoplastics. • Processing 600 tons of SCGs annually. • Mainly suitable for injection molding and 3D printing in various applications including automotive, tableware, and packaging products. • Collaborating for R&D with the Department of Chemistry "Giulio Natta" of the Politecnico di Milano and Fondazione Politecnico di Milano. • Filing patent application for "extraction of nanocellulose from the coffee ground and its functionalization" • Aiming to increase SCGs contained at least 50% in the developed materials. • Creating many sustainable materials including the following: • 100% biodegradable material from PLA and SCGs (10–20% in variable composition). • 100% recycled material from SCGs (10%) and recycled LDPE which is flexible, lightweight, and translucent properties. • High thermal resistance material combining from HDPE and SCGs (10%). • Collaborating with local social enterprises and creating a social economy impact.	[413,414]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Biochemicals and Biomaterials	Coffee oil, Antioxidant compounds, Polymers, and Lignin	SCGs	Ecobean	Poland	Total equity funding of USD 9.59 million (2022–2023).	• Aiming to introduce coffee-derived chemicals to the market with the lowest carbon footprint possible. • Expecting to process up to 1000 tons of coffee waste annually. • Developing a process for completely valorizing coffee waste into low-carbon footprint chemicals by collaborating with Warsaw University of Technology. • Generating sustainable chemicals including the following: • Coffee oil: rich in aroma and color, also abundant in fatty acids and antioxidants, such as caffeine, vitamin E, sterols, tocopherols, and diterpene. • Antioxidants: rich in polyphenols and flavonoids. • Polylactide (PLA): biodegradable and compostable polymer with properties similar to PET and PS. • Protein additives: powder combining of gypsum and lactic acid bacteria (rich in proteins and vitamins). • Lignin: constituted about 20–25% of dry coffee waste. • Inventing technology for fractionation of coffee oil extracts to be used as fuels' additive, collaborating with Prio liquid fuels distributor. • Building collaboration with other companies such as Starbucks, Delta, Vattenfall, and Econti to create a sustainable community.	[415,416]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/Project	City/Country	Financial Report	Finding	Ref.
	Eco-composite polymer to reusable cup	Coffee husk	Huskee	Australia	Raised more than USD 114,000 via Kickstarter campaign in 2018.	• Working with the coffee farmers in Yunnan, China. • Creating durable and reusable cups. • Preventing 600 tons of coffee husk waste diverted from landfill. • Selling around 2.67 million Huskee cups in 57 countries.	[417–420]
Biochemicals and Biomaterials	Biochemicals, Antioxidant compounds, Bio-oil, and Polymers	SCGs	Kaffe Bueno	Copenhagen, Denmark	Total equity funding of USD 8.13 million (2020–2024) with annual revenue of USD 28.7 K.	• The world's first coffee biorefinery. • Using sustainable technologies including green chemistry, biotech, and nanotechnology to produce valuable compounds from coffee waste. • Processing 500 tons of coffee grounds annually, with plans to expand to a capacity of 1500 tons soon. • Generating active and multifunctional ingredients for a wide range of industries, including the following: • KAFFOIL: coffee-derived lipophilic extracts for personal care and cosmetic formulations. • KLEANSTANT: bio-based anionic surfactant with cleansing, emulsifying, foaming, and antioxidative properties. • KAFFAGE: amphiphilic biopolymer extracted from defatted coffee, containing high polyphenolic groups, benefits for anti-aging and sun care. • KAFFIBRE: a natural exfoliating ingredient with a particle size of <150 μm, replacing plastic microbeads and contributing to a more gentle and scratch-free exfoliation. • KAFFAIR: active ingredient for hair and scalp which helps fortify cuticles and follicles, defending against hair loss (available test *in vitro*, now ongoing *in vivo*). • Ongoing development of upcycled coffee waste for animal health and agrochemical industry.	[421–424]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/Project	City/Country	Financial Report	Finding	Ref.
Biochemicals and Biomaterials	Polymer	SCGs	Kaffeeform	Berlin, Germany	Private financing of EUR 40,000 (USD 44,000) in 2016.	• Petroleum-based free materials. • Generating from coffee grounds and biopolymers. • For the processing, SCGs are collected from local cafés by bicycle, and then it is dried and processed with other plant-based polymers. • Transforming them into lightweight and durable materials that can be molded into various shapes and sizes.	[425,426]
	Polymer	Coffee Pulp + Silverskin	PTT	Thailand	• Total revenue THB 3.2 trillion (USD 95 billion). • Net profit margins of 4.94%. • Net profit growth of 22.87% in FY2023.	• Combining coffee chaff with other polymers to create bioplastics, commodity plastics, and recycled plastics. • Producing either non-biodegradable or biodegradable plastic. • Coffee chaff-derived bioplastic is 100% degradable with 2–5 years of lifespan depending on the thickness and biodegradability. • Reducing manufacturing costs, particularly for bioplastics. • These materials are safe for food contact.	[427–429]
Food ingredients and nutraceuticals	Beverage (called NESCAFÉ NATIV Cascara)	Coffee husk (Cascara)	Nestle	Australia	As mentioned above in Nestlé company.	• A carbonated soft drink based on organic cascara with free from preservatives, artificial colors, and flavors. • Infusing sun-dried cascara with water and native Australian botanical flavors, obtaining unique flavors with floral and fruity. • Containing caffeine content as the same as one cup of coffee. • Reducing waste from coffee farming and providing farmers with a new revenue stream.	[430,431]

Table 5. *Cont.*

Main Application	Application Type	Coffee Waste	Company/ Project	City/ Country	Financial Report	Finding	Ref.
Food ingredients and nutraceuticals	Beverages (called Cascara Latte)	Coffee husk (Cascara)	Starbuck	USA	As mentioned above in Starbucks company.	• Coffee latte with cascara syrup and cascara sprinkle (first introduced in 2017). • Making a syrup by boiling coffee husk with water and sugar. • Mix coffee husk extracts with cane sugar for a cascara sprinkle. • It can be used in various food products including in bakery and beverages.	[432,433]
	Beverage (called Tabifruit)	Coffee husk	Supracafe Ltd.	Spain	The total amount of the operation was EUR 600,000 (USD 658,000) in 2017.	• Producing 365,000 kg of coffee annually, accounting for 50 million cups of Arabica coffee. • Creating infusion tea bags from coffee husk combined with other fruits (such as passion fruit, orange, and berries) to make flavor and aroma varieties of the beverage. • Containing high antioxidant properties.	[434–436]
	Functional ingredients for food products	Coffee cherry pulp	The Coffee Cherry Co.	Seattle, USA	N/A	• Producing highly nutritious coffee cherry powder (11.4 g of protein, 51 g of fiber, 530 mg of caffeine per 100 g of coffee cherry powder). • Creating new jobs at coffee processing mills, particularly for women in coffee-growing communities. • Decreasing CO_2 emissions by reducing fruit decaying in the field. • Creating new revenue for farmers.	[437]

5.2. Challenges and Constraints

To minimize waste and balance ecological, social, and financial sustainability in the coffee value chain, several challenges and constraints must be faced for successful industrial applications on both the producing and consuming sides. On the production side, technical barriers present significant challenges to the transition towards a circular economy, indicating a lack of necessary technologies to implement circular economy practices [267,438]. Many of the valorization technologies remain at the laboratory stage. Scaling up from the bench scale to the pilot scale and ultimately to the industrial scale is very crucial and requires significant investment and effort. Additionally, there is a need for innovative, cost-effective technologies that can more efficiently extract specific components from coffee waste while reducing the overall costs of product development [439]. Knowledge mobilization and technology transfer from leading companies, typically based in developed countries, to local firms in agricultural nations rich in upstream waste resources, will significantly accelerate the international utilization of coffee waste. Economic feasibility is also a key element to evaluate the profitability of the process. However, there is relatively limited research focused on economic investments. For instance, the use of coffee husk waste to produce animal feed and cascara tea was investigated, showing the potential for these products [440]. Additionally, another research studied biodiesel production from spent coffee grounds (SCGs), comparing SCGs with eight other common oil feedstocks. They found that producing biodiesel from SCGs required the highest initial capital investment (USD 15,120,000), but the lowest operational cost (USD 1,913,250 per year) compared to other feedstocks. SCG biodiesel had the lowest operating cost at USD 0.24/kg, while other raw materials were significantly more expensive, including peanut oil (USD 1.78), tallow (USD 1.35), rapeseed (USD 1.19), coconut oil (USD 1.09), soybean oil (USD 1.06), sunflower oil (USD 0.99), palm oil (USD 0.87), and Jatropha oil (USD 0.77) [441]. Recent research also highlights the use of coffee grounds in biorefinery processes. One study [92] explored the supercritical fluid extraction (SFE) of SCGs for biorefinery. The process involved operating 24 h a day, 330 days a year, with three 1 m^3 extraction beds, and a 2 h extraction time at 300 bar and 50 °C, using 30 kg of CO_2 per kilogram of SCGs per hour. This setup resulted in an optimal production yield of 454 tons of SCG oil per year, costing EUR 2.4 million (including labor, utilities, waste treatment, and raw materials), with a net income of EUR 56.6 million. For producing bioethanol using multiple coffee crop residues (stems, pulp, and mucilage), its production cost is USD 0.504–0.515 per liter for large, medium, and small capacity. The CO_2 emissions were slightly affected by the scale of the plant [442]. Regardless of how environmentally friendly a method may be, it will not succeed in industrial production if it fails to provide sufficient economic benefits to cover all costs and generate income. This perspective aligns with findings from various studies emphasizing the importance of economic feasibility in the adoption of biorefinery technologies [267,443,444]. Therefore, a holistic viewpoint of technological–economic–environmental evaluations, including techno-economic analysis (TEA) and life cycle assessment (LCA), along with the inclusion of life cycle emission costs, is necessary for decision-making.

The heterogeneity of wastes from various sources, influenced by coffee type, brewing method, and processing conditions, complicates the standardization and optimization of extraction processes [445]. This variability can lead to inconsistencies in yield, quality, and consistency of the extracted compounds, making it challenging to develop universal extraction methods suitable for all types of coffee waste [446]. Logistical difficulties, particularly the collection of SCGs from coffee shops and households, also pose significant obstacles [445]. The viable pathway towards circular bioeconomy is significantly influenced by logistical challenges associated with the collection and transportation of raw materials [267]. Due to the relatively small volume of coffee grounds generated from coffee shops, these establishments often lack the time and human resources necessary to manage recycling efforts independently [447,448]. Community engagement would be essential for advancing the circular economy of coffee waste, involving various stakeholders, particularly the agricultural stakeholder network, including, e.g., farmers, local communities, and agricultural cooperatives for upstream coffee waste, and the brewing stakeholder network, comprising roasters and coffee shops, as well as waste management services, to support effective collection, repurposing, and upcycling initiatives. Laws and regulations are addressed in the literature on challenges to circular economy [438,449,450]. Regulatory drivers appear to be the most prevalent type of circular economy drivers [451]. Regulatory interventions ensure safety in circular economy innovation. So, regulations should be tailored to fit the specific needs and capabilities of different players in the industry [452].

On the consuming side, consumer interest and awareness of circular economy products, especially those derived from coffee waste, are growing, driven by sustainability trends and eco-consciousness. Consumers play a pivotal role in the loop of the circular economy. Their purchasing decisions, preferences, and behaviors directly influence the demand for sustainable products and the success of circular practices [453,454]. Consumers are generally willing to engage with circular economy products but may be obstructed by practical barriers such as insufficient product information and market availability. Price, satisfaction, and the quality of products (including durability and repairability in cases such as container and furniture applications) remain key factors influencing purchasing decisions [438,453,455]. Consumer behavior: The role of consumers and users in the circular economy is powerful, as it can drive shifts in purchasing habits and influence how products are utilized [456]. Circular behaviors extend beyond individual products and are deeply integrated into consumers' lifestyles. As consumers actively engage in initiatives supporting the circular economy, factors such as food supply security, convenience, and social pressure to recycle emerge as powerful motivators driving their participation [456,457].

6. Conclusions

The availability and variety of coffee waste—including pulp, husk, mucilage, and parchment from the upstream process of deriving green beans, silverskin (coffee chaff), and spent coffee grounds from the downstream processes of roasting and brewing—position these materials as promising raw inputs for biorefineries aimed at a bio-circular economy. Numerous researchers are exploring the various components of these by-products, and in recent years, several viable options for their utilization have emerged, which were discussed in this review. The authors consolidated the research and development on coffee waste valorization into four categories: (1) agriculture, (2) biofuels and bioenergy, (3) biochemicals and biomaterials, and (4) food ingredients and nutraceuticals.

Despite the extensive research conducted, the application of coffee waste remains largely limited to an industrial scale. This review summarized the current commercialization landscape worldwide. Among these materials, spent coffee grounds (SCGs) are the most favorable for large-scale upcycling, followed by husk and silverskin. SCGs are commercially upcycled for applications across almost all categories, including agriculture (as composting materials), biofuels (such as biodiesel and biogas), biomass for steam boilers, and biochemicals and biomaterials (including coffee oil, antioxidant compounds, polymers, and colorants). However, in the food ingredients and nutraceuticals category, coffee husk predominates. The challenges and constraints involved in navigating the path to commercialization were also discussed.

Author Contributions: Conceptualization, K.P. and W.K.; writing—original draft preparation, K.P. and P.W.; writing—review and editing, W.K., A.P., K.K., V.N.-V., S.A. (Sushil Adhikari), P.C., T.K. and S.A. (Suttichai Assabumrungrat); supervision, W.K.; funding acquisition, W.K. and S.A. (Suttichai Assabumrungrat). All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Silpakorn University under the Postdoctoral fellowship program, the 2020–2021 Global Challenges Research Fund (GCRF) block grant funded by the UK Research and Innovation (Aston University), The Office of the Permanent Secretary of the Ministry of Higher Education, Science, Research and Innovation (Reinventing University Grant), and the IROAST Visiting Professor and Visiting Associate Professor invitation program, and Biosystems Engineering Department at Auburn University under the Research Visiting Scholar program.

Acknowledgments: This research was supported by Silpakorn University under the Postdoctoral fellowship program, the 2020–2021 Global Challenges Research Fund (GCRF) block grant funded by the UK Research and Innovation (Aston University), The Office of the Permanent Secretary of the Ministry of Higher Education, Science, Research and Innovation (Reinventing University Grant), and the IROAST Visiting Professor and Visiting Associate Professor invitation program, and Biosystems Engineering Department at Auburn University under the Research Visiting Scholar program.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kazi, F.K.; Fortman, J.A.; Anex, R.P.; Hsu, D.D.; Aden, A.; Dutta, A.; Kothandaraman, G. Techno-Economic Comparison of Process Technologies for Biochemical Ethanol Production from Corn Stover. *Fuel* **2010**, *89*, S20–S28. [CrossRef]
2. Zhang, Y.; Dubé, M.A.; McLean, D.D.; Kates, M. Biodiesel Production from Waste Cooking Oil: 2. Economic Assessment and Sensitivity Analysis. *Bioresour. Technol.* **2003**, *90*, 229–240. [CrossRef] [PubMed]
3. Cao, F.; Chen, Y.; Zhai, F.; Li, J.; Wang, J.; Wang, X.; Wang, S.; Zhu, W. Biodiesel Production from High Acid Value Waste Frying Oil Catalyzed by Superacid Heteropolyacid. *Biotechnol. Bioeng.* **2008**, *101*, 93–100. [PubMed]
4. Kaza, S.; Yao, L.C.; Bhada-Tata, P.; Van Woerden, F. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*; Urban Development: Washington, DC, USA; World Bank: Washington, DC, USA, 2018; ISBN 978-1-4648-1329-0.
5. Ravindran, R.; Jaiswal, A.K. Exploitation of Food Industry Waste for High-Value Products. *Trends Biotechnol.* **2016**, *34*, 58–69. [CrossRef]
6. Osorio-Arias, J.; Delgado-Arias, S.; Duarte-Correa, Y.; Largo-Ávila, E.; Montaño, D.; Simpson, R.; Vega-Castro, O. New Powder Material Obtained from Spent Coffee Ground and Whey Protein; Thermal and Morphological Analysis. *Mater. Chem. Phys.* **2020**, *240*, 122171. [CrossRef]
7. Sisti, L.; Celli, A.; Totaro, G.; Cinelli, P.; Signori, F.; Lazzeri, A.; Bikaki, M.; Corvini, P.; Ferri, M.; Tassoni, A.; et al. Monomers, Materials and Energy from Coffee By-Products: A Review. *Sustainability* **2021**, *13*, 6921. [CrossRef]
8. ICO. *Coffee Market Report—June 2021*; International Coffee Organization (ICO): London, UK, 2021.
9. ICO. *Annual Review Coffee Year 2021/2022*; International Coffee Organization (ICO): London, UK, 2022; Volume 95.
10. ICO. *Coffee Report and Outlook*; International Coffee Organization (ICO): London, UK, 2023; Volume 1.
11. Toschi, T.G.; Cardenia, V.; Bonaga, G.; Mandrioli, M.; Rodriguez-Estrada, M.T. Coffee Silverskin: Characterization, Possible Uses, and Safety Aspects. *J. Agric. Food Chem.* **2014**, *62*, 10836–10844. [CrossRef]
12. Murthy, P.S.; Madhava Naidu, M. Sustainable Management of Coffee Industry By-Products and Value Addition—A Review. *Resour. Conserv. Recycl.* **2012**, *66*, 45–58. [CrossRef]
13. Mata, T.M.; Martins, A.A.; Caetano, N.S. Bio-Refinery Approach for Spent Coffee Grounds Valorization. *Bioresour. Technol.* **2018**, *247*, 1077–1084. [CrossRef]
14. Navya, P.N.; Pushpa, S.M. Production, Statistical Optimization and Application of Endoglucanase from Rhizopus Stolonifer Utilizing Coffee Husk. *Bioprocess Biosyst. Eng.* **2013**, *36*, 1115–1123. [CrossRef]
15. Arpi, N.; Muzaifa, M.; Sulaiman, M.I.; Andini, R.; Kesuma, S.I. Chemical Characteristics of Cascara, Coffee Cherry Tea, Made of Various Coffee Pulp Treatments. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *709*, 012030. [CrossRef]
16. Martinez-Saez, N.; García, A.T.; Pérez, I.D.; Rebollo-Hernanz, M.; Mesías, M.; Morales, F.J.; Martín-Cabrejas, M.A.; del Castillo, M.D. Use of Spent Coffee Grounds as Food Ingredient in Bakery Products. *Food Chem.* **2017**, *216*, 114–122. [CrossRef] [PubMed]
17. Martinez-Saez, N.; del Castillo, M.D. Development of Sustainable Novel Foods and Beverages Based on Coffee By-Products for Chronic Diseases. In *Encyclopedia of Food Security and Sustainability*; Ferranti, P., Berry, E.M., Anderson, J.R., Eds.; Elsevier: Oxford, UK, 2019; pp. 307–315, ISBN 978-0-12-812688-2.
18. Bessada, S.; Alves, R.C.; Oliveira, M.P.P. Coffee Silverskin: A Review on Potential Cosmetic Applications. *Cosmetics* **2018**, *5*, 5. [CrossRef]
19. Ribeiro, H.; Marto, J.; Raposo, S.; Agapito, M.; Isaac, V.; Chiari, B.G.; Lisboa, P.F.; Paiva, A.; Barreiros, S.; Simões, P. From Coffee Industry Waste Materials to Skin-friendly Products with Improved Skin Fat Levels. *Eur. J. Lipid Sci. Technol.* **2013**, *115*, 330–336. [CrossRef]
20. Vázquez-Sánchez, K.; Martinez-Saez, N.; Rebollo-Hernanz, M.; del Castillo, M.D.; Gaytán-Martínez, M.; Campos-Vega, R. In Vitro Health Promoting Properties of Antioxidant Dietary Fiber Extracted from Spent Coffee (*Coffee arabica* L.) Grounds. *Food Chem.* **2018**, *261*, 253–259. [CrossRef]
21. Fernandez-Gomez, B.; Lezama, A.; Amigo-Benavent, M.; Ullate, M.; Herrero, M.; Martín, M.Á.; Mesa, M.D.; del Castillo, M.D. Insights on the Health Benefits of the Bioactive Compounds of Coffee Silverskin Extract. *J. Funct. Foods* **2016**, *25*, 197–207. [CrossRef]
22. Tarigan, J.B.; Ginting, M.; Mubarokah, S.N.; Sebayang, F.; Karo-karo, J.; Nguyen, T.T.; Ginting, J.; Sitepu, E.K. Direct Biodiesel Production from Wet Spent Coffee Grounds. *RSC Adv.* **2019**, *9*, 35109–35116. [CrossRef]
23. Orrego, D.; Zapata-Zapata, A.D.; Kim, D. Ethanol Production from Coffee Mucilage Fermentation by *S. cerevisiae* Immobilized in Calcium-Alginate Beads. *Bioresour. Technol. Rep.* **2018**, *3*, 200–204. [CrossRef]

24. Andrade, T.S.; Vakros, J.; Mantzavinos, D.; Lianos, P. Biochar Obtained by Carbonization of Spent Coffee Grounds and Its Application in the Construction of an Energy Storage Device. *Chem. Eng. J. Adv.* **2020**, *4*, 100061. [CrossRef]
25. Quyen, V.T.; Pham, T.-H.; Kim, J.; Thanh, D.M.; Thang, P.Q.; Van Le, Q.; Jung, S.H.; Kim, T. Biosorbent Derived from Coffee Husk for Efficient Removal of Toxic Heavy Metals from Wastewater. *Chemosphere* **2021**, *284*, 131312. [CrossRef]
26. Torres Castillo, N.E.; Ochoa Sierra, J.S.; Oyervides-Muñoz, M.A.; Sosa-Hernández, J.E.; Iqbal, H.M.N.; Parra-Saldívar, R.; Melchor-Martínez, E.M. Exploring the Potential of Coffee Husk as Caffeine Bio-Adsorbent—A Mini-Review. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100070. [CrossRef]
27. Huang, L.; Mu, B.; Yi, X.; Li, S.; Wang, Q. Sustainable Use of Coffee Husks For Reinforcing Polyethylene Composites. *J. Polym. Environ.* **2018**, *26*, 48–58. [CrossRef]
28. Nguyen, T.A.; Nguyen, Q.T. Hybrid Biocomposites Based on Used Coffee Grounds and Epoxy Resin: Mechanical Properties and Fire Resistance. *Int. J. Chem. Eng.* **2021**, *2021*, 1919344. [CrossRef]
29. Dericiler, K.; Kocanali, A.; Buldu-Akturk, M.; Erdem, E.; Saner Okan, B. Upcycling Process of Transforming Waste Coffee into Spherical Graphene by Flash Pyrolysis for Sustainable Supercapacitor Manufacturing with Virgin Graphene Electrodes and Its Comparative Life Cycle Assessment. *Biomass Convers. Biorefinery* **2022**, *14*, 1073–1088. [CrossRef]
30. Hong, K.H. Effects of Tannin Mordanting on Coloring and Functionalities of Wool Fabrics Dyed with Spent Coffee Grounds. *Fash. Text.* **2018**, *5*, 33. [CrossRef]
31. Franca, A.S.; Oliveira, L.S. Coffee Processing Solid Wastes: Current Uses and Future Perspectives. In *Agricultural Wastes*; Nova: New York, NY, USA, 2009; pp. 155–190, ISBN 9781607413059.
32. Massaya, J.; Prates Pereira, A.; Mills-Lamptey, B.; Benjamin, J.; Chuck, C.J. Conceptualization of a Spent Coffee Grounds Biorefinery: A Review of Existing Valorisation Approaches. *Food Bioprod. Process.* **2019**, *118*, 149–166. [CrossRef]
33. Janissen, B.; Huynh, T. Chemical Composition and Value-Adding Applications of Coffee Industry by-Products: A Review. *Resour. Conserv. Recycl.* **2018**, *128*, 110–117. [CrossRef]
34. Klingel, T.; Kremer, J.I.; Gottstein, V.; Rajcic de Rezende, T.; Schwarz, S.; Lachenmeier, D.W. A Review of Coffee By-Products Including Leaf, Flower, Cherry, Husk, Silver Skin, and Spent Grounds as Novel Foods within the European Union. *Foods* **2020**, *9*, 665. [CrossRef]
35. Iriondo-DeHond, A.; Iriondo-DeHond, M.; del Castillo, M.D. Applications of Compounds from Coffee Processing By-Products. *Biomolecules* **2020**, *10*, 1219. [CrossRef]
36. Esquivel, P.; Jiménez, V.M. Functional Properties of Coffee and Coffee By-Products. *Food Res. Int.* **2012**, *46*, 488–495. [CrossRef]
37. Pandey, A.; Soccol, C.R.; Nigam, P.; Brand, D.; Mohan, R.; Roussos, S. Biotechnological Potential of Coffee Pulp and Coffee Husk for Bioprocesses. *Biochem. Eng. J.* **2000**, *6*, 153–162. [CrossRef] [PubMed]
38. de Melo Pereira, G.V.; de Carvalho Neto, D.P.; Magalhães Júnior, A.I.; do Prado, F.G.; Pagnoncelli, M.G.B.; Karp, S.G.; Soccol, C.R. Chemical Composition and Health Properties of Coffee and Coffee By-Products. In *Advances in Food and Nutrition Research*; Toldrá, F., Ed.; Academic Press: Cambridge, MA, USA, 2020; Volume 91, pp. 65–96, ISBN 1043-4526.
39. Campos, R.C.; Pinto, V.R.A.; Melo, L.F.; da Rocha, S.J.S.S.; Coimbra, J.S. New Sustainable Perspectives for "Coffee Wastewater" and Other by-Products: A Critical Review. *Future Foods* **2021**, *4*, 100058. [CrossRef]
40. Arya, S.S.; Venkatram, R.; More, P.R.; Vijayan, P. The Wastes of Coffee Bean Processing for Utilization in Food: A Review. *J. Food Sci. Technol.* **2022**, *59*, 429–444. [CrossRef] [PubMed]
41. Echeverria, M.C.; Nuti, M. Valorisation of the Residues of Coffee Agro-Industry: Perspectives and Limitations. *Open Waste Manag. J.* **2017**, *10*, 13–22. [CrossRef]
42. Orrego, D.; Zapata-Zapata, A.; Kim, D. Optimization and Scale-Up of Coffee Mucilage Fermentation for Ethanol Production. *Energies* **2018**, *11*, 786. [CrossRef]
43. Heeger, A.; Kosińska-Cagnazzo, A.; Cantergiani, E.; Andlauer, W. Bioactives of Coffee Cherry Pulp and Its Utilisation for Production of Cascara Beverage. *Food Chem.* **2017**, *221*, 969–975. [CrossRef]
44. Torres-Valenzuela, L.S.; Serna-Jiménez, J.A.; Martínez, K. Coffee By-Products: Nowadays and Perspectives. In *Coffee—Production and Research*; Castanheira, D.T., Ed.; IntechOpen: Rijeka, Croatia, 2020.
45. Mirón-Mérida, V.A.; Barragán-Huerta, B.E.; Gutiérrez-Macías, P. Coffee Waste: A Source of Valuable Technologies for Sustainable Development. In *Valorization of Agri-Food Wastes and By-Products*; Bhat, R., Ed.; Academic Press: Cambridge, MA, USA, 2021; pp. 173–198, ISBN 978-0-12-824044-1.
46. Hejna, A. Potential Applications of By-Products from the Coffee Industry in Polymer Technology—Current State and Perspectives. *Waste Manag.* **2021**, *121*, 296–330. [CrossRef]
47. Mussatto, S.I.; Machado, E.M.S.; Martins, S.; Teixeira, J.A. Production, Composition, and Application of Coffee and Its Industrial Residues. *Food Bioprocess Technol.* **2011**, *4*, 661–672. [CrossRef]
48. SCA. The Impact of Mucilage Removers on Coffee Sustainability and Quality. Available online: https://sca.coffee/sca-news/25-magazine/issue-6/english/water-saving-demucilagers (accessed on 14 August 2023).
49. Neu, A.K.; Pleissner, D.; Mehlmann, K.; Schneider, R.; Puerta-Quintero, G.I.; Venus, J. Fermentative Utilization of Coffee Mucilage Using Bacillus Coagulans and Investigation of Down-Stream Processing of Fermentation Broth for Optically Pure l(+)-Lactic Acid Production. *Bioresour. Technol.* **2016**, *211*, 398–405. [CrossRef]

50. Valdespino-León, M.; Calderón-Domínguez, G.; De La Paz Salgado-Cruz, M.; Rentería-Ortega, M.; Farrera-Rebollo, R.R.; Morales-Sánchez, E.; Gaona-Sánchez, V.A.; Terrazas-Valencia, F. Biodegradable Electrosprayed Pectin Films: An Alternative to Valorize Coffee Mucilage. *Waste Biomass Valorization* **2021**, *12*, 2477–2494. [CrossRef]
51. Pardo, L.M.F.; Castillo, N.V.; Durán, Y.M.V.; Rosero, J.A.J.; Lozano Moreno, J.A. Comprehensive Analysis of Ethanol Production from Coffee Mucilage under Sustainability Indicators. *Chem. Eng. Process. Process Intensif.* **2022**, *182*, 109183. [CrossRef]
52. Cárdenas, E.L.M.; Zapata-Zapata, A.D.; Kim, D. Hydrogen Production from Coffee Mucilage in Dark Fermentation with Organic Wastes. *Energies* **2018**, *12*, 71. [CrossRef]
53. Hernández, M.A.; Rodríguez Susa, M.; Andres, Y. Use of Coffee Mucilage as a New Substrate for Hydrogen Production in Anaerobic Co-Digestion with Swine Manure. *Bioresour. Technol.* **2014**, *168*, 112–118. [CrossRef] [PubMed]
54. KC, Y.; Subba, R.; Shiwakoti, L.D.; Dhungana, P.K.; Bajagain, R.; Chaudhary, D.K.; Pant, B.R.; Bajgai, T.R.; Lamichhane, J.; Timilsina, S.; et al. Utilizing Coffee Pulp and Mucilage for Producing Alcohol-Based Beverage. *Fermentation* **2021**, *7*, 53. [CrossRef]
55. Sierra-López, L.D.; Hernandez-Tenorio, F.; Marín-Palacio, L.D.; Giraldo-Estrada, C. Coffee Mucilage Clarification: A Promising Raw Material for the Food Industry. *Food Humanit.* **2023**, *1*, 689–695. [CrossRef]
56. Cantele, C.; Tedesco, M.; Ghirardello, D.; Zeppa, G.; Bertolino, M. Coffee Silverskin as a Functional Ingredient in Vegan Biscuits: Physicochemical and Sensory Properties and In Vitro Bioaccessibility of Bioactive Compounds. *Foods* **2022**, *11*, 717. [CrossRef]
57. Narita, Y.; Inouye, K. Review on Utilization and Composition of Coffee Silverskin. *Food Res. Int.* **2014**, *61*, 16–22.
58. Behrouzian, F.; Amini, A.M.; Alghooneh, A.; Razavi, S.M.A. Characterization of Dietary Fiber from Coffee Silverskin: An Optimization Study Using Response Surface Methodology. *Bioact. Carbohydr. Diet. Fibre* **2016**, *8*, 58–64. [CrossRef]
59. Ballesteros, L.F.; Teixeira, J.A.; Mussatto, S.I. Chemical, Functional, and Structural Properties of Spent Coffee Grounds and Coffee Silverskin. *Food Bioprocess Technol.* **2014**, *7*, 3493–3503. [CrossRef]
60. Rodríguez-Durán, L.V.; Favela-Torres, E.; Aguilar, C.N.; Saucedo-Castañeda, G. Coffee Pulp as Potential Source of Phenolic Bioactive Compounds. In *Handbook of Research on Food Science and Technology: Volume 1: Food Technology and Chemistry*; Chavez-Gonzalez, M., Buenrostro-Figueroa, J.J., Aguilar, C.N., Eds.; Apple Academic Press: Palm Bay, FL, USA, 2018; p. 24, ISBN 9780429487859.
61. Manasa, V.; Padmanabhan, A.; Anu Appaiah, K.A. Utilization of Coffee Pulp Waste for Rapid Recovery of Pectin and Polyphenols for Sustainable Material Recycle. *Waste Manag.* **2021**, *120*, 762–771. [CrossRef]
62. Bondam, A.F.; Diolinda da Silveira, D.; Pozzada dos Santos, J.; Hoffmann, J.F. Phenolic Compounds from Coffee By-Products: Extraction and Application in the Food and Pharmaceutical Industries. *Trends Food Sci. Technol.* **2022**, *123*, 172–186. [CrossRef]
63. Machado, M.; Espírito Santo, L.; Machado, S.; Lobo, J.C.; Costa, A.S.G.; Oliveira, M.B.P.P.; Ferreira, H.; Alves, R.C. Bioactive Potential and Chemical Composition of Coffee By-Products: From Pulp to Silverskin. *Foods* **2023**, *12*, 2354. [CrossRef] [PubMed]
64. Esquivel, P.; Viñas, M.; Steingass, C.B.; Gruschwitz, M.; Guevara, E.; Carle, R.; Schweiggert, R.M.; Jiménez, V.M. Coffee (*Coffea arabica* L.) by-Products as a Source of Carotenoids and Phenolic Compounds—Evaluation of Varieties With Different Peel Color. *Front. Sustain. Food Syst.* **2020**, *4*, 590597. [CrossRef]
65. Gemechu, F.G. Embracing Nutritional Qualities, Biological Activities and Technological Properties of Coffee Byproducts in Functional Food Formulation. *Trends Food Sci. Technol.* **2020**, *104*, 235–261. [CrossRef]
66. Strieder, M.M.; Velásquez Piñas, J.A.; Ampese, L.C.; Costa, J.M.; Carneiro, T.F.; Rostagno, M.A. Coffee Biorefinery: The Main Trends Associated with Recovering Valuable Compounds from Solid Coffee Residues. *J. Clean. Prod.* **2023**, *415*, 137716. [CrossRef]
67. Myo, H.; Khat-udomkiri, N. Optimization of Ultrasound-Assisted Extraction of Bioactive Compounds from Coffee Pulp Using Propylene Glycol as a Solvent and Their Antioxidant Activities. *Ultrason. Sonochem.* **2022**, *89*, 106127. [CrossRef]
68. dos Santos, É.M.; de Macedo, L.M.; Ataide, J.A.; Delafiori, J.; de Oliveira Guarnieri, J.P.; Rosa, P.C.P.; Ruiz, A.L.T.G.; Lancellotti, M.; Jozala, A.F.; Catharino, R.R.; et al. Antioxidant, Antimicrobial and Healing Properties of an Extract from Coffee Pulp for the Development of a Phytocosmetic. *Sci. Rep.* **2024**, *14*, 4453. [CrossRef]
69. Mullen, W.; Nemzer, B.; Stalmach, A.; Ali, S.; Combet, E. Polyphenolic and Hydroxycinnamate Contents of Whole Coffee Fruits from China, India, and Mexico. *J. Agric. Food Chem.* **2013**, *61*, 5298–5309. [CrossRef]
70. das Neves, J.V.G.; Borges, M.V.; Silva, D.d.M.; Leite, C.X.d.S.; Santos, M.R.C.; de Lima, N.G.B.; Lannes, S.C.d.S.; da Silva, M.V. Total Phenolic Content and Primary Antioxidant Capacity of Aqueous Extracts of Coffee Husk: Chemical Evaluation and Beverage Development. *Food Sci. Technol.* **2019**, *39*, 348–353. [CrossRef]
71. Silva, M.d.O.; Honfoga, J.N.B.; de Medeiros, L.L.; Madruga, M.S.; Bezerra, T.K.A. Obtaining Bioactive Compounds from the Coffee Husk (*Coffea arabica* L.) Using Different Extraction Methods. *Molecules* **2020**, *26*, 46. [CrossRef]
72. Cangussu, L.B.; Melo, J.C.; Franca, A.S.; Oliveira, L.S. Chemical Characterization of Coffee Husks, a by-Product of *Coffea arabica* Production. *Foods* **2021**, *10*, 3125. [CrossRef] [PubMed]
73. Rebollo-Hernanz, M.; Aguilera, Y.; Gil-Ramírez, A.; Benítez, V.; Cañas, S.; Braojos, C.; Martin-Cabrejas, M.A. Biorefinery and Stepwise Strategies for Valorizing Coffee By-Products as Bioactive Food Ingredients and Nutraceuticals. *Appl. Sci.* **2023**, *13*, 8326. [CrossRef]
74. Alves, R.C.; Rodrigues, F.; Antónia Nunes, M.; Vinha, A.F.; Oliveira, M.B.P.P. State of the Art in Coffee Processing By-Products. In *Handbook of Coffee Processing By-Products*; Galanakis, C.M., Ed.; Academic Press: Cambridge, MA, USA, 2017; pp. 1–26, ISBN 978-0-12-811290-8.
75. Iriondo-DeHond, A.; Aparicio García, N.; Fernandez-Gomez, B.; Guisantes-Batan, E.; Velázquez Escobar, F.; Blanch, G.P.; San Andres, M.I.; Sanchez-Fortun, S.; del Castillo, M.D. Validation of Coffee By-Products as Novel Food Ingredients. *Innov. Food Sci. Emerg. Technol.* **2019**, *51*, 194–204. [CrossRef]

76. Bresciani, L.; Calani, L.; Bruni, R.; Brighenti, F.; Del Rio, D. Phenolic Composition, Caffeine Content and Antioxidant Capacity of Coffee Silverskin. *Food Res. Int.* **2014**, *61*, 196–201. [CrossRef]
77. Castaldo, L.; Graziani, G.; Gaspari, A.; Izzo, L.; Luz, C.; Mañes, J.; Rubino, M.; Meca, G.; Ritieni, A. Study of the Chemical Components, Bioactivity and Antifungal Properties of the Coffee Husk. *J. Food Res.* **2018**, *7*, 43. [CrossRef]
78. Konstantinidis, N.; Franke, H.; Schwarz, S.; Lachenmeier, D.W. Risk Assessment of Trigonelline in Coffee and Coffee By-Products. *Molecules* **2023**, *28*, 3460. [CrossRef]
79. Mirón-Mérida, V.A.; Yáñez-Fernández, J.; Montañez-Barragán, B.; Barragán Huerta, B.E. Valorization of Coffee Parchment Waste (*Coffea arabica*) as a Source of Caffeine and Phenolic Compounds in Antifungal Gellan Gum Films. *LWT* **2019**, *101*, 167–174. [CrossRef]
80. Aguilera, Y.; Rebollo-Hernanz, M.; Cañas, S.; Taladrid, D.; Martín-Cabrejas, M.A. Response Surface Methodology to Optimise the Heat-Assisted Aqueous Extraction of Phenolic Compounds from Coffee Parchment and Their Comprehensive Analysis. *Food Funct.* **2019**, *10*, 4739–4750. [CrossRef]
81. Zengin, G.; Sinan, K.I.; Mahomoodally, M.F.; Angeloni, S.; Mustafa, A.M.; Vittori, S.; Maggi, F.; Caprioli, G. Chemical Composition, Antioxidant and Enzyme Inhibitory Properties of Different Extracts Obtained from Spent Coffee Ground and Coffee Silverskin. *Foods* **2020**, *9*, 713. [CrossRef]
82. Nzekoue, F.K.; Angeloni, S.; Navarini, L.; Angeloni, C.; Freschi, M.; Hrelia, S.; Vitali, L.A.; Sagratini, G.; Vittori, S.; Caprioli, G. Coffee Silverskin Extracts: Quantification of 30 Bioactive Compounds by a New HPLC-MS/MS Method and Evaluation of Their Antioxidant and Antibacterial Activities. *Food Res. Int.* **2020**, *133*, 109128. [CrossRef]
83. Regazzoni, L.; Saligari, F.; Marinello, C.; Rossoni, G.; Aldini, G.; Carini, M.; Orioli, M. Coffee Silver Skin as a Source of Polyphenols: High Resolution Mass Spectrometric Profiling of Components and Antioxidant Activity. *J. Funct. Foods* **2016**, *20*, 472–485. [CrossRef]
84. Hussein, H.; Abouamer, W.; Ali, H.; Elkhadragy, M.; Yehia, H.; Farouk, A. The Valorization of Spent Coffee Ground Extract as a Prospective Insecticidal Agent against Some Main Key Pests of Phaseolus Vulgaris in the Laboratory and Field. *Plants* **2022**, *11*, 1124. [CrossRef] [PubMed]
85. Balzano, M.; Loizzo, M.R.; Tundis, R.; Lucci, P.; Nunez, O.; Fiorini, D.; Giardinieri, A.; Frega, N.G.; Pacetti, D. Spent Espresso Coffee Grounds as a Source of Anti-Proliferative and Antioxidant Compounds. *Innov. Food Sci. Emerg. Technol.* **2020**, *59*, 102254. [CrossRef]
86. Andrade, C.; Perestrelo, R.; Câmara, J.S. Bioactive Compounds and Antioxidant Activity from Spent Coffee Grounds as a Powerful Approach for Its Valorization. *Molecules* **2022**, *27*, 7504. [CrossRef]
87. Ramón-Gonçalves, M.; Gómez-Mejía, E.; Rosales-Conrado, N.; León-González, M.E.; Madrid, Y. Extraction, Identification and Quantification of Polyphenols from Spent Coffee Grounds by Chromatographic Methods and Chemometric Analyses. *Waste Manag.* **2019**, *96*, 15–24. [CrossRef]
88. Kamil, M.; Ramadan, K.M.; Awad, O.I.; Ibrahim, T.K.; Inayat, A.; Ma, X. Environmental Impacts of Biodiesel Production from Waste Spent Coffee Grounds and Its Implementation in a Compression Ignition Engine. *Sci. Total Environ.* **2019**, *675*, 13–30. [CrossRef]
89. Cervera-Mata, A.; Delgado, G.; Fernández-Arteaga, A.; Fornasier, F.; Mondini, C. Spent Coffee Grounds By-Products and Their Influence on Soil C–N Dynamics. *J. Environ. Manag.* **2022**, *302*, 114075. [CrossRef]
90. Blinová, L.; Sirotiak, M.; Bartošová, A.; Soldán, M. Review: Utilization of Waste From Coffee Production. *Res. Pap. Fac. Mater. Sci. Technol. Slovak Univ. Technol.* **2017**, *25*, 91–101. [CrossRef]
91. Phimsen, S.; Kiatkittipong, W.; Yamada, H.; Tagawa, T.; Kiatkittipong, K.; Laosiripojana, N.; Assabumrungrat, S. Oil Extracted from Spent Coffee Grounds for Bio-Hydrotreated Diesel Production. *Energy Convers. Manag.* **2016**, *126*, 1028–1036. [CrossRef]
92. De Melo, M.M.R.; Barbosa, H.M.A.; Passos, C.P.; Silva, C.M. Supercritical Fluid Extraction of Spent Coffee Grounds: Measurement of Extraction Curves, Oil Characterization and Economic Analysis. *J. Supercrit. Fluids* **2014**, *86*, 150–159. [CrossRef]
93. Bijla, L.; Aissa, R.; Laknifli, A.; Bouyahya, A.; Harhar, H.; Gharby, S. Spent Coffee Grounds: A Sustainable Approach toward Novel Perspectives of Valorization. *J. Food Biochem.* **2022**, *46*, e14190. [CrossRef] [PubMed]
94. Yamane, K.; Kono, M.; Fukunaga, T.; Iwai, K.; Sekine, R.; Watanabe, Y.; Iijima, M. Field Evaluation of Coffee Grounds Application for Crop Growth Enhancement, Weed Control, and Soil Improvement. *Plant Prod. Sci.* **2014**, *17*, 93–102. [CrossRef]
95. Sanchez-Hernandez, J.C.; Domínguez, J. Vermicompost Derived from Spent Coffee Grounds: Assessing the Potential for Enzymatic Bioremediation. In *Handbook of Coffee Processing By-Products*; Academic Press: Cambridge, MA, USA, 2017; pp. 369–398, ISBN 9780128112915.
96. Hardgrove, S.J.; Livesley, S.J. Applying Spent Coffee Grounds Directly to Urban Agriculture Soils Greatly Reduces Plant Growth. *Urban For. Urban Green.* **2016**, *18*, 1–8. [CrossRef]
97. Mohanpuria, P.; Yadav, S.K. Retardation in Seedling Growth and Induction of Early Senescence in Plants upon Caffeine Exposure Is Related to Its Negative Effect on Rubisco. *Photosynthetica* **2009**, *47*, 293–297. [CrossRef]
98. Cruz, S.; Marques dos Santos Cordovil, C.S.C. Espresso Coffee Residues as a Nitrogen Amendment for Small-Scale Vegetable Production. *J. Sci. Food Agric.* **2015**, *95*, 3059–3066. [CrossRef]
99. Ribeiro, J.P.; Vicente, E.D.; Gomes, A.P.; Nunes, M.I.; Alves, C.; Tarelho, L.A.C. Effect of Industrial and Domestic Ash from Biomass Combustion, and Spent Coffee Grounds, on Soil Fertility and Plant Growth: Experiments at Field Conditions. *Environ. Sci. Pollut. Res.* **2017**, *24*, 15270–15277. [CrossRef]

100. Cruz, R.; Morais, S.; Mendes, E.; Pereira, J.A.; Baptista, P.; Casal, S. Improvement of Vegetables Elemental Quality by Espresso Coffee Residues. *Food Chem.* **2014**, *148*, 294–299. [CrossRef]
101. Cervera-Mata, A.; Pastoriza, S.; Rufián-Henares, J.Á.; Párraga, J.; Martín-García, J.M.; Delgado, G. Impact of Spent Coffee Grounds as Organic Amendment on Soil Fertility and Lettuce Growth in Two Mediterranean Agricultural Soils. *Arch. Agron. Soil Sci.* **2018**, *64*, 790–804. [CrossRef]
102. Santos, C.; Fonseca, J.; Aires, A.; Coutinho, J.; Trindade, H. Effect of Different Rates of Spent Coffee Grounds (SCG) on Composting Process, Gaseous Emissions and Quality of End-Product. *Waste Manag.* **2017**, *59*, 37–47. [CrossRef]
103. Cervera-Mata, A.; Navarro-Alarcón, M.; Rufián-Henares, J.Á.; Pastoriza, S.; Montilla-Gómez, J.; Delgado, G. Phytotoxicity and Chelating Capacity of Spent Coffee Grounds: Two Contrasting Faces in Its Use as Soil Organic Amendment. *Sci. Total Environ.* **2020**, *717*, 137247. [CrossRef]
104. Azim, K.; Soudi, B.; Boukhari, S.; Perissol, C.; Roussos, S.; Thami Alami, I. Composting Parameters and Compost Quality: A Literature Review. *Org. Agric.* **2018**, *8*, 141–158. [CrossRef]
105. Cooperband, L.R. Composting: Art and Science of Organic Waste Conversion to a Valuable Soil Resource. *Lab. Med.* **2000**, *31*, 283–290. [CrossRef]
106. Takala, B. Utilization of Coffee Husk and Pulp Waste as Soil Amendment. A Review. *J. Nat. Sci. Res.* **2021**, *12*, 10–16. [CrossRef]
107. Insam, H.; de Bertoldi, M. Chapter 3 Microbiology of the Composting Process. *Waste Manag. Ser.* **2007**, *8*, 25–48. [CrossRef]
108. Hoseini, M.; Cocco, S.; Casucci, C.; Cardelli, V.; Corti, G. Coffee By-Products Derived Resources. A Review. *Biomass Bioenergy* **2021**, *148*, 106009. [CrossRef]
109. Bernal, M.P.; Alburquerque, J.A.; Moral, R. Composting of Animal Manures and Chemical Criteria for Compost Maturity Assessment. A Review. *Bioresour. Technol.* **2009**, *100*, 5444–5453. [CrossRef]
110. Kasongo, R.K.; Verdoodt, A.; Kanyankagote, P.; Baert, G.; Van Ranst, E. Coffee Waste as an Alternative Fertilizer with Soil Improving Properties for Sandy Soils in Humid Tropical Environments. *Soil Use Manag.* **2011**, *27*, 94–102. [CrossRef]
111. Ur Rahman, S.; Han, J.-C.; Ahmad, M.; Ashraf, M.N.; Khaliq, M.A.; Yousaf, M.; Wang, Y.; Yasin, G.; Nawaz, M.F.; Khan, K.A.; et al. Aluminum Phytotoxicity in Acidic Environments: A Comprehensive Review of Plant Tolerance and Adaptation Strategies. *Ecotoxicol. Environ. Saf.* **2024**, *269*, 115791. [CrossRef]
112. Oliveira, L.S.; Franca, A.S. Chapter 31—An Overview of the Potential Uses for Coffee Husks. In *Coffee in Health and Disease Prevention*; Preedy, V.R., Ed.; Academic Press: San Diego, CA, USA, 2015; pp. 283–291, ISBN 978-0-12-409517-5.
113. Nguyen, A.D.; Tran, T.D.; Vo, T.P.K. Evaluation of Coffee Husk Compost for Improving Soil Fertility and Sustainable Coffee Production in Rural Central Highland of Vietnam. *Resour. Environ.* **2013**, *3*, 77–82. [CrossRef]
114. Dadi, D.; Daba, G.; Beyene, A.; Luis, P.; Van der Bruggen, B. Composting and Co-Composting of Coffee Husk and Pulp with Source-Separated Municipal Solid Waste: A Breakthrough in Valorization of Coffee Waste. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 263–277. [CrossRef]
115. Ulsido, M.D.; Li, M. Effect of Organic Matter from Coffee Pulp Compost on Yield Response of Chickpeas (*Cicer arietinum* L.) in Ethiopia. In Proceedings of the 15th Internal Scientific Conference "Engineering for Rural Development", Jelgava, Latvia, 25–27 May 2016; Malinovska, L., Osadcuks, V., Eds.; Latvia University of Agriculture: Jelgava, Latvia, 2016; pp. 1339–1347.
116. Jibril, T.; Bekele, G. Effect of Coffee Husk Compost and NPSB Fertilizers on Selected Soil Chemical Properties of Potato Field in Chora District, South West Ethiopia. *Appl. Environ. Soil Sci.* **2022**, *2022*, 7397872. [CrossRef]
117. Nduka, B.A.; Adewale, D.B.; Akanbi, O.S.O.; Adejobi, K.B. Nursery Soil Amendments for Cashew Seedling Production: A Comparative Analysis of Coffee Husk and NPK. *J. Agric. Sci.* **2015**, *7*, 111. [CrossRef]
118. Islam, M.M.; Akhter, S.; Majid, N.M.; Ferdous, J.; Alam, M.S. Integrated Nutrient Management for Potato (Solanum Tuberosum) in Grey Terrace Soil (Aric Albaquipt). *Aust. J. Crop Sci.* **2013**, *7*, 1235–1241.
119. Cruz, R.; Mendes, E.; Torrinha, Á.; Morais, S.; Pereira, J.A.; Baptista, P.; Casal, S. Revalorization of Spent Coffee Residues by a Direct Agronomic Approach. *Food Res. Int.* **2015**, *73*, 190–196. [CrossRef]
120. Vela-Cano, M.; Cervera-Mata, A.; Purswani, J.; Pozo, C.; Delgado, G.; González-López, J. Bacterial Community Structure of Two Mediterranean Agricultural Soils Amended with Spent Coffee Grounds. *Appl. Soil Ecol.* **2019**, *137*, 12–20. [CrossRef]
121. Cervera-Mata, A.; Martín-García, J.M.; Delgado, R.; Párraga, J.; Sánchez-Marañón, M.; Delgado, G. Short-Term Effects of Spent Coffee Grounds on the Physical Properties of Two Mediterranean Agricultural Soils. *Int. Agrophysics* **2019**, *33*, 205–216. [CrossRef]
122. Cervera-Mata, A.; Aranda, V.; Ontiveros-Ortega, A.; Comino, F.; Martín-García, J.M.; Vela-Cano, M.; Delgado, G. Hydrophobicity and Surface Free Energy to Assess Spent Coffee Grounds as Soil Amendment. Relationships with Soil Quality. *Catena* **2021**, *196*, 104826. [CrossRef]
123. Cervera-Mata, A.; Molinero-García, A.; Martín-García, J.M.; Delgado, G. Sequential Effects of Spent Coffee Grounds on Soil Physical Properties. *Soil Use Manag.* **2023**, *39*, 286–297. [CrossRef]
124. Turek, M.E.; Freitas, K.S.; Armindo, R.A. Spent Coffee Grounds as Organic Amendment Modify Hydraulic Properties in a Sandy Loam Brazilian Soil. *Agric. Water Manag.* **2019**, *222*, 313–321. [CrossRef]
125. Emmanuel, S.A.; Yoo, J.; Kim, E.J.; Chang, J.S.; Park, Y.I.; Koh, S.C. Development of Functional Composts Using Spent Coffee Grounds, Poultry Manure and Biochar through Microbial Bioaugmentation. *J. Environ. Sci. Health Part B Pestic. Food Contam. Agric. Wastes* **2017**, *52*, 802–811. [CrossRef]
126. Picca, G.; Plaza, C.; Madejón, E.; Panettieri, M. Compositing of Coffee Silverskin with Carbon Rich Materials Leads to High Quality Soil Amendments. *Waste Biomass Valorization* **2023**, *14*, 297–307. [CrossRef]

127. Prasad, M. *Review of the Use of Peat Moss in Horticulture: Final Report of the Chairman of the Working Group*; Department of Housing, Local Government and Heritage: Dublin, Ireland, 2021.
128. International Peatland Society (IPS). Peat. Available online: https://peatlands.org/peat/ (accessed on 8 July 2024).
129. Herrera, F.; Castillo, J.E.; Chica, A.F.; López Bellido, L. Use of Municipal Solid Waste Compost (MSWC) as a Growing Medium in the Nursery Production of Tomato Plants. *Bioresour. Technol.* **2008**, *99*, 287–296. [CrossRef] [PubMed]
130. Ronga, D.; Pane, C.; Zaccardelli, M.; Pecchioni, N. Use of Spent Coffee Ground Compost in Peat-Based Growing Media for the Production of Basil and Tomato Potting Plants. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 356–368. [CrossRef]
131. Picca, G.; Goñi-Urtiaga, A.; Gomez-Ruano, C.; Plaza, C.; Panettieri, M. Suitability of Co-Composted Biochar with Spent Coffee Grounds Substrate for Tomato (*Solanum lycopersicum*) Fruiting Stage. *Horticulturae* **2023**, *9*, 89. [CrossRef]
132. Ding, X.; Jiang, Y.; Zhao, H.; Guo, D.; He, L.; Liu, F.; Zhou, Q.; Nandwani, D.; Hui, D.; Yu, J. Electrical Conductivity of Nutrient Solution Influenced Photosynthesis, Quality, and Antioxidant Enzyme Activity of Pakchoi (*Brassica campestris* L. ssp. *Chinensis*) in a Hydroponic System. *PLoS ONE* **2018**, *13*, e0202090. [CrossRef]
133. Fornes, F.; Mendoza-Hernández, D.; García-de-la-Fuente, R.; Abad, M.; Belda, R.M. Composting versus Vermicomposting: A Comparative Study of Organic Matter Evolution through Straight and Combined Processes. *Bioresour. Technol.* **2012**, *118*, 296–305. [CrossRef]
134. Musyoka, S.N.; Liti, D.M.; Ogello, E.O.; Meulenbroek, P.; Waidbacher, H. Using Earthworm, Eisenia Fetida, to Bio-Convert Agro-Industrial Wastes for Aquaculture Nutrition. *BioResources* **2020**, *15*, 574–587. [CrossRef]
135. Martinkosky, L.; Barkley, J.; Sabadell, G.; Gough, H.; Davidson, S. Earthworms (*Eisenia fetida*) Demonstrate Potential for Use in Soil Bioremediation by Increasing the Degradation Rates of Heavy Crude Oil Hydrocarbons. *Sci. Total Environ.* **2017**, *580*, 734–743. [CrossRef]
136. Vyas, P.; Sharma, S.; Gupta, J. Vermicomposting with Microbial Amendment: Implications for Bioremediation of Industrial and Agricultural Waste. *BioTechnologia* **2022**, *103*, 203–215. [CrossRef]
137. Morikawa, C.K.; Saigusa, M. Recycling Coffee and Tea Wastes to Increase Plant Available Fe in Alkaline Soils. *Plant Soil* **2008**, *304*, 249–255. [CrossRef]
138. González-Moreno, M.A.; García Gracianteparaluceta, B.; Marcelino Sádaba, S.; Zaratiegui Urdin, J.; Robles Domínguez, E.; Pérez Ezcurdia, M.A.; Seco Meneses, A. Feasibility of Vermicomposting of Spent Coffee Grounds and Silverskin from Coffee Industries: A Laboratory Study. *Agronomy* **2020**, *10*, 1125. [CrossRef]
139. Hanc, A.; Hrebeckova, T.; Grasserova, A.; Cajthaml, T. Conversion of Spent Coffee Grounds into Vermicompost. *Bioresour. Technol.* **2021**, *341*, 125925. [CrossRef]
140. Zergaw, Y.; Kebede, T.; Berhe, D.T. Direct Application of Coffee Pulp Vermicompost Produced from Epigeic Earthworms and Its Residual Effect on Vegetative and Reproductive Growth of Hot Pepper (*Capsicum annuum* L.). *Sci. World J.* **2023**, *2023*, 7366925. [CrossRef]
141. Raphael, K.; Velmourougane, K. Chemical and Microbiological Changes during Vermicomposting of Coffee Pulp Using Exotic (*Eudrilus eugeniae*) and Native Earthworm (*Perionyx ceylanesis*) Species. *Biodegradation* **2011**, *22*, 497–507. [CrossRef]
142. Massaya, J.; Mills-Lamptey, B.; Chuck, C.J. Soil Amendments and Biostimulants from the Hydrothermal Processing of Spent Coffee Grounds. *Waste Biomass Valorization* **2022**, *13*, 2889–2904. [CrossRef]
143. Cha, J.S.; Park, S.H.; Jung, S.-C.; Ryu, C.; Jeon, J.-K.; Shin, M.-C.; Park, Y.-K. Production and Utilization of Biochar: A Review. *J. Ind. Eng. Chem.* **2016**, *40*, 1–15. [CrossRef]
144. Nava-Bravo, I.; Escamilla-Alvarado, C.; Cano-Gómez, J.J.; Valencia-Vázquez, R.; Galván-Arzola, U.; Cuevas-García, R. Bio-Crude and Biochar Production and Properties from Corn Stover at Low Energy-Intensive Hydrothermal Liquefaction. *Biomass Convers. Biorefinery* **2024**. [CrossRef]
145. Rehrah, D.; Reddy, M.R.; Novak, J.M.; Bansode, R.R.; Schimmel, K.A.; Yu, J.; Watts, D.W.; Ahmedna, M. Production and Characterization of Biochars from Agricultural By-Products for Use in Soil Quality Enhancement. *J. Anal. Appl. Pyrolysis* **2014**, *108*, 301–309. [CrossRef]
146. Stylianou, M.; Christou, A.; Dalias, P.; Polycarpou, P.; Michael, C.; Agapiou, A.; Papanastasiou, P.; Fatta-Kassinos, D. Physicochemical and Structural Characterization of Biochar Derived from the Pyrolysis of Biosolids, Cattle Manure and Spent Coffee Grounds. *J. Energy Inst.* **2020**, *93*, 2063–2073. [CrossRef]
147. Rodriguez, J.A.; Lustosa Filho, J.F.; Melo, L.C.A.; de Assis, I.R.; de Oliveira, T.S. Influence of Pyrolysis Temperature and Feedstock on the Properties of Biochars Produced from Agricultural and Industrial Wastes. *J. Anal. Appl. Pyrolysis* **2020**, *149*, 104839. [CrossRef]
148. Rodriguez Ortiz, L.; Torres, E.; Zalazar, D.; Zhang, H.; Rodriguez, R.; Mazza, G. Influence of Pyrolysis Temperature and Bio-Waste Composition on Biochar Characteristics. *Renew. Energy* **2020**, *155*, 837–847. [CrossRef]
149. Yang, C.; Liu, J.; Lu, S. Pyrolysis Temperature Affects Pore Characteristics of Rice Straw and Canola Stalk Biochars and Biochar-Amended Soils. *Geoderma* **2021**, *397*, 115097. [CrossRef]
150. Lataf, A.; Jozefczak, M.; Vandecasteele, B.; Viaene, J.; Schreurs, S.; Carleer, R.; Yperman, J.; Marchal, W.; Cuypers, A.; Vandamme, D. The Effect of Pyrolysis Temperature and Feedstock on Biochar Agronomic Properties. *J. Anal. Appl. Pyrolysis* **2022**, *168*, 105728. [CrossRef]

151. Domingues, R.R.; Trugilho, P.F.; Silva, C.A.; De Melo, I.C.N.A.; Melo, L.C.A.; Magriotis, Z.M.; Sánchez-Monedero, M.A. Properties of Biochar Derived from Wood and High-Nutrient Biomasses with the Aim of Agronomic and Environmental Benefits. *PLoS ONE* **2017**, *12*, e0176884. [CrossRef] [PubMed]
152. Song, W.; Guo, M. Quality Variations of Poultry Litter Biochar Generated at Different Pyrolysis Temperatures. *J. Anal. Appl. Pyrolysis* **2012**, *94*, 138–145. [CrossRef]
153. Bruun, E.W.; Hauggaard-Nielsen, H.; Ibrahim, N.; Egsgaard, H.; Ambus, P.; Jensen, P.A.; Dam-Johansen, K. Influence of Fast Pyrolysis Temperature on Biochar Labile Fraction and Short-Term Carbon Loss in a Loamy Soil. *Biomass Bioenergy* **2011**, *35*, 1182–1189. [CrossRef]
154. Lehmann, J.; Joseph, S. Biochar for Environmental Management: An Introduction. In *Biochar for Environmental Management Science and Technology*; Lehmann, J., Joseph, S., Eds.; Earthscan Publishers Ltd.: London, UK, 2009; pp. 1–9.
155. Rondon, M.A.; Lehmann, J.; Ramírez, J.; Hurtado, M. Biological Nitrogen Fixation by Common Beans (*Phaseolus vulgaris* L.) Increases with Bio-Char Additions. *Biol. Fertil. Soils* **2007**, *43*, 699–708. [CrossRef]
156. Pouangam Ngalani, G.; Ondo, J.A.; Njimou, J.R.; Nanseu Njiki, C.P.; Prudent, P.; Ngameni, E. Effect of Coffee Husk and Cocoa Pods Biochar on Phosphorus Fixation and Release Processes in Acid Soils from West Cameroon. *Soil Use Manag.* **2023**, *39*, 817–832. [CrossRef]
157. Pouangam Ngalani, G.; Dzemze Kagho, F.; Peguy, N.N.C.; Prudent, P.; Ondo, J.A.; Ngameni, E. Effects of Coffee Husk and Cocoa Pods Biochar on the Chemical Properties of an Acid Soil from West Cameroon. *Arch. Agron. Soil Sci.* **2023**, *69*, 744–758. [CrossRef]
158. Lehmann, J.; Da Silva, J.P.; Steiner, C.; Nehls, T.; Zech, W.; Glaser, B. Nutrient Availability and Leaching in an Archaeological Anthrosol and a Ferralsol of the Central Amazon Basin: Fertilizer, Manure and Charcoal Amendments. *Plant Soil* **2003**, *249*, 343–357. [CrossRef]
159. Nguyen, V.T.; Vo, T.D.H.; Tran, T.; Nguyen, T.N.; Le, T.N.C.; Bui, X.T.; Bach, L.G. Biochar Derived from the Spent Coffee Ground for Ammonium Adsorption from Aqueous Solution. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100141. [CrossRef]
160. Tangmankongworakoon, N. An Approach to Produce Biochar from Coffee Residue for Fuel and Soil Amendment Purpose. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 37–44. [CrossRef]
161. Steinbeiss, S.; Gleixner, G.; Antonietti, M. Effect of Biochar Amendment on Soil Carbon Balance and Soil Microbial Activity. *Soil Biol. Biochem.* **2009**, *41*, 1301–1310. [CrossRef]
162. Dawerasha, S.S.; Nebiyu, A.; Ahmed, M.; Haile, B. Effect of Coffee Husk Biochar and Inorganic NP Fertilizer on Soil Properties, Growth and Yield of Potato (*Solanum tuberosum* L.) on Acidic Soil of Southwest Ethiopia. *CABI Agric. Biosci.* **2024**, *5*, 56. [CrossRef]
163. Gebre, T.; Singh, S.; Zewide, I. Potato Yield Enhancement by Combined Use of NPS Blended Fertilizer and Coffee Husk Biochar and Its Economic Analysis. *Trop. Agric.* **2020**, *97*, 240–252.
164. Singh, C.; Tiwari, S.; Gupta, V.K.; Singh, J.S. The Effect of Rice Husk Biochar on Soil Nutrient Status, Microbial Biomass and Paddy Productivity of Nutrient Poor Agriculture Soils. *CATENA* **2018**, *171*, 485–493. [CrossRef]
165. Warnock, D.D.; Lehmann, J.; Kuyper, T.W.; Rillig, M.C. Mycorrhizal Responses to Biochar in Soil—Concepts and Mechanisms. *Plant Soil* **2007**, *300*, 9–20. [CrossRef]
166. Lima, J.R.d.S.; de Moraes Silva, W.; de Medeiros, E.V.; Duda, G.P.; Corrêa, M.M.; Martins Filho, A.P.; Clermont-Dauphin, C.; Antonino, A.C.D.; Hammecker, C. Effect of Biochar on Physicochemical Properties of a Sandy Soil and Maize Growth in a Greenhouse Experiment. *Geoderma* **2018**, *319*, 14–23. [CrossRef]
167. Filho, A.P.M.; de Medeiros, E.V.; Lima, J.R.S.; da Costa, D.P.; Duda, G.P.; da Silva, J.S.A.; de Oliveira, J.B.; Antonino, A.C.D.; Menezes, R.S.C.; Hammecker, C. Impact of Coffee Biochar on Carbon, Microbial Biomass and Enzyme Activities of a Sandy Soil Cultivated with Bean. *An. Acad. Bras. Cienc.* **2021**, *93*, e20200096. [CrossRef]
168. Asfaw, E.; Nebiyu, A.; Bekele, E.; Ahmed, M.; Astatkie, T. Coffee-Husk Biochar Application Increased AMF Root Colonization, P Accumulation, N2 Fixation, and Yield of Soybean Grown in a Tropical Nitisol, Southwest Ethiopia. *J. Plant Nutr. Soil Sci.* **2019**, *182*, 419–428. [CrossRef]
169. Yang, J.; Zhao, Z.; Hu, Y.; Abbey, L.; Cesarino, I.; Goonetilleke, A.; He, Q. Exploring the Properties and Potential Uses of Biocarbon from Spent Coffee Grounds: A Comparative Look at Dry and Wet Processing Methods. *Processes* **2023**, *11*, 2099. [CrossRef]
170. Zhang, X.; Zhang, Y.; Ngo, H.H.; Guo, W.; Wen, H.; Zhang, D.; Li, C.; Qi, L. Characterization and Sulfonamide Antibiotics Adsorption Capacity of Spent Coffee Grounds Based Biochar and Hydrochar. *Sci. Total Environ.* **2020**, *716*, 137015. [CrossRef] [PubMed]
171. Cervera-Mata, A.; Lara, L.; Fernández-Arteaga, A.; Ángel Rufián-Henares, J.; Delgado, G. Washed Hydrochar from Spent Coffee Grounds: A Second Generation of Coffee Residues. Evaluation as Organic Amendment. *Waste Manag.* **2021**, *120*, 322–329. [CrossRef] [PubMed]
172. Bargmann, I.; Rillig, M.C.; Buss, W.; Kruse, A.; Kuecke, M. Hydrochar and Biochar Effects on Germination of Spring Barley. *J. Agron. Crop Sci.* **2013**, *199*, 360–373. [CrossRef]
173. Hitzl, M.; Mendez, A.; Owsianiak, M.; Renz, M. Making Hydrochar Suitable for Agricultural Soil: A Thermal Treatment to Remove Organic Phytotoxic Compounds. *J. Environ. Chem. Eng.* **2018**, *6*, 7029–7034. [CrossRef]
174. Jeníček, L.; Tunklová, B.; Malaťák, J.; Neškudla, M.; Velebil, J. Use of Spent Coffee Ground as an Alternative Fuel and Possible Soil Amendment. *Materials* **2022**, *15*, 6722. [CrossRef]
175. Woolf, D.; Amonette, J.E.; Street-Perrott, F.A.; Lehmann, J.; Joseph, S. Sustainable Biochar to Mitigate Global Climate Change. *Nat. Commun.* **2010**, *1*, 56. [CrossRef]

176. Ali, S.; Rizwan, M.; Qayyum, M.F.; Ok, Y.S.; Ibrahim, M.; Riaz, M.; Arif, M.S.; Hafeez, F.; Al-Wabel, M.I.; Shahzad, A.N. Biochar Soil Amendment on Alleviation of Drought and Salt Stress in Plants: A Critical Review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 12700–12712. [CrossRef]
177. Kamali, M.; Jahaninafard, D.; Mostafaie, A.; Davarazar, M.; Gomes, A.P.D.; Tarelho, L.A.C.; Dewil, R.; Aminabhavi, T.M. Scientometric Analysis and Scientific Trends on Biochar Application as Soil Amendment. *Chem. Eng. J.* **2020**, *395*, 125128. [CrossRef]
178. Carnier, R.; Coscione, A.R.; Delaqua, D.; Puga, A.P.; de Abreu, C.A. Jack Bean Development in Multimetal Contaminated Soil Amended with Coffee Waste-Derived Biochars. *Processes* **2022**, *10*, 2157. [CrossRef]
179. Al Masud, M.A.; Shin, W.S.; Sarker, A.; Septian, A.; Das, K.; Deepo, D.M.; Iqbal, M.A.; Islam, A.R.M.T.; Malafaia, G. A Critical Review of Sustainable Application of Biochar for Green Remediation: Research Uncertainty and Future Directions. *Sci. Total Environ.* **2023**, *904*, 166813. [CrossRef] [PubMed]
180. Afshar, M.; Mofatteh, S. Biochar for a Sustainable Future: Environmentally Friendly Production and Diverse Applications. *Results Eng.* **2024**, *23*, 102433. [CrossRef]
181. Chaurra, A.M.; Molina Bastidas, J.C.; Infante Santos, C.; Wilches Rodríguez, J.C. Valorization of Coffee Pulp in the Production of Pleurotus Pulmonarius in Rural Communities of Colombia. *ACS Food Sci. Technol.* **2023**, *3*, 1314–1322. [CrossRef]
182. Leifa, F.; Soccol, C.R.; Pandey, A. Production of Mushrooms on Brazilian Coffee Industry Residues. In *Coffee Biotechnology and Quality*; Sera, T., Soccol, C.R., Pandey, A., Roussos, S., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 427–436, ISBN 978-94-017-1068-8.
183. Martínez-Carrera, D.; Aguilar, A.; Martínez, W.; Bonilla, M.; Morales, P.; Sobal, M. Commercial Production and Marketing of Edible Mushrooms Cultivated on Coffee Pulp in Mexico. In *Coffee Biotechnology and Quality*; Sera, T., Soccol, C.R., Pandey, A., Roussos, S., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 471–488, ISBN 978-94-017-1068-8.
184. Lopez, J.C.C.; Thepanondh, S.; Sachdev, H.; Avelar, A.M.P.; Leon, M.C.D.C. Sustainability and Economic Feasibility through the Production of Oyster Mushroom (*Pleurotus ostreatus* (Jacq.) p. Kumm.) Derived from the Waste of Coffee-Industry: A Case Study in the Western Area of San Salvador, El Salvador. *Pol. J. Environ. Stud.* **2021**, *30*, 5617–5628. [CrossRef]
185. El-Ramady, H.; Abdalla, N.; Badgar, K.; Llanaj, X.; Törős, G.; Hajdú, P.; Eid, Y.; Prokisch, J. Edible Mushrooms for Sustainable and Healthy Human Food: Nutritional and Medicinal Attributes. *Sustainability* **2022**, *14*, 4941. [CrossRef]
186. Assemie, A.; Abaya, G. The Effect of Edible Mushroom on Health and Their Biochemistry. *Int. J. Microbiol.* **2022**, *2022*, 8744788. [CrossRef]
187. Diamantopoulou, P.; Fourtaka, K.; Melanouri, E.M.; Dedousi, M.; Diamantis, I.; Gardeli, C.; Papanikolaou, S. Examining the Impact of Substrate Composition on the Biochemical Properties and Antioxidant Activity of Pleurotus and Agaricus Mushrooms. *Fermentation* **2023**, *9*, 689. [CrossRef]
188. Liu, J.; Jia, L.; Kan, J.; Jin, C. In Vitro and in Vivo Antioxidant Activity of Ethanolic Extract of White Button Mushroom (Agaricus Bisporus). *Food Chem. Toxicol.* **2013**, *51*, 310–316. [CrossRef]
189. Arunachalam, K.; Sasidharan, S.P.; Yang, X. A Concise Review of Mushrooms Antiviral and Immunomodulatory Properties That May Combat against COVID-19. *Food Chem. Adv.* **2022**, *1*, 100023. [CrossRef]
190. Nozaki, H.; Itonori, S.; Sugita, M.; Nakamura, K.; Ohba, K.; Suzuki, A.; Kushi, Y. Mushroom Acidic Glycosphingolipid Induction of Cytokine Secretion from Murine T Cells and Proliferation of NK1.1 α/β TCR-Double Positive Cells in Vitro. *Biochem. Biophys. Res. Commun.* **2008**, *373*, 435–439. [CrossRef]
191. Zhang, M.; Huang, J.; Xie, X.; Holman, C.D.J. Dietary Intakes of Mushrooms and Green Tea Combine to Reduce the Risk of Breast Cancer in Chinese Women. *Int. J. Cancer* **2009**, *124*, 1404–1408. [CrossRef] [PubMed]
192. Moon, S.-M.; Kim, J.-S.; Kim, H.-J.; Choi, M.S.; Park, B.R.; Kim, S.-G.; Ahn, H.; Chun, H.S.; Shin, Y.K.; Kim, J.-J.; et al. Purification and Characterization of a Novel Fibrinolytic α Chymotrypsin like Serine Metalloprotease from the Edible Mushroom, Lyophyllum Shimeji. *J. Biosci. Bioeng.* **2014**, *117*, 544–550. [CrossRef] [PubMed]
193. Jedinak, A.; Dudhgaonkar, S.; Wu, Q.; Simon, J.; Sliva, D. Anti-Inflammatory Activity of Edible Oyster Mushroom Is Mediated through the Inhibition of NF-KB and AP-1 Signaling. *Nutr. J.* **2011**, *10*, 52. [CrossRef]
194. Dubey, S.K.; Chaturvedi, V.K.; Mishra, D.; Bajpeyee, A.; Tiwari, A.; Singh, M.P. Role of Edible Mushroom as a Potent Therapeutics for the Diabetes and Obesity. *3 Biotech* **2019**, *9*, 450. [CrossRef]
195. Wang, M.; Zhao, R. A Review on Nutritional Advantages of Edible Mushrooms and Its Industrialization Development Situation in Protein Meat Analogues. *J. Future Foods* **2023**, *3*, 1–7. [CrossRef]
196. Morales, D.; Tabernero, M.; Largo, C.; Polo, G.; Piris, A.J.; Soler-Rivas, C. Effect of Traditional and Modern Culinary Processing, Bioaccessibility, Biosafety and Bioavailability of Eritadenine, a Hypocholesterolemic Compound from Edible Mushrooms. *Food Funct.* **2018**, *9*, 6360–6368. [CrossRef]
197. Ren, Z.; Guo, Z.; Meydani, S.N.; Wu, D. White Button Mushroom Enhances Maturation of Bone Marrow-Derived Dendritic Cells and Their Antigen Presenting Function in Mice. *J. Nutr.* **2008**, *138*, 544–550. [CrossRef]
198. Suwannarach, N.; Kumla, J.; Zhao, Y.; Kakumyan, P. Impact of Cultivation Substrate and Microbial Community on Improving Mushroom Productivity: A Review. *Biology* **2022**, *11*, 569. [CrossRef]
199. Elkanah, F.A.; Oke, M.A.; Adebayo, E.A. Substrate Composition Effect on the Nutritional Quality of Pleurotus Ostreatus (MK751847) Fruiting Body. *Heliyon* **2022**, *8*, e11841. [CrossRef]

200. Hoa, H.T.; Wang, C.-L.; Wang, C.-H. The Effects of Different Substrates on the Growth, Yield, and Nutritional Composition of Two Oyster Mushrooms (*Pleurotus ostreatus* and *Pleurotus cystidiosus*). *Mycobiology* **2015**, *43*, 423–434. [CrossRef]
201. Atila, F. Comparative Study on the Mycelial Growth and Yield of Ganoderma Lucidum (Curt.: Fr.) Karst. on Different Lignocellulosic Wastes. *Acta Ecol. Sin.* **2020**, *40*, 153–157. [CrossRef]
202. Muswati, C.; Simango, K.; Tapfumaneyi, L.; Mutetwa, M.; Ngezimana, W. The Effects of Different Substrate Combinations on Growth and Yield of Oyster Mushroom (*Pleurotus ostreatus*). *Int. J. Agron.* **2021**, *2021*, 9962285. [CrossRef]
203. Dissasa, G. Cultivation of Different Oyster Mushroom (*Pleurotus* Species) on Coffee Waste and Determination of Their Relative Biological Efficiency and Pectinase Enzyme Production, Ethiopia. *Int. J. Microbiol.* **2022**, *2022*, 5219939. [CrossRef] [PubMed]
204. Freitas, A.C.; Antunes, M.B.; Rodrigues, D.; Sousa, S.; Amorim, M.; Barroso, M.F.; Carvalho, A.; Ferrador, S.M.; Gomes, A.M. Use of Coffee By-products for the Cultivation of Pleurotus Citrinopileatus and Pleurotus Salmoneo-stramineus and Its Impact on Biological Properties of Extracts Thereof. *Int. J. Food Sci. Technol.* **2018**, *53*, 1914–1924. [CrossRef]
205. Fan, L.; Pandey, A.; Mohan, R.; Soccol, C.R. Use of Various Coffee Industry Residues for the Cultivation of Pleurotus Ostreatus in Solid State Fermentation. *Acta Biotechnol.* **2000**, *20*, 41–52. [CrossRef]
206. Calzada, J.F.; de Leon, R.; de Arriola, M.C.; Rolz, C. Growth of Mushrooms on Wheat Straw and Coffee Pulp: Strain Selection. *Biol. Wastes* **1987**, *20*, 217–226. [CrossRef]
207. Velázquez-Cedeño, M.A.; Mata, G.; Savoie, J.M. Waste-Reducing Cultivation of Pleurotus Ostreatus and Pleurotus Pulmonarius on Coffee Pulp: Changes in the Production of Some Lignocellulolytic Enzymes. *World J. Microbiol. Biotechnol.* **2002**, *18*, 201–207. [CrossRef]
208. Yoshimura, H.; Washio, H.; Yoshida, S.; Seino, T.; Otaka, M.; Matsubara, K.; Matsubara, M. Promoting Effect of Wood Vinegar Compounds on Fruit-Body Formation of Pleurotus Ostreatus. *Mycoscience* **1995**, *36*, 173–177. [CrossRef]
209. Fan, L.; Soccol, A.T.; Pandey, A.; Vandenberghe, L.P.D.S.; Soccol, C.R. Effect of Caffeine and Tannins on Cultivation and Fructification of Pleurotus on Coffee Husks. *Braz. J. Microbiol.* **2006**, *37*, 420–424. [CrossRef]
210. Gąsecka, M.; Magdziak, Z.; Siwulski, M.; Jasińska, A.; Budzyńska, S.; Rzymski, P.; Kalač, P.; Niedzielski, P.; Pankiewicz, J.; Mleczek, M. Effect of Thymus Vulgaris Post-Extraction Waste and Spent Coffee Grounds on the Quality of Cultivated Pleurotus Eryngii. *J. Food Process. Preserv.* **2020**, *44*, e14648. [CrossRef]
211. Mata, G.; Salmones, D.; Pérez-Merlo, R. Hydrolytic Enzyme Activities in Shiitake Mushroom (*Lentinula edodes*) Strains Cultivated on Coffee Pulp. *Rev. Argent. Microbiol.* **2016**, *48*, 191–195. [CrossRef] [PubMed]
212. Carrasco-Cabrera, C.P.; Bell, T.L.; Kertesz, M.A. Caffeine Metabolism during Cultivation of Oyster Mushroom (*Pleurotus ostreatus*) with Spent Coffee Grounds. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 5831–5841. [CrossRef] [PubMed]
213. Alsanad, M.A.; Sassine, Y.N.; El Sebaaly, Z.; Abou Fayssal, S. Spent Coffee Grounds Influence on Pleurotus Ostreatus Production, Composition, Fatty Acid Profile, and Lignocellulose Biodegradation Capacity. *CyTA J. Food* **2021**, *19*, 11–20. [CrossRef]
214. Grogan, R.A. *Agricultural Pesticides: Usage Trends and Analysis of Data Sources*; Nova: New York, NY, USA, 2011; ISBN 9781611225310.
215. Chitara, M.K.; Singh, R.P.; Gupta, P.K.; Mishra, D.; Jatav, S.S.; Sharma, S.; Jatav, H.S. The Risk Associated with Crop Ecosystem Management and Pesticides Pollution. In *Ecosystem Services: Types, Management and Benefits*; Nova: New York, NY, USA, 2022; pp. 151–164, ISBN 9781685077471.
216. Rao, M.S. Innovations, Commercialization and Registration of Biopesticides. In *Biopesticides in Horticultural Crops*; CRC Press: London, UK, 2021; pp. 1–11, ISBN 9781000486803.
217. Swapan, C.; Mainak, B.; Deewa, B.; Tanmoy, M. Natural Pesticides for Pest Control in Agricultural Crops: An Alternative and Eco-Friendly Method. *Plant Sci. Today* **2023**, *11*, 433–450. [CrossRef]
218. Usha Rani, P.; Pratyusha, S. Defensive Role of Gossypium Hirsutum L. Anti-Oxidative Enzymes and Phenolic Acids in Response to Spodoptera Litura F. Feeding. *J. Asia. Pac. Entomol.* **2013**, *16*, 131–136. [CrossRef]
219. Bedmutha, R.; Booker, C.J.; Ferrante, L.; Briens, C.; Berruti, F.; Yeung, K.K.C.; Scott, I.; Conn, K. Insecticidal and Bactericidal Characteristics of the Bio-Oil from the Fast Pyrolysis of Coffee Grounds. *J. Anal. Appl. Pyrolysis* **2011**, *90*, 224–231. [CrossRef]
220. Breedlove, B. Deadly, Dangerous, and Decorative Creatures. *Emerg. Infect. Dis.* **2022**, *28*, 495–496. [CrossRef]
221. Poopathi, S.; Mani, C. Use of Coffee Husk Waste for Production of Biopesticides for Mosquito Control. In *Coffee in Health and Disease Prevention*; Preedy, V.R., Ed.; Elsevier: San Diego, CA, USA, 2015; pp. 293–300, ISBN 9780124167162.
222. Nath, C.P.; Singh, R.G.; Choudhary, V.K.; Datta, D.; Nandan, R.; Singh, S.S. Challenges and Alternatives of Herbicide-Based Weed Management. *Agronomy* **2024**, *14*, 126. [CrossRef]
223. Monteiro, A.; Santos, S. Sustainable Approach to Weed Management: The Role of Precision Weed Management. *Agronomy* **2022**, *12*, 118. [CrossRef]
224. Martínez, S.S.; Sánchez, J.V. Herbicides: Applications, Degradation, and Environmental Impact. In *Herbicides: Properties, Crop Protection and Environmental Hazards*; Nova: New York, NY, USA, 2011; pp. 67–120.
225. Gaur, N.; Diwan, B.; Choudhary, R. Bioremediation of Organic Pesticides Using Nanomaterials. In *Nano-Bioremediation: Fundamentals and Applications*; Iqbal, H.M.N., Bilal, M., Nguyen, T.A., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 517–540.
226. Sant'Anna, V.; Biondo, E.; Kolchinski, E.M.; da Silva, L.F.S.; Corrêa, A.P.F.; Bach, E.; Brandelli, A. Total Polyphenols, Antioxidant, Antimicrobial and Allelopathic Activities of Spend Coffee Ground Aqueous Extract. *Waste Biomass Valorization* **2017**, *8*, 439–442. [CrossRef]
227. Huang, J.; Li, B.; Xian, X.; Hu, Y.; Lin, X. Efficient Bioethanol Production from Spent Coffee Grounds Using Liquid Hot Water Pretreatment without Detoxification. *Fermentation* **2024**, *10*, 436. [CrossRef]

228. Choi, I.S.; Wi, S.G.; Kim, S.-B.; Bae, H.-J. Conversion of Coffee Residue Waste into Bioethanol with Using Popping Pretreatment. *Bioresour. Technol.* **2012**, *125*, 132–137. [CrossRef] [PubMed]
229. Ummalyma, S.B.; Supriya, R.D.; Sindhu, R.; Binod, P.; Nair, R.B.; Pandey, A.; Gnansounou, E. Biological Pretreatment of Lignocellulosic Biomass—Current Trends and Future Perspectives. In *Second and Third Generation of Feedstocks*; Basile, A., Dalena, F., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 197–212.
230. Nguyen, Q.A.; Cho, E.; Trinh, L.T.P.; Jeong, J.; Bae, H.-J. Development of an Integrated Process to Produce D-Mannose and Bioethanol from Coffee Residue Waste. *Bioresour. Technol.* **2017**, *244*, 1039–1048. [CrossRef] [PubMed]
231. Li, M.-F.; Yang, S.; Sun, R.-C. Recent Advances in Alcohol and Organic Acid Fractionation of Lignocellulosic Biomass. *Bioresour. Technol.* **2016**, *200*, 971–980. [CrossRef]
232. Chiyanzy, I.; Brienzo, M.; García-Aparicio, M.; Agudelo, R.; Görgens, J. Spent Coffee Ground Mass Solubilisation by Steam Explosion and Enzymatic Hydrolysis. *J. Chem. Technol. Biotechnol.* **2015**, *90*, 449–458. [CrossRef]
233. Dadi, D.; Beyene, A.; Simoens, K.; Soares, J.; Demeke, M.M.; Thevelein, J.M.; Bernaerts, K.; Luis, P.; Van der Bruggen, B. Valorization of Coffee Byproducts for Bioethanol Production Using Lignocellulosic Yeast Fermentation and Pervaporation. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 821–832. [CrossRef]
234. Xiros, C.; Topakas, E.; Christakopoulos, P. Hydrolysis and Fermentation for Cellulosic Ethanol Production. In *Advances in Bioenergy*; Lund, P.D., Byrne, J., Berndes, G., Vasalos, I.A., Eds.; Wiley: Hoboken, NJ, USA, 2016; pp. 11–31, ISBN 9781118957844.
235. Meng, Q.-S.; Liu, C.-G.; Zhao, X.-Q.; Bai, F.-W. Engineering Trichoderma Reesei Rut-C30 with the Overexpression of Egl1 at the Ace1 Locus to Relieve Repression on Cellulase Production and to Adjust the Ratio of Cellulolytic Enzymes for More Efficient Hydrolysis of Lignocellulosic Biomass. *J. Biotechnol.* **2018**, *285*, 56–63. [CrossRef]
236. Srivastava, N.; Srivastava, M.; Mishra, P.K.; Gupta, V.K.; Molina, G.; Rodriguez-Couto, S.; Manikanta, A.; Ramteke, P.W. Applications of Fungal Cellulases in Biofuel Production: Advances and Limitations. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2379–2386. [CrossRef]
237. Selvam, K.; Govarthanan, M.; Kamala-Kannan, S.; Govindharaju, M.; Senthilkumar, B.; Selvankumar, T.; Sengottaiyan, A. Process Optimization of Cellulase Production from Alkali-Treated Coffee Pulp and Pineapple Waste Using Acinetobacter Sp. TSK-MASC. *RSC Adv.* **2014**, *4*, 13045–13051. [CrossRef]
238. Catalán, E.; Komilis, D.; Sánchez, A. Environmental Impact of Cellulase Production from Coffee Husks by Solid-State Fermentation: A Life-Cycle Assessment. *J. Clean. Prod.* **2019**, *233*, 954–962. [CrossRef]
239. Marín, M.; Artola, A.; Sánchez, A. Optimization of Down-Stream for Cellulases Produced Under Solid-State Fermentation of Coffee Husk. *Waste Biomass Valorization* **2019**, *10*, 2761–2772. [CrossRef]
240. Morales-Martínez, J.L.; Aguilar-Uscanga, M.G.; Bolaños-Reynoso, E.; López-Zamora, L. Optimization of Chemical Pretreatments Using Response Surface Methodology for Second-Generation Ethanol Production from Coffee Husk Waste. *BioEnergy Res.* **2021**, *14*, 815–827. [CrossRef]
241. Mussatto, S.I.; Roberto, I.C. Alternatives for Detoxification of Diluted-Acid Lignocellulosic Hydrolyzates for Use in Fermentative Processes: A Review. *Bioresour. Technol.* **2004**, *93*, 1–10. [CrossRef] [PubMed]
242. Gouvea, B.M.; Torres, C.; Franca, A.S.; Oliveira, L.S.; Oliveira, E.S. Feasibility of Ethanol Production from Coffee Husks. *Biotechnol. Lett.* **2009**, *31*, 1315–1319. [CrossRef]
243. Mussatto, S.I.; Machado, E.M.S.; Carneiro, L.M.; Teixeira, J.A. Sugars Metabolism and Ethanol Production by Different Yeast Strains from Coffee Industry Wastes Hydrolysates. *Appl. Energy* **2012**, *92*, 763–768. [CrossRef]
244. Madson, P.W.; Lococo, D.B. Recovery of Volatile Products from Dilute High-Fouling Process Streams. *Appl. Biochem. Biotechnol.* **2000**, *84–86*, 1049–1062. [CrossRef]
245. Rocha, M.V.P.; de Matos, L.J.B.L.; de Lima, L.P.; Figueiredo, P.M.d.S.; Lucena, I.L.; Fernandes, F.A.N.; Gonçalves, L.R.B. Ultrasound-Assisted Production of Biodiesel and Ethanol from Spent Coffee Grounds. *Bioresour. Technol.* **2014**, *167*, 343–348. [CrossRef]
246. Uddin, M.N.; Techato, K.; Rasul, M.G.; Hassan, N.M.S.; Mofijur, M. Waste Coffee Oil: A Promising Source for Biodiesel Production. *Energy Procedia* **2019**, *160*, 677–682. [CrossRef]
247. Somnuk, K.; Eawlex, P.; Prateepchaikul, G. Optimization of Coffee Oil Extraction from Spent Coffee Grounds Using Four Solvents and Prototype-Scale Extraction Using Circulation Process. *Agric. Nat. Resour.* **2017**, *51*, 181–189. [CrossRef]
248. Todaka, M.; Kowhakul, W.; Masamoto, H.; Shigematsu, M. Improvement of Oxidation Stability of Biodiesel by an Antioxidant Component Contained in Spent Coffee Grounds. *Biofuels* **2021**, *12*, 227–235. [CrossRef]
249. Bui, H.N.; Do, H.Q.; Duong, H.T.G.; Perng, Y.-S.; Dam, V.N.; Nguyen, V.-T.; Bui, H.M. Taguchi Optimization and Life Cycle Assessment of Biodiesel Production from Spent Ground Coffee. *Environ. Dev. Sustain.* **2022**, *24*, 12900–12916. [CrossRef]
250. Veitía-de-Armas, L.; Reynel-Ávila, H.E.; Bonilla-Petriciolet, A.; Jáuregui-Rincón, J. Green Solvent-Based Lipid Extraction from Guava Seeds and Spent Coffee Grounds to Produce Biodiesel: Biomass Valorization and Esterification/Transesterification Route. *Ind. Crops Prod.* **2024**, *214*, 118535. [CrossRef]
251. Leow, Y.; Yew, P.Y.M.; Chee, P.L.; Loh, X.J.; Kai, D. Recycling of Spent Coffee Grounds for Useful Extracts and Green Composites. *RSC Adv.* **2021**, *11*, 2682–2692. [CrossRef]
252. Im, G.; Yeom, S.H. Repeated Biodiesel Production from Waste Coffee Grounds via a One-Step Direct Process with a Cartridge Containing Solid Catalysts Manufactured from Waste Eggshells. *Biotechnol. Bioprocess Eng.* **2020**, *25*, 623–632. [CrossRef]
253. Son, J.; Kim, B.; Park, J.; Yang, J.; Lee, J.W. Wet in Situ Transesterification of Spent Coffee Grounds with Supercritical Methanol for the Production of Biodiesel. *Bioresour. Technol.* **2018**, *259*, 465–468. [CrossRef]

254. Tuntiwiwattanapun, N.; Monono, E.; Wiesenborn, D.; Tongcumpou, C. In-Situ Transesterification Process for Biodiesel Production Using Spent Coffee Grounds from the Instant Coffee Industry. *Ind. Crops Prod.* **2017**, *102*, 23–31. [CrossRef]
255. Najdanovic-Visak, V.; Lee, F.Y.-L.; Tavares, M.T.; Armstrong, A. Kinetics of Extraction and in Situ Transesterification of Oils from Spent Coffee Grounds. *J. Environ. Chem. Eng.* **2017**, *5*, 2611–2616. [CrossRef]
256. Park, J.; Kim, B.; Lee, J.W. In-Situ Transesterification of Wet Spent Coffee Grounds for Sustainable Biodiesel Production. *Bioresour. Technol.* **2016**, *221*, 55–60. [CrossRef]
257. Park, J.; Kim, B.; Son, J.; Lee, J.W. Solvo-Thermal in Situ Transesterification of Wet Spent Coffee Grounds for the Production of Biodiesel. *Bioresour. Technol.* **2018**, *249*, 494–500. [CrossRef]
258. Phimsen, S.; Kiatkittipong, W.; Yamada, H.; Tagawa, T.; Kiatkittipong, K.; Laosiripojana, N.; Assabumrungrat, S. Nickel Sulfide, Nickel Phosphide and Nickel Carbide Catalysts for Bio-Hydrotreated Fuel Production. *Energy Convers. Manag.* **2017**, *151*, 324–333. [CrossRef]
259. Kiatkittipong, W.; Pongsiriyakul, K.; Lim, J.W.; Kiatkittipong, K.; Wongsurakul, P.; Yodpetch, V.; Boonyasuwat, S.; Assabumrungrat, S. Bioresources and Biofuels—From Classical to Perspectives and Trends. In *A-Z of Biorefinery*; Thongchul, N., Kokossis, A., Assabumrungrat, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 165–220, ISBN 978-0-12-819248-1.
260. Passadis, K.; Fragoulis, V.; Stoumpou, V.; Novakovic, J.; Barampouti, E.M.; Mai, S.; Moustakas, K.; Malamis, D.; Loizidou, M. Study of Valorisation Routes of Spent Coffee Grounds. *Waste Biomass Valorization* **2020**, *11*, 5295–5306. [CrossRef]
261. Kwon, E.E.; Yi, H.; Jeon, Y.J. Sequential Co-Production of Biodiesel and Bioethanol with Spent Coffee Grounds. *Bioresour. Technol.* **2013**, *136*, 475–480. [CrossRef] [PubMed]
262. Vardon, D.R.; Moser, B.R.; Zheng, W.; Witkin, K.; Evangelista, R.L.; Strathmann, T.J.; Rajagopalan, K.; Sharma, B.K. Complete Utilization of Spent Coffee Grounds To Produce Biodiesel, Bio-Oil, and Biochar. *ACS Sustain. Chem. Eng.* **2013**, *1*, 1286–1294. [CrossRef]
263. Czekała, W.; Łukomska, A.; Pulka, J.; Bojarski, W.; Pochwatka, P.; Kowalczyk-Juśko, A.; Oniszczuk, A.; Dach, J. Waste-to-Energy: Biogas Potential of Waste from Coffee Production and Consumption. *Energy* **2023**, *276*, 127604. [CrossRef]
264. Kim, J.; Kim, H.; Baek, G.; Lee, C. Anaerobic Co-Digestion of Spent Coffee Grounds with Different Waste Feedstocks for Biogas Production. *Waste Manag.* **2017**, *60*, 322–328. [CrossRef]
265. Kim, D.; Cha, J.; Lee, C. Enhanced Methane Production with Co-Feeding Spent Coffee Grounds Using Spare Capacity of Existing Anaerobic Food Waste Digesters. *Sci. Rep.* **2024**, *14*, 4472. [CrossRef]
266. Albarracin, L.T.; Mas, I.R.; Fuess, L.T.; Rodriguez, R.P.; Volpi, M.P.C.; de Souza Moraes, B. The Bioenergetic Potential from Coffee Processing Residues: Towards an Industrial Symbiosis. *Resources* **2024**, *13*, 21. [CrossRef]
267. Rajesh Banu, J.; Kavitha, S.; Yukesh Kannah, R.; Dinesh Kumar, M.; Preethi; Atabani, A.E.; Kumar, G. Biorefinery of Spent Coffee Grounds Waste: Viable Pathway towards Circular Bioeconomy. *Bioresour. Technol.* **2020**, *302*, 122821. [CrossRef]
268. Zabaniotou, A.; Kamaterou, P. Food Waste Valorization Advocating Circular Bioeconomy—A Critical Review of Potentialities and Perspectives of Spent Coffee Grounds Biorefinery. *J. Clean. Prod.* **2019**, *211*, 1553–1566. [CrossRef]
269. del Castillo Bilbao, M.D.; Ibáñez Ezequiel, M.E.; Amigo Benavent, M.; Herrero Calleja, M.; Plaza del Moral, M.; Ullate Artiz, M. Application of Products of Coffee Silverskin in Anti-Ageing Cosmetics and Functional Food. Patent No. WO/2013/004873, 2013.
270. Guglielmetti, A.; Fernandez-Gomez, B.; Zeppa, G.; Del Castillo, M.D. 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. *Pol. J. Food Nutr. Sci.* **2019**, *69*, 157–166. [CrossRef]
271. Rios, M.B.; Iriondo-DeHond, A.; Iriondo-DeHond, M.; Herrera, T.; Velasco, D.; Gómez-Alonso, S.; Callejo, M.J.; Del Castillo, M.D. Effect of Coffee Cascara Dietary Fiber on the Physicochemical, Nutritional and Sensory Properties of a Gluten-Free Bread Formulation. *Molecules* **2020**, *25*, 1358. [CrossRef] [PubMed]
272. Rivas-Vela, C.I.; Amaya-Llano, S.L.; Castaño-Tostado, E. Effect of Extrusion Process on the Obtention of a Flour from Coffee Pulp *Coffea arabica* Variety Red Caturra and Its Use in Bakery Products. *J. Food Sci. Technol.* **2023**, *60*, 2792–2801. [CrossRef] [PubMed]
273. Gocmen, D.; Sahan, Y.; Yildiz, E.; Coskun, M.; Aroufai, İ.A. Use of Coffee Silverskin to Improve the Functional Properties of Cookies. *J. Food Sci. Technol.* **2019**, *56*, 2979–2988. [CrossRef] [PubMed]
274. Ateş, G.; Elmacı, Y. Physical, Chemical and Sensory Characteristics of Fiber-Enriched Cakes Prepared with Coffee Silverskin as Wheat Flour Substitution. *J. Food Meas. Charact.* **2019**, *13*, 755–763. [CrossRef]
275. Bouayed, J.; Deußer, H.; Hoffmann, L.; Bohn, T. Bioaccessible and Dialysable Polyphenols in Selected Apple Varieties Following in Vitro Digestion vs. Their Native Patterns. *Food Chem.* **2012**, *131*, 1466–1472. [CrossRef]
276. Ateş, G.; Elmacı, Y. Coffee Silverskin as Fat Replacer in Cake Formulations and Its Effect on Physical, Chemical and Sensory Attributes of Cakes. *LWT* **2018**, *90*, 519–525. [CrossRef]
277. Koay, H.Y.; Azman, A.T.; Mohd Zin, Z.; Portman, K.L.; Hasmadi, M.; Rusli, N.D.; Aidat, O.; Zainol, M.K. Assessing the Impact of Spent Coffee Ground (SCG) Concentrations on Shortbread: A Study of Physicochemical Attributes and Sensory Acceptance. *Future Foods* **2023**, *8*, 100245. [CrossRef]
278. Martinez-Saez, N.; Hochkogler, C.; Somoza, V.; Del Castillo, M. Biscuits with No Added Sugar Containing Stevia, Coffee Fibre and Fructooligosaccharides Modifies α-Glucosidase Activity and the Release of GLP-1 from HuTu-80 Cells and Serotonin from Caco-2 Cells after In Vitro Digestion. *Nutrients* **2017**, *9*, 694. [CrossRef]

279. Fåk, F.; Jakobsdottir, G.; Kulcinskaja, E.; Marungruang, N.; Matziouridou, C.; Nilsson, U.; Stålbrand, H.; Nyman, M. The Physico-Chemical Properties of Dietary Fibre Determine Metabolic Responses, Short-Chain Fatty Acid Profiles and Gut Microbiota Composition in Rats Fed Low- and High-Fat Diets. *PLoS ONE* **2015**, *10*, e0127252. [CrossRef]
280. Abioye, R.O.; Nwamba, O.C.; Okagu, O.D.; Udenigwe, C.C. Synergistic Effect of Acarbose–Chlorogenic Acid on α-Glucosidase Inhibition: Kinetics and Interaction Studies Reveal Mixed-Type Inhibition and Denaturant Effect of Chlorogenic Acid. *ACS Food Sci. Technol.* **2023**, *3*, 1255–1268. [CrossRef]
281. Xiao, J.; Kai, G.; Yamamoto, K.; Chen, X. Advance in Dietary Polyphenols as α-Glucosidases Inhibitors: A Review on Structure-Activity Relationship Aspect. *Crit. Rev. Food Sci. Nutr.* **2013**, *53*, 818–836. [CrossRef] [PubMed]
282. Voigt, J.-P.; Fink, H. Serotonin Controlling Feeding and Satiety. *Behav. Brain Res.* **2015**, *277*, 14–31. [CrossRef] [PubMed]
283. Holst, J.J. The Physiology of Glucagon-like Peptide 1. *Physiol. Rev.* **2007**, *87*, 1409–1439. [CrossRef] [PubMed]
284. Bertolino, M.; Barbosa-Pereira, L.; Ghirardello, D.; Botta, C.; Rolle, L.; Guglielmetti, A.; Borotto Dalla Vecchia, S.; Zeppa, G. Coffee Silverskin as Nutraceutical Ingredient in Yogurt: Its Effect on Functional Properties and Its Bioaccessibility. *J. Sci. Food Agric.* **2019**, *99*, 4267–4275. [CrossRef]
285. Minekus, M.; Alminger, M.; Alvito, P.; Ballance, S.; Bohn, T.; Bourlieu, C.; Carrière, F.; Boutrou, R.; Corredig, M.; Dupont, D.; et al. A Standardised Static in Vitro Digestion Method Suitable for Food—An International Consensus. *Food Funct.* **2014**, *5*, 1113–1124. [CrossRef]
286. Scalbert, A.; Johnson, I.T.; Saltmarsh, M. Polyphenols: Antioxidants and Beyond. *Am. J. Clin. Nutr.* **2005**, *81*, 215S–217S. [CrossRef]
287. Bassoli, B.K.; Cassolla, P.; Borba-Murad, G.R.; Constantin, J.; Salgueiro-Pagadigorria, C.L.; Bazotte, R.B.; da Silva, R.S.d.S.F.; de Souza, H.M. Chlorogenic Acid Reduces the Plasma Glucose Peak in the Oral Glucose Tolerance Test: Effects on Hepatic Glucose Release and Glycaemia. *Cell Biochem. Funct.* **2008**, *26*, 320–328. [CrossRef]
288. Choi, J.-H.; Kim, S. Investigation of the Anticoagulant and Antithrombotic Effects of Chlorogenic Acid. *J. Biochem. Mol. Toxicol.* **2017**, *31*, e21865. [CrossRef]
289. Glade, M.J. Caffeine—Not Just a Stimulant. *Nutrition* **2010**, *26*, 932–938. [CrossRef]
290. Iriondo-DeHond, M.; Iriondo-DeHond, A.; Herrera, T.; Fernández-Fernández, A.M.; Sorzano, C.O.S.; Miguel, E.; del Castillo, M.D. Sensory Acceptance, Appetite Control and Gastrointestinal Tolerance of Yogurts Containing Coffee-Cascara Extract and Inulin. *Nutrients* **2020**, *12*, 627. [CrossRef]
291. Martinez-Saez, N.; Ullate, M.; Martin-Cabrejas, M.A.; Martorell, P.; Genovés, S.; Ramon, D.; del Castillo, M.D. A Novel Antioxidant Beverage for Body Weight Control Based on Coffee Silverskin. *Food Chem.* **2014**, *150*, 227–234. [CrossRef] [PubMed]
292. Murthy, P.S.; Manjunatha, M.R.; Sulochannama, G.; Naidu, M.M. Extraction, Characterization and Bioactivity of Coffee Anthocyanins. *Eur. J. Biol. Sci.* **2012**, *4*, 13–19. [CrossRef]
293. Patil, S.; Pimpley, V.; Warudkar, K.; Murthy, P.S. Valorisation of Coffee Pulp for Development of Innovative Probiotic Beverage Using Kefir: Physicochemical, Antioxidant, Sensory Analysis and Shelf Life Studies. *Waste Biomass Valorization* **2022**, *13*, 905–916. [CrossRef]
294. Brand, D.; Pandey, A.; Roussos, S.; Brand, I.; Soccol, C.R. Microbial Degradation of Caffeine and Tannins from Coffee Husk. In *Coffee Biotechnology and Quality*; Sera, T., Soccol, C.R., Pandey, A., Roussos, S., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 393–400, ISBN 978-94-017-1068-8.
295. Lopes, A.C.A.; Andrade, R.P.; de Oliveira, L.C.C.; Lima, L.M.Z.; Santiago, W.D.; de Resende, M.L.V.; das Graças Cardoso, M.; Duarte, W.F. Production and Characterization of a New Distillate Obtained from Fermentation of Wet Processing Coffee By-Products. *J. Food Sci. Technol.* **2020**, *57*, 4481–4491. [CrossRef]
296. Sampaio, A.; Dragone, G.; Vilanova, M.; Oliveira, J.M.; Teixeira, J.A.; Mussatto, S.I. Production, Chemical Characterization, and Sensory Profile of a Novel Spirit Elaborated from Spent Coffee Ground. *LWT* **2013**, *54*, 557–563. [CrossRef]
297. Machado, E.; Mussatto, S.I.; Teixeira, J.; Vilanova, M.; Oliveira, J. Increasing the Sustainability of the Coffee Agro-Industry: Spent Coffee Grounds as a Source of New Beverages. *Beverages* **2018**, *4*, 105. [CrossRef]
298. Liu, Y.; Lu, Y.; Liu, S.Q. The Potential of Spent Coffee Grounds Hydrolysates Fermented with Torulaspora Delbrueckii and Pichia Kluyveri for Developing an Alcoholic Beverage: The Yeasts Growth and Chemical Compounds Modulation by Yeast Extracts. *Curr. Res. Food Sci.* **2021**, *4*, 489–498. [CrossRef]
299. Liu, Y.; Yuan, W.; Lu, Y.; Liu, S.Q. Biotransformation of Spent Coffee Grounds by Fermentation with Monocultures of Saccharomyces Cerevisiae and Lachancea Thermotolerans Aided by Yeast Extracts. *LWT* **2021**, *138*, 110751. [CrossRef]
300. Zhao, X.; Procopio, S.; Becker, T. Flavor Impacts of Glycerol in the Processing of Yeast Fermented Beverages: A Review. *J. Food Sci. Technol.* **2015**, *52*, 7588–7598. [CrossRef]
301. Rosas-Sánchez, G.A.; Hernández-Estrada, Z.J.; Suárez-Quiroz, M.L.; González-Ríos, O.; Rayas-Duarte, P. Coffee Cherry Pulp By-Product as a Potential Fiber Source for Bread Production: A Fundamental and Empirical Rheological Approach. *Foods* **2021**, *10*, 742. [CrossRef]
302. Littardi, P.; Rinaldi, M.; Grimaldi, M.; Cavazza, A.; Chiavaro, E. Effect of Addition of Green Coffee Parchment on Structural, Qualitative and Chemical Properties of Gluten-Free Bread. *Foods* **2020**, *10*, 5. [CrossRef] [PubMed]
303. Pourfarzad, A.; Mahdavian-Mehr, H.; Sedaghat, N. Coffee Silverskin as a Source of Dietary Fiber in Bread-Making: Optimization of Chemical Treatment Using Response Surface Methodology. *LWT Food Sci. Technol.* **2013**, *50*, 599–606. [CrossRef]
304. Garcia-Serna, E.; Martinez-Saez, N.; Mesias, M.; Morales, F.J.; del Castillo, M.D. Use of Coffee Silverskin and Stevia to Improve the Formulation of Biscuits. *Pol. J. Food Nutr. Sci.* **2014**, *64*, 243–251. [CrossRef]

305. Badr, A.N.; El-Attar, M.M.; Ali, H.S.; Elkhadragy, M.F.; Yehia, H.M.; Farouk, A. Spent Coffee Grounds Valorization as Bioactive Phenolic Source Acquired Antifungal, Anti-Mycotoxigenic, and Anti-Cytotoxic Activities. *Toxins* **2022**, *14*, 109. [CrossRef]
306. Beltrán-Medina, E.A.; Guatemala-Morales, G.M.; Padilla-Camberos, E.; Corona-González, R.I.; Mondragón-Cortez, P.M.; Arriola-Guevara, E. Evaluation of the Use of a Coffee Industry By-Product in a Cereal-Based Extruded Food Product. *Foods* **2020**, *9*, 1008. [CrossRef]
307. Damat, D.; Anggriani, R.; Setyobudi, R.H.; Soni, P. Dietary Fiber and Antioxidant Activity of Gluten-Free Cookies with Coffee Cherry Flour Addition. *Coffee Sci.* **2019**, *14*, 493–500. [CrossRef]
308. Cubero-Castillo, E.; Bonilla-Leiva, A.R.; García-Velasques, E. Coffee Berry Processing By-Product Valorization: Coffee Parchment as a Potential Fiber Source to Enrich Bakery Goods. *J. Food Nutr. Popul. Health* **2017**, *1*, 1–7.
309. Han, I.; Lee, C.S. Quality Properties and Bioactivities of American Cookies with Coffee Extract Residues. *LWT* **2021**, *151*, 112173. [CrossRef]
310. Trà, T.T.T.; Phúc, L.N.; Yến, V.T.N.; Sang, L.T.; Thu, N.T.A.; Nguyệt, T.N.M.; Mẫn, L.V.V. Use of Wheat Flour and Spent Coffee Grounds in the Production of Cookies with High Fiber and Antioxidant Content: Effects of Spent Coffee Grounds Ratio on the Product Quality. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *947*, 012044. [CrossRef]
311. Aguilar-Raymundo, V.G.; Sánchez-Páez, R.; Gutiérrez-Salomón, A.L.; Barajas-Ramírez, J.A. Spent Coffee Grounds Cookies: Sensory and Texture Characteristics, Proximate Composition, Antioxidant Activity, and Total Phenolic Content. *J. Food Process. Preserv.* **2019**, *43*, e14223. [CrossRef]
312. Meerasri, J.; Sothornvit, R. Novel Development of Coffee Oil Extracted from Spent Coffee Grounds as a Butter Substitute in Bakery Products. *J. Food Process. Preserv.* **2022**, *46*, e16687. [CrossRef]
313. Parra-Campos, A.; Ordóñez-Santos, L.E. Natural Pigment Extraction Optimization from Coffee Exocarp and Its Use as a Natural Dye in French Meringue. *Food Chem.* **2019**, *285*, 59–66. [CrossRef] [PubMed]
314. Benincá, D.B.; do Carmo, L.B.; Grancieri, M.; Aguiar, L.L.; Lima Filho, T.; Costa, A.G.V.; Oliveira, D.d.S.; Saraiva, S.H.; Silva, P.I. Incorporation of Spent Coffee Grounds in Muffins: A Promising Industrial Application. *Food Chem. Adv.* **2023**, *3*, 100329. [CrossRef]
315. Severini, C.; Caporizzi, R.; Fiore, A.G.; Ricci, I.; Onur, O.M.; Derossi, A. Reuse of Spent Espresso Coffee as Sustainable Source of Fibre and Antioxidants. A Map on Functional, Microstructure and Sensory Effects of Novel Enriched Muffins. *LWT* **2020**, *119*, 108877. [CrossRef]
316. Iriondo-DeHond, A.; Elizondo, A.S.; Iriondo-DeHond, M.; Ríos, M.B.; Mufari, R.; Mendiola, J.A.; Ibañez, E.; del Castillo, M.D. Assessment of Healthy and Harmful Maillard Reaction Products in a Novel Coffee Cascara Beverage: Melanoidins and Acrylamide. *Foods* **2020**, *9*, 620. [CrossRef]
317. Nguyen Le, B.X.; Van, T.P.; Phan, Q.K.; Pham, G.B.; Quang, H.P.; Do, A.D. Coffee Husk By-Product as Novel Ingredients for Cascara Kombucha Production. *J. Microbiol. Biotechnol.* **2024**, *34*, 673–680. [CrossRef]
318. Masino, F.; Montevecchi, G.; Calvini, R.; Foca, G.; Antonelli, A. Sensory Evaluation and Mixture Design Assessment of Coffee-Flavored Liquor Obtained from Spent Coffee Grounds. *Food Qual. Prefer.* **2022**, *96*, 104427. [CrossRef]
319. Phan, D.T.A.; Ha, H.T.; Ho, T.T. An Extract and Fractions from *Coffea arabica* Sediment on Antioxidant and Anti-Tyrosinase Activities, and on the Quality of Whiteleg Shrimp (*Litopenaus vannamei*) during Refrigerated Storage. *Prev. Nutr. Food Sci.* **2021**, *26*, 346–356. [CrossRef]
320. Lin, C.; Toto, C.; Were, L. Antioxidant Effectiveness of Ground Roasted Coffee in Raw Ground Top Round Beef with Added Sodium Chloride. *LWT* **2015**, *60*, 29–35. [CrossRef]
321. Hashimoto, T.A.; Caporaso, F.; Toto, C.; Were, L. Antioxidant Capacity and Sensory Impact of Coffee Added to Ground Pork. *Eur. Food Res. Technol.* **2019**, *245*, 977–986. [CrossRef]
322. El-Chaghaby, G.A.; Shehta, H.A.; Rashad, S.; Rawash, E.-S.A.; Eid, H.R. Evaluation of the Antioxidant and Antimicrobial Activities of the Spent Coffee Extracts and Their Applications as Natural Food Preservatives of Chicken Fillets. *Nov. Res. Microbiol. J.* **2024**, *8*, 2303–2319. [CrossRef]
323. Estévez, M.; Cava, R. Lipid and Protein Oxidation, Release of Iron from Heme Molecule and Colour Deterioration during Refrigerated Storage of Liver Pâté. *Meat Sci.* **2004**, *68*, 551–558. [CrossRef] [PubMed]
324. Lund, M.N.; Heinonen, M.; Baron, C.P.; Estévez, M. Protein Oxidation in Muscle Foods: A Review. *Mol. Nutr. Food Res.* **2011**, *55*, 83–95. [CrossRef] [PubMed]
325. Kim, J.H.; Ahn, D.U.; Eun, J.B.; Moon, S.H. Antioxidant Effect of Extracts from the Coffee Residue in Raw and Cooked Meat. *Antioxidants* **2016**, *5*, 21. [CrossRef]
326. Sánchez-Escalante, A.; Djenane, D.; Torrescano, G.; Beltrán, J.A.; Roncales, P. Antioxidant Action of Borage, Rosemary, Oregano, and Ascorbic Acid in Beef Patties Packaged in Modified Atmosphere. *J. Food Sci.* **2003**, *68*, 339–344. [CrossRef]
327. Estévez, M.; Cava, R. Effectiveness of Rosemary Essential Oil as an Inhibitor of Lipid and Protein Oxidation: Contradictory Effects in Different Types of Frankfurters. *Meat Sci.* **2006**, *72*, 348–355. [CrossRef]
328. Yanishlieva, N.V.; Marinova, E.M. Stabilisation of Edible Oils with Natural Antioxidants. *Eur. J. Lipid Sci. Technol.* **2001**, *103*, 752–767. [CrossRef]
329. Qi, J.; Xu, Y.; Zhang, W.; Xie, X.; Xiong, G.; Xu, X. Short-Term Frozen Storage of Raw Chicken Meat Improves Its Flavor Traits upon Stewing. *LWT* **2021**, *142*, 111029. [CrossRef]

330. Jully, K.M.M.; Toto, C.S.; Were, L. Antioxidant Effect of Spent, Ground, and Lyophilized Brew from Roasted Coffee in Frozen Cooked Pork Patties. *LWT Food Sci. Technol.* **2016**, *66*, 244–251. [CrossRef]
331. de Farias Marques, A.D.J.; de Lima Tavares, J.; de Carvalho, L.M.; Leite Abreu, T.; Alves Pereira, D.; Moreira Fernandes Santos, M.; Suely Madruga, M.; de Medeiros, L.L.; Kênia Alencar Bezerra, T. Oxidative Stability of Chicken Burgers Using Organic Coffee Husk Extract. *Food Chem.* **2022**, *393*, 133451. [CrossRef]
332. Sasse, A.; Colindres, P.; Brewer, M.S. Effect of Natural and Synthetic Antioxidants on the Oxidative Stability of Cooked, Frozen Pork Patties. *J. Food Sci.* **2009**, *74*, S30–S35. [CrossRef] [PubMed]
333. Lourith, N.; Xivivadh, K.; Boonkong, P.; Kanlayavattanakul, M. Spent Coffee Waste: A Sustainable Source of Cleansing Agent for a High-Performance Makeup Remover. *Sustain. Chem. Pharm.* **2022**, *29*, 100826. [CrossRef]
334. Kanlayavattanakul, M.; Lourith, N.; Chaikul, P. Valorization of Spent Coffee Grounds as the Specialty Material for Dullness and Aging of Skin Treatments. *Chem. Biol. Technol. Agric.* **2021**, *8*, 55. [CrossRef]
335. Shankaranand, V.S.; Lonsane, B.K. Coffee Husk: An Inexpensive Substrate for Production of Citric Acid by Aspergillus Niger in a Solid-State Fermentation System. *World J. Microbiol. Biotechnol.* **1994**, *10*, 165–168. [CrossRef]
336. Machado, C.M.M.; Soccol, C.R.; de Oliveira, B.H.; Pandey, A. Gibberellic Acid Production by Solid-State Fermentation in Coffee Husk. *Appl. Biochem. Biotechnol.* **2002**, *102*, 179–191. [CrossRef]
337. Hudeckova, H.; Neureiter, M.; Obruca, S.; Frühauf, S.; Marova, I. Biotechnological Conversion of Spent Coffee Grounds into Lactic Acid. *Lett. Appl. Microbiol.* **2018**, *66*, 306–312. [CrossRef]
338. Dessie, W.; Zhu, J.; Xin, F.; Zhang, W.; Jiang, Y.; Wu, H.; Ma, J.; Jiang, M. Bio-Succinic Acid Production from Coffee Husk Treated with Thermochemical and Fungal Hydrolysis. *Bioprocess Biosyst. Eng.* **2018**, *41*, 1461–1470. [CrossRef]
339. Niglio, S.; Procentese, A.; Russo, M.E.; Sannia, G.; Marzocchella, A. Investigation of Enzymatic Hydrolysis of Coffee Silverskin Aimed at the Production of Butanol and Succinic Acid by Fermentative Processes. *BioEnergy Res.* **2019**, *12*, 312–324. [CrossRef]
340. Kim, B.; Yang, J.; Kim, M.; Lee, J.W. One-Pot Selective Production of Levulinic Acid and Formic Acid from Spent Coffee Grounds in a Catalyst-Free Biphasic System. *Bioresour. Technol.* **2020**, *303*, 122898. [CrossRef]
341. Pileidis, F.D.; Titirici, M.-M. Corrigendum: Levulinic Acid Biorefineries: New Challenges for Efficient Utilization of Biomass. *ChemSusChem* **2016**, *9*, 652–655. [CrossRef]
342. Schneider, R.; Mehlmann, K.; Venus, J.; Alexandri, M. Recent Advances in D-Lactic Acid Production from Renewable Resources. *Food Technol. Biotechnol.* **2019**, *57*, 293–304. [CrossRef]
343. Pettinato, M.; Drago, E.; Campardelli, R.; Perego, P. Spent Coffee Grounds Extract for Active Packaging Production. *Chem. Eng. Trans.* **2021**, *87*, 583–588. [CrossRef]
344. Oliveira, G.; Passos, C.P.; Ferreira, P.; Coimbra, M.A.; Gonçalves, I. Coffee By-Products and Their Suitability for Developing Active Food Packaging Materials. *Foods* **2021**, *10*, 683. [CrossRef] [PubMed]
345. Singh, T.; Pandey, V.K.; Dash, K.K.; Zanwar, S.; Singh, R. Natural Bio-Colorant and Pigments: Sources and Applications in Food Processing. *J. Agric. Food Res.* **2023**, *12*, 100628. [CrossRef]
346. Murthy, P.S.; Naidu, M.M. Recovery of Phenolic Antioxidants and Functional Compounds from Coffee Industry By-Products. *Food Bioprocess Technol.* **2012**, *5*, 897–903. [CrossRef]
347. Prata, E.R.B.A.; Oliveira, L.S. Fresh Coffee Husks as Potential Sources of Anthocyanins. *LWT Food Sci. Technol.* **2007**, *40*, 1555–1560. [CrossRef]
348. Moreira, M.D.; Melo, M.M.; Coimbra, J.M.; dos Reis, K.C.; Schwan, R.F.; Silva, C.F. Solid Coffee Waste as Alternative to Produce Carotenoids with Antioxidant and Antimicrobial Activities. *Waste Manag.* **2018**, *82*, 93–99. [CrossRef]
349. Panusa, A.; Zuorro, A.; Lavecchia, R.; Marrosu, G.; Petrucci, R. Recovery of Natural Antioxidants from Spent Coffee Grounds. *J. Agric. Food Chem.* **2013**, *61*, 4162–4168. [CrossRef]
350. Zhang, H.; Zhang, H.; Troise, A.D.; Fogliano, V. Melanoidins from Coffee, Cocoa, and Bread Are Able to Scavenge α-Dicarbonyl Compounds under Simulated Physiological Conditions. *J. Agric. Food Chem.* **2019**, *67*, 10921–10929. [CrossRef]
351. Rufián-Henares, J.A.; Pastoriza, S. Chapter 20—Melanoidins in Coffee. In *Coffee in Health and Disease Prevention*; Preedy, V.R., Ed.; Academic Press: San Diego, CA, USA, 2015; pp. 183–188, ISBN 978-0-12-409517-5.
352. Sutakwa, A.; Nadia, L.S.; Suharman, S. Addition of Blue Pea Flower (*Clitoria ternatea* L.) Extract Increase Antioxidant Activity in Yogurt from Various Types of Milk. *J. Agercolere* **2021**, *3*, 31–37. [CrossRef]
353. Aguilera, Y.; Mojica, L.; Rebollo-Hernanz, M.; Berhow, M.; de Mejía, E.G.; Martín-Cabrejas, M.A. Black Bean Coats: New Source of Anthocyanins Stabilized by β-Cyclodextrin Copigmentation in a Sport Beverage. *Food Chem.* **2016**, *212*, 561–570. [CrossRef] [PubMed]
354. Khoo, H.E.; Azlan, A.; Tang, S.T.; Lim, S.M. Anthocyanidins and Anthocyanins: Colored Pigments as Food, Pharmaceutical Ingredients, and the Potential Health Benefits. *Food Nutr. Res.* **2017**, *61*, 1361779. [CrossRef] [PubMed]
355. Ngamwonglumlert, L.; Devahastin, S.; Chiewchan, N. Natural Colorants: Pigment Stability and Extraction Yield Enhancement via Utilization of Appropriate Pretreatment and Extraction Methods. *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 3243–3259. [CrossRef] [PubMed]
356. Rodriguez-Amaya, D.B. Natural Food Pigments and Colorants. *Curr. Opin. Food Sci.* **2016**, *7*, 20–26. [CrossRef]
357. Nabi, B.G.; Mukhtar, K.; Ahmed, W.; Manzoor, M.F.; Ranjha, M.M.A.N.; Kieliszek, M.; Bhat, Z.F.; Aadil, R.M. Natural Pigments: Anthocyanins, Carotenoids, Chlorophylls, and Betalains as Colorants in Food Products. *Food Biosci.* **2023**, *52*, 102403. [CrossRef]

358. Roy, S.; Rhim, J.-W. Anthocyanin Food Colorant and Its Application in PH-Responsive Color Change Indicator Films. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 2297–2325. [CrossRef]
359. Rodriguez-Amaya, D.B. Update on Natural Food Pigments—A Mini-Review on Carotenoids, Anthocyanins, and Betalains. *Food Res. Int.* **2019**, *124*, 200–205. [CrossRef]
360. Liu, Y.; Liu, Y.; Tao, C.; Liu, M.; Pan, Y.; Lv, Z. Effect of Temperature and PH on Stability of Anthocyanin Obtained from Blueberry. *J. Food Meas. Charact.* **2018**, *12*, 1744–1753. [CrossRef]
361. Li, Y.; Hu, K.; Huang, C.; Hu, Y.; Ji, H.; Liu, S.; Gao, J. Improvement of Solubility, Stability and Antioxidant Activity of Carotenoids Using Deep Eutectic Solvent-Based Microemulsions. *Colloids Surf. B Biointerfaces* **2022**, *217*, 112591. [CrossRef]
362. Bocker, R.; Silva, E.K. Pulsed Electric Field Assisted Extraction of Natural Food Pigments and Colorings from Plant Matrices. *Food Chem. X* **2022**, *15*, 100398. [CrossRef]
363. González-Peña, M.A.; Ortega-Regules, A.E.; Anaya de Parrodi, C.; Lozada-Ramírez, J.D. Chemistry, Occurrence, Properties, Applications, and Encapsulation of Carotenoids—A Review. *Plants* **2023**, *12*, 313. [CrossRef] [PubMed]
364. Lozada-Ramírez, J.D.; Guerrero-Moras, M.C.; González-Peña, M.A.; Silva-Pereira, T.S.; Anaya de Parrodi, C.; Ortega-Regules, A.E. Stabilization of Anthocyanins from Coffee (*Coffea arabica* L.) Husks and In Vivo Evaluation of Their Antioxidant Activity. *Molecules* **2023**, *28*, 1353. [CrossRef] [PubMed]
365. Ribeiro, J.S.; Veloso, C.M. Microencapsulation of Natural Dyes with Biopolymers for Application in Food: A Review. *Food Hydrocoll.* **2021**, *112*, 106374. [CrossRef]
366. Tores de la Cruz, S.; Iriondo-DeHond, A.; Herrera, T.; Lopez-Tofiño, Y.; Galvez-Robleño, C.; Prodanov, M.; Velazquez-Escobar, F.; Abalo, R.; del Castillo, M.D. An Assessment of the Bioactivity of Coffee Silverskin Melanoidins. *Foods* **2019**, *8*, 68. [CrossRef]
367. Jiang, Y.; Zhang, Y.; Deng, Y. Latest Advances in Active Materials for Food Packaging and Their Application. *Foods* **2023**, *12*, 4055. [CrossRef]
368. Ahmed, M.W.; Haque, M.A.; Mohibbullah, M.; Khan, M.S.I.; Islam, M.A.; Mondal, M.H.T.; Ahmmed, R. A Review on Active Packaging for Quality and Safety of Foods: Current Trends, Applications, Prospects and Challenges. *Food Packag. Shelf Life* **2022**, *33*, 100913. [CrossRef]
369. Ghazvini, A.K.A.; Ormondroyd, G.; Curling, S.; Saccani, A.; Sisti, L. An Investigation on the Possible Use of Coffee Silverskin in PLA/PBS Composites. *J. Appl. Polym. Sci.* **2022**, *139*, 52264. [CrossRef]
370. Moustafa, H.; Guizani, C.; Dufresne, A. Sustainable Biodegradable Coffee Grounds Filler and Its Effect on the Hydrophobicity, Mechanical and Thermal Properties of Biodegradable PBAT Composites. *J. Appl. Polym. Sci.* **2017**, *134*, 44498. [CrossRef]
371. Sarasini, F.; Luzi, F.; Dominici, F.; Maffei, G.; Iannone, A.; Zuorro, A.; Lavecchia, R.; Torre, L.; Carbonell-Verdu, A.; Balart, R.; et al. Effect of Different Compatibilizers on Sustainable Composites Based on a PHBV/PBAT Matrix Filled with Coffee Silverskin. *Polymers* **2018**, *10*, 1256. [CrossRef]
372. Moustafa, H.; Guizani, C.; Dupont, C.; Martin, V.; Jeguirim, M.; Dufresne, A. Utilization of Torrefied Coffee Grounds as Reinforcing Agent to Produce High-Quality Biodegradable PBAT Composites for Food Packaging Applications. *ACS Sustain. Chem. Eng.* **2017**, *5*, 1906–1916. [CrossRef]
373. Schutz, G.F.; Alves, R.M.V.; Vieira, R.P. Development of Starch-Based Films Reinforced with Coffee Husks for Packaging Applications. *J. Polym. Environ.* **2023**, *31*, 1955–1966. [CrossRef]
374. Hernández-Varela, J.D.; Chanona-Pérez, J.J.; Foruzanmehr, R.; Medina, D.I. Assessing the Reinforcement Effect by Response Surface Methodology of Holocellulose from Spent Coffee Grounds on Biopolymeric Films as Food Packaging Materials. *Biopolymers* **2024**, *115*, e23585. [CrossRef] [PubMed]
375. Turan, D.; Wang, Y.; Grundmann, D.; Paillart, M.; Dieleman, R.; Rahn, A. Coffee By-Product Cascara as an Edible Active Coating for Enhancing Hazelnut Preservation and Packaging. *Food Packag. Shelf Life* **2024**, *45*, 101350. [CrossRef]
376. Collazo-Bigliardi, S.; Ortega-Toro, R.; Chiralt, A. Improving Properties of Thermoplastic Starch Films by Incorporating Active Extracts and Cellulose Fibres Isolated from Rice or Coffee Husk. *Food Packag. Shelf Life* **2019**, *22*, 100383. [CrossRef]
377. Yang, J.; Li, Y.; Liu, B.; Wang, K.; Li, H.; Peng, L. Carboxymethyl Cellulose-Based Multifunctional Film Integrated with Polyphenol-Rich Extract and Carbon Dots from Coffee Husk Waste for Active Food Packaging Applications. *Food Chem.* **2024**, *448*, 139143. [CrossRef]
378. Papadaki, A.; Kachrimanidou, V.; Lappa, I.K.; Andriotis, H.; Eriotou, E.; Mandala, I.; Kopsahelis, N. Tuning the Physical and Functional Properties of Whey Protein Edible Films: Effect of PH and Inclusion of Antioxidants from Spent Coffee Grounds. *Sustain. Chem. Pharm.* **2022**, *27*, 100700. [CrossRef]
379. Dordevic, D.; Gablo, N.; Zelenkova, L.; Dordevic, S.; Tremlova, B. Utilization of Spent Coffee Grounds as a Food By-Product to Produce Edible Films Based on κ-Carrageenan with Biodegradable and Active Properties. *Foods* **2024**, *13*, 1833. [CrossRef]
380. Collazo-Bigliardi, S.; Ortega-Toro, R.; Chiralt, A. Using Lignocellulosic Fractions of Coffee Husk to Improve Properties of Compatibilised Starch-PLA Blend Films. *Food Packag. Shelf Life* **2019**, *22*, 100423. [CrossRef]
381. Sung, S.H.; Chang, Y.; Han, J. Development of Polylactic Acid Nanocomposite Films Reinforced with Cellulose Nanocrystals Derived from Coffee Silverskin. *Carbohydr. Polym.* **2017**, *169*, 495–503. [CrossRef]
382. Cavanagh, Q.; Brooks, M.S.-L.; Rupasinghe, H.P.V. Innovative Technologies Used to Convert Spent Coffee Grounds into New Food Ingredients: Opportunities, Challenges, and Prospects. *Future Foods* **2023**, *8*, 100255. [CrossRef]
383. Hoinkes, C.; Blumer, F. Why the Nescafé Plan Fails to Benefit Farmers. Available online: https://www.publiceye.ch/en/topics/soft-commodity-trading/why-the-nescafe-plan-fails-to-benefit-farmers (accessed on 3 October 2024).

384. Foreign Agricultural Service (USDA). Production—Coffee. Available online: https://fas.usda.gov/data/production/commodity/0711100 (accessed on 3 October 2024).
385. Rennie, D. *Leading the World of Coffee*; Nestlé: Vevey, Switzerland, 2022.
386. Nestlé. *Creating Shared Value and Sustainability Report 2023*; Nestlé: Vevey, Switzerland, 2023.
387. Lekto Woodfuels Ltd. The Rise and Fall of Coffee Logs: From Richard Branson's Backing to Bankruptcy (Updated November 2023). Available online: https://www.lektowoodfuels.co.uk/blogs/news/bio-bean-coffee-logs?srsltid=AfmBOorcAbevaXwlEtwrVMf0YfPj9qWxCuOVC0ML55BmbDMQ1WJj65Lo (accessed on 16 August 2024).
388. Mattinson, A. Coffee Logs Supplier Bio-Bean Collapses Following on-Site Fire. Available online: https://www.thegrocer.co.uk/news/coffee-logs-supplier-bio-bean-collapses-following-on-site-fire/678767.article (accessed on 16 August 2024).
389. Envar. Envar Composting Ltd. Acquires Bio-Bean Ltd. Available online: https://www.envar.co.uk/envar-composting-ltd-acquires-bio-bean-ltd/ (accessed on 19 August 2024).
390. Langenbahn, H.J. Upcycled Coffee By-Products and Food Safety. Challenges for Coffee Producers. Available online: https://www.thezerowastecoffeeproject.com/post/upcycled-coffee-by-products-and-food-safety (accessed on 1 October 2024).
391. NEFF. Permafungi: Breeding Mushrooms with Old Coffee Grounds. Available online: https://www.neff-home.com/theingredient/story/mushrooms (accessed on 18 August 2024).
392. The European Circular Economy Stakeholder Platform. PermaFungi—Recycling Coffee Grounds into Upcycled Products. Available online: https://circulareconomy.europa.eu/platform/en/good-practices/permafungi-recycling-coffee-grounds-upcycled-products (accessed on 18 August 2024).
393. Permafungi. *Press Kit 2019*; PermaFungi: Brussels, Belgium, 2019; Available online: https://www.permafungi.be/wp-content/uploads/2019/02/Press-Kit-2019.pdf (accessed on 18 August 2024).
394. Marnix, A. Financial Data of Permafungi. Available online: https://www.companyweb.be/en/0546704074/permafungi (accessed on 5 October 2024).
395. Imbibe Coffee Roasters. Zero Waste Coffee. Available online: https://imbibe.ie/wholesale/zero-waste/ (accessed on 18 August 2024).
396. Nestlé. *Financial Statements 2023*; Nestlé: Vevey, Switzerland, 2024.
397. Arthur, R. Coffee Power: Nestlé Waters Announces Swiss Biogas Plant—With a Little Help from Nespresso. Available online: https://www.beveragedaily.com/Article/2015/04/02/Coffee-power-Nestle-Waters-announces-Swiss-biogas-plant-with-a-little-help-from-Nespresso (accessed on 16 August 2024).
398. Nestle. Nestlé Waters Starts Building Swiss Biogas Plant. Available online: https://www.nestle.com/media/news/nestle-waters-swiss-biogas-plant (accessed on 16 August 2024).
399. Starbucks Corporation. *Starbucks Fiscal 2023 Annual Report*; Starbucks Corporation: Seattle, WA, USA, 2024.
400. Starbucks. Starbucks' Eco-Friendly Mission Reinforced by #GroundsForYourGarden Encouraging Customers to Enrich Soil with Coffee Grounds. Available online: https://www.starbucks.co.th/ground-for-your-garden/ (accessed on 20 August 2024).
401. Starbucks. Starbucks Grounds For Your Garden: Rooted in a Mission to Help Local Communities Grow. Available online: https://stories.starbucks.ca/en-ca/stories/2021/starbucks-grounds-for-your-garden-rooted-in-a-mission-to-help-local-communities-grow/ (accessed on 20 August 2024).
402. Tracxn. Bio-Bean. Available online: https://platform.tracxn.com/a/d/company/Y0xg7jiQSNapicDNFM0soH0BXhp8t_dmfyPZoQmuvlk/bio-bean.com#a:key-metrics (accessed on 3 October 2024).
403. Nestle Spent Coffee Grounds Help Power Queensland Factory. Available online: https://www.nestle.com.au/en/stories/recycled-coffee (accessed on 16 August 2024).
404. Agència Catalana de Notícies (ACN). Nestlé to Invest €17.2m in Biomass Boiler in Girona Plant. Available online: https://www.catalannews.com/business/item/nestle-to-invest-17-2m-in-biomass-boiler-in-girona-plant (accessed on 16 August 2024).
405. Invest in Spain (ICEX). Nestlé Boosts Environmental Sustainability in Spanish Factories. Available online: https://www.investinspain.org/content/icex-invest/en/noticias-main/2023/nestle.html (accessed on 16 August 2023).
406. Veolia Coffee Grounds. Available online: https://www.anz.veolia.com/services/recycling-waste-services/recycling/organics/coffee-grounds (accessed on 22 August 2024).
407. Veolia Turning Waste into Renewable Energy. Available online: https://www.veolia.hu/en/our-services/industrial/case-studies/food-beverage/netherlands-douwe-egberts-master-blenders-demb (accessed on 22 August 2024).
408. Veolia Coffee Grounds Turned into Renewable Energy. Available online: https://www.veolia.in/about-us/cop21/our-solutions/coffee-grounds-turned-renewable-energy (accessed on 22 August 2024).
409. Veolia Environnement. *Veolia—Operating & Financial Review*; Veolia Environnement: Aubervilliers, France, 2023; Volume 2023.
410. Caffee Inc. Start Creating Eco-Friendly Coffee Based Products Your Customers Will Love. Available online: https://caffeinc.nl/ (accessed on 19 August 2024).
411. Caffe Inc. Caffee Inc.—Linkedin. Available online: https://www.linkedin.com/posts/caffeinc_last-thursday-caffe-inc-hosted-an-open-day-activity-7211691073075621888-xwJW (accessed on 3 October 2024).
412. Caffee Inc. Caffe Inc. Signs Contract for €4 Million to Build Recycling Plant for Coffee Waste in Amsterdam. Available online: https://caffeinc.nl/updates/caffe-inc-signs-contract-for-e4-million-to-build-recycling-plant-for-coffee-waste-in-amsterdam/ (accessed on 3 October 2024).
413. Coffeefrom Materials. Available online: https://coffeefrom.it/en/materials/#bio (accessed on 20 August 2024).

414. Gallo, L. Turning Coffee Waste into Thermoplastics with CoffeeFrom. Available online: https://www.forestvalley.org/article/turning-coffee-waste-into-thermoplastics-with-coffee-from (accessed on 3 October 2024).
415. Ecobean Products with Potential. Available online: https://ecobean.pl (accessed on 20 August 2024).
416. Tracxn. Ecobean. Available online: https://platform.tracxn.com/a/d/company/-9qWzxUeU6zV3nwbCOvZnbmm5LHXzIbi0-RXF4_9fSU/ecobean.pl#a:key-metrics (accessed on 3 October 2024).
417. Huskee. HuskeeLoop. Available online: https://huskee.co/huskeeloop/ (accessed on 20 August 2024).
418. Melo, C. Sustainable Solutions: Repurposing Coffee Waste for a Greener Future. Available online: https://www.eraofwe.com/coffee-lab/en/articles/sustainable-solutions-repurposing-coffee-waste-for-a-greener-future (accessed on 20 August 2024).
419. Huskee. HuskeeCup: Waste Made Beautiful. Available online: https://www.kickstarter.com/projects/1366930566/huskeecup-waste-made-beautiful?ref=discovery&term=Huskee&total_hits=1&category_id=28 (accessed on 3 October 2024).
420. Australian Circular Economy Hub Huskee. Creating Reusable Coffee Cups from Coffee Husk Waste. Available online: https://acehub.org.au/knowledge-hub/case-studies/huskee (accessed on 3 October 2024).
421. Kaffe Bueno. We Make It Natural. Available online: https://www.kaffebueno.com/ (accessed on 17 August 2024).
422. Monagas, D.C. World's First Coffee Biorefinery Opens in Denmark. Available online: https://worldbiomarketinsights.com/worlds-first-coffee-biorefinery-opens-in-denmark/ (accessed on 3 October 2024).
423. Monagas, D.C. Kaffe Bueno Secures €6.2 Million in Series A Round Led by Global Biorefinery Leader Borregaard. Available online: https://worldbiomarketinsights.com/kaffe-bueno-secures-e6-2-million-in-series-a-round-led-by-global-biorefinery-leader-borregaard/ (accessed on 3 October 2024).
424. Tracxn Kaffe Bueno. Available online: https://platform.tracxn.com/a/d/company/MlFsjODwQdnKEyy1IltTK-2W5XVdAOJJhwLddqj827Y/kaffebueno.com#a:key-metrics (accessed on 3 October 2024).
425. Kaffeeform. Available online: https://www.kaffeeform.com/en/material/ (accessed on 20 August 2024).
426. Morrison, L. The People Getting Rich off the Discards of Our Addiction. Available online: https://www.bbc.com/worklife/article/20160818-the-people-getting-rich-off-the-discards-of-our-addiction (accessed on 3 October 2024).
427. Krasaephol, S. PTT InI's Product—Coffee Chaff. Available online: https://www.pttplc.com/en/Products/Ourbusinessbypttplc/Technologyandengineeringunit/Technologyandengineering/Pttinis-Product/Content-26913.aspx (accessed on 17 September 2024).
428. PTT Public Company Limited. *Financial Report 2023*; PTT Public Company Limited: Bangkok, Thailand, 2023.
429. The Stock Exchange of Thailand (SET). PTT—Factsheet. Available online: https://www.set.or.th/en/market/product/stock/quote/ptt/factsheet (accessed on 5 October 2024).
430. Nestle. NESCAFÉ NATIV Cascara. Available online: https://www.nestle.com.au/en/brands/cascara (accessed on 16 August 2024).
431. Nestle. Nestlé Tackles Upstream Food Waste Through Product and Technology Innovation. Available online: https://www.nestle.com/aboutus/research-development/news/nestle-science-technology-new-value-agricultural-side-streams (accessed on 16 August 2024).
432. Hedlund, D. What Is a Cascara Latte? Available online: https://www.eraofwe.com/coffee-lab/en/articles/what-is-a-cascara-latte (accessed on 20 August 2024).
433. Starbucks Introducing Starbucks First New Beverage of 2017, the Cascara Latte. Available online: https://stories.starbucks.com/stories/2017/starbucks-cascara-latte/ (accessed on 20 August 2024).
434. Supracafe ¿Conoces La Infusión de Cáscara de Café? Supracafé Maximiza Su Sostenibilidad Con Tabifruit. Available online: https://www.supracafe.com/blogs/news/conoces-la-infusion-de-cascara-de-cafe-supracafe-maximiza-su-sostenibilidad-con-tabifruit (accessed on 16 September 2024).
435. Invest in Spain (ICEX). Supracafé. Available online: https://www.investinspain.org/content/icex-invest/en/casos-exito-main/NEW2015493859_EN_US.html (accessed on 5 October 2024).
436. COFIDES. Supracafe Expands Its Colombian Subsidiary with COFIDES Financial Support. Available online: https://www.cofides.es/en/noticias/notas-de-prensa/supracafe-expands-its-colombian-subsidiary-cofides-financial-support (accessed on 5 October 2024).
437. The Coffee Cherry, Co. Available online: https://coffeecherryco.com (accessed on 17 August 2024).
438. Kirchherr, J.; Piscicelli, L.; Bour, R.; Kostense-Smit, E.; Muller, J.; Huibrechtse-Truijens, A.; Hekkert, M. Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecol. Econ.* **2018**, *150*, 264–272. [CrossRef]
439. Johnson, K.; Liu, Y.; Lu, M. A Review of Recent Advances in Spent Coffee Grounds Upcycle Technologies and Practices. *Front. Chem. Eng.* **2022**, *4*, 838605. [CrossRef]
440. Sumadi; Ardhiarisca, O.; Putra, R. Production and Calculation of Economic Value of the Coffee Skin Waste Products. In Proceedings of the First International Conference on Social Science, Humanity, and Public Health (ICOSHIP 2020), Jember, Indonesia, 7–8 November 2020; Atlantis Press: Paris, France, 2021; pp. 41–44.
441. Kamil, M.; Ramadan, K.M.; Olabi, A.G.; Al-Ali, E.I.; Ma, X.; Awad, O.I. Economic, Technical, and Environmental Viability of Biodiesel Blends Derived from Coffee Waste. *Renew. Energy* **2020**, *147*, 1880–1894. [CrossRef]
442. Duarte, A.; Uribe, J.C.; Sarache, W.; Calderón, A. Economic, Environmental, and Social Assessment of Bioethanol Production Using Multiple Coffee Crop Residues. *Energy* **2021**, *216*, 119170. [CrossRef]
443. Lee, Y.-G.; Cho, E.-J.; Maskey, S.; Nguyen, D.-T.; Bae, H.-J. Value-Added Products from Coffee Waste: A Review. *Molecules* **2023**, *28*, 3562. [CrossRef]

444. Proença, J.F.; Torres, A.C.; Marta, B.; Silva, D.S.; Fuly, G.; Pinto, H.L. Sustainability in the Coffee Supply Chain and Purchasing Policies: A Case Study Research. *Sustainability* **2022**, *14*, 459. [CrossRef]
445. Ahmed, H.; Abolore, R.S.; Jaiswal, S.; Jaiswal, A.K. Toward Circular Economy: Potentials of Spent Coffee Grounds in Bioproducts and Chemical Production. *Biomass* **2024**, *4*, 286–312. [CrossRef]
446. McNutt, J.; He, Q. Spent Coffee Grounds: A Review on Current Utilization. *J. Ind. Eng. Chem.* **2019**, *71*, 78–88. [CrossRef]
447. Nanda, P.V.; Usman, I. Green Business Opportunity of Coffee Ground Waste through Reverse Logistics. *J. Glob. Bus. Adv.* **2017**, *10*, 721. [CrossRef]
448. Nguyen, G.N.T.; Sarker, T. Sustainable Coffee Supply Chain Management: A Case Study in Buon Me Thuot City, Daklak, Vietnam. *Int. J. Corp. Soc. Responsib.* **2018**, *3*, 1–17. [CrossRef]
449. van Keulen, M.; Kirchherr, J. The Implementation of the Circular Economy: Barriers and Enablers in the Coffee Value Chain. *J. Clean. Prod.* **2021**, *281*, 125033. [CrossRef]
450. Gallego-Schmid, A.; López-Eccher, C.; Muñoz, E.; Salvador, R.; Cano-Londoño, N.A.; Barros, M.V.; Bernal, D.C.; Mendoza, J.M.F.; Nadal, A.; Guerrero, A.B. Circular Economy in Latin America and the Caribbean: Drivers, Opportunities, Barriers and Strategies. *Sustain. Prod. Consum.* **2024**, *51*, 118–136. [CrossRef]
451. de Jesus, A.; Mendonça, S. Lost in Transition? Drivers and Barriers in the Eco-Innovation Road to the Circular Economy. *Ecol. Econ.* **2018**, *145*, 75–89. [CrossRef]
452. Bonnín Roca, J.; Vaishnav, P.; Morgan, M.G.; Mendonça, J.; Fuchs, E. When Risks Cannot Be Seen: Regulating Uncertainty in Emerging Technologies. *Res. Policy* **2017**, *46*, 1215–1233. [CrossRef]
453. Vidal-Ayuso, F.; Akhmedova, A.; Jaca, C. The Circular Economy and Consumer Behaviour: Literature Review and Research Directions. *J. Clean. Prod.* **2023**, *418*, 137824. [CrossRef]
454. Chrispim, M.C.; Mattsson, M.; Ulvenblad, P. Perception and Awareness of Circular Economy within Water-Intensive and Bio-Based Sectors: Understanding, Benefits and Barriers. *J. Clean. Prod.* **2024**, *464*, 142725. [CrossRef]
455. Peluso, M. Coffee By-Products: Economic Opportunities for Sustainability and Innovation in the Coffee Industry. *Proceedings* **2023**, *89*, 6. [CrossRef]
456. Ungerman, O.; Dědková, J. Consumer Behavior in the Model of the Circular Economy in the Field of Handling Discarded Items. *PLoS ONE* **2024**, *19*, e0300707. [CrossRef]
457. Aschemann-Witzel, J.; Ares, G.; Thøgersen, J.; Monteleone, E. A Sense of Sustainability?—How Sensory Consumer Science Can Contribute to Sustainable Development of the Food Sector. *Trends Food Sci. Technol.* **2019**, *90*, 180–186. [CrossRef]