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Review

A Comprehensive Review on Sustainable Conversion of Spent Coffee Grounds into Energy Resources and Environmental Applications

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Abstract

Spent coffee grounds (SCGs), a globally abundant by-product of the coffee industry, represent a significant source of lignocellulosic biomass with considerable valorization potential. Rich in organic compounds, lipids, and antioxidants, SCGs are increasingly recognized as a sustainable feedstock for energy, materials, and environmental applications within a circular bioeconomy framework. This review critically examines recent advances in SCG valorization via thermochemical, biochemical, and material-based pathways. The review focuses on the conversion of SCGs into biofuels (biodiesel, bioethanol, biogas, and bio-oil), activated carbon for water and air purification, biodegradable polymers, and soil-enhancing amendments. Comparative analyses of process conditions, product yields, and techno-economic feasibility are provided through summarized tables. Although laboratory-scale studies demonstrate promising outcomes, challenges persist in terms of process scalability, environmental impacts, feedstock variability, and lack of regulatory standardization. Furthermore, comprehensive life cycle assessments and policy integration remain underdeveloped. By merging all findings, this review identifies key knowledge gaps and outlines strategic directions for future research, including the development of integrated valorization platforms, hybrid conversion systems, and industrial-scale implementation. The findings support the role of SCG valorization in advancing sustainable resource management and contribute directly to the achievement of multiple Sustainable Development Goals.

Keywords: spent coffee grounds; waste valorization; circular bioeconomy; thermochemical conversion; biochemical processes; biofuels and bio-based materials; sustainable resource recovery

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1. Introduction

The scalation of greenhouse gas (GHG) emissions is a result of both economic progress and human behavior. Carbon dioxide (CO_2) levels have risen by more than 50% since pre-industrial times, primarily due to emissions from fossil fuels and land use practices,

particularly agriculture [1]. Greenhouse gases, including CO_2, methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons, and sulfur hexafluorides, are the primary drivers of climate change [2]. Their impact is observed in the form of global warming, which presents a formidable challenge to the world. Of these gases, CO_2 plays a crucial role, owing to its high concentration and extended lifespan in the atmosphere, in comparison to other greenhouse gases. The agricultural industry ranks among the most significant contributors of GHG emissions globally, accounting for at least 20% of worldwide emissions, with Asia representing over 44% of these emissions in the agricultural sector [3]. Therefore, it is necessary to take immediate measures to control CO_2 emissions. To counterbalance CO_2 emissions, one promising solution is the utilization of biomass, which comprises plant-based sources or biologically generated materials. Biomass is a natural, non-fossil organic substance with innate chemical energy potential that could provide a sustainable and environmentally friendly approach [4]. Annual biomass supply is estimated to be over 105 billion metric tons of carbon [5], and it can be derived from a variety of sources, including agriculture, urban waste, and forestry, such as paper waste, wood, household waste, wastewater, and agricultural residues. Several techniques can be utilized to convert biomass into biofuels and biobased products [6–9].

Coffee is one of the most widely traded and consumed brewed beverages globally, making it the second-largest biomass commodity after petroleum [10]. The antioxidants present in coffee have been found to offer protection against various chronic and cancerous diseases. Additionally, coffee consumption has been linked to cellular protection against damage and lower mortality rates in individuals with neurological and heart diseases [11]. As per the International Coffee Organization, annual coffee production has witnessed a rise from 140 to 167.01 million 60 kg bags from 2010 to 2020/21. Nevertheless, the coffee industry worldwide generates a considerable amount of agricultural waste and by-products, with almost 90% of the coffee berry weight discarded as waste during the manufacturing process. This waste stream includes spent coffee grounds (SCGs), which constitute a significant proportion of the total waste generated by the industry [12]. Given the magnitude of coffee waste generated, exploring the potential of coffee waste as a biomass resource is critical to developing sustainable and efficient biomass utilization strategies.

The brewing of coffee generates substantial amounts of SCGs, and due to the high global consumption of coffee, significant volumes are produced annually across both commercial establishments and households worldwide [13]. With an estimated 650 kg of SCG produced per ton of green coffee [14], improper disposal of this waste can have severe environmental and public health consequences. Dumping SCG in landfills can contribute to the production of CH_4, a potent GHG that is more than 25 times as effective as CO_2 at trapping heat in the atmosphere [15]. Moreover, SCGs contain high levels of organic matter and caffeine, which can negatively impact soil and water quality, leading to nutrient imbalances and potential contamination with heavy metals and other harmful substances [16]. Additionally, SCGs can attract pests like rodents and insects, producing unpleasant odors that can create nuisances for nearby communities, and they can take years to decompose. Workers who handle SCGs without appropriate personal protective equipment may be at risk of respiratory problems due to the inhalation of coffee dust and other particulate matter.

With their rich organic content and unique composition, SCGs possess the potential to serve as a valuable source of value-added products. Rather than simply disposing of this waste into surface water or landfills, the utilization of SCGs in various applications could significantly reduce the amount of waste generated while simultaneously creating new avenues for development. Numerous studies have explored the potential of SCGs

as a feedstock for biodiesel, bioethanol, and a source of steam, sugars, activated carbon, and an adsorbent for metal ions and dye removal [17–21]. By leveraging these applications, SCGs can represent a crucial resource for the coffee industry and play an integral role in establishing a circular economy. Efficient management and valorization of SCG not only have the potential to create a sustainable economy but also contribute to reducing the carbon footprint of the coffee industry. With the appropriate strategies in place, the coffee industry can seize the opportunity to foster a more sustainable and environmentally responsible future. The objective of this paper is to present a comprehensive and up-to-date review of the latest research on the valorization of SCGs. Through a meticulous evaluation of diverse valorization methods such as pyrolysis, hydrothermal treatment, and microbial conversion, this paper will analyze the efficiency and environmental impact of each approach. Additionally, the paper will assess the potential applications of the resulting products and carry out an evaluation of the economic feasibility and scalability of SCG valorization technologies. By consolidating existing knowledge and identifying research gaps, this review paper aims to make a significant contribution towards the development of more sustainable and efficient strategies for the management and valorization of SCGs. Through the synthesis of the latest research, this paper aims to provide a roadmap for future researchers and practitioners to pursue innovative and sustainable ways to convert SCGs into value-added products, while mitigating the environmental impact of waste disposal.

To clarify the novelty of the present review, Table 1 compares the scope of earlier reviews on SCG valorization with the current work. Most prior studies have been limited to specific valorization routes or application domains, whereas this review provides an integrated analysis.

Table 1. Comparison of the scope of previous reviews on SCG valorization with the present review. "✓" indicates that the review explicitly discussed the category, while "×" indicates that it was absent.

SCG Origin, and Composition	Products and Applications				Valorizing Processes						Ref.
					Pyrolysis						
	Bio-Oil	Biochar	Biogas	Activated Carbon	Carbonization + Chem Act	Carbonization + Phy Act	Carbonization	Gasification	Hydrothermal Carbonization	Biological (Anaerobic Digestion)	
✓	×	×	×	×	×	×	×	×	×	×	[22]
✓	✓	✓	✓	×	×	×	✓	×	×	×	[23]
×	✓	✓	✓	✓	×	×	✓	✓	×	×	[24]
✓	×	✓	×	✓	×	×	✓	×	✓	×	[25]
✓	✓	✓	✓	×	×	×	✓	×	×	✓	[26]
✓	×	✓	✓	✓	×	×	✓	×	×	✓	[27]
✓	✓	×	×	×	×	×	×	×	✓	×	[28]
✓	✓	×	×	×	✓	×	×	×	×	×	[29]
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Current review

2. SCG Origin and Composition

SCGs are the solid remnants of coffee beans that have undergone the brewing process, resulting in a dry, coarse powder that lacks any discernible flavor [30]. They are the residual solids of coffee beans, composed of carbon-rich organic matter originally formed through photosynthesis [31]. As an extremely versatile feedstock, biomass can take on various shapes and physical properties, such as being moist or dry, dense or porous, with high or low ash content, and in different forms—from tiny particles to large chunks. This manufacturing waste is a chemically rich substrate, containing macronutrients such as proteins, lipids, carbohydrates, and nitrogenous compounds, along with various bioactive compounds [10]. However, improper disposal in landfills can lead to serious environmental concerns, such as the release of excessive nitrogen oxides (NOx) and CO_2. Furthermore, the process of SCG degradation requires an increased supply of oxygen, which can result in the

release of tannins, polyphenols, and residual caffeine (the trace amounts remaining after brewing) into the environment. This process can result in the leaching of contaminants into groundwater, increased GHG emissions, and localized air pollution due to volatile organic compounds [23]. Fortunately, proper management of SCG waste can mitigate these harmful effects and unlock vast potential of up to 4.40–4.65 million tons of usable feedstock [19]. Strategic valorization of this non-edible byproduct can mitigate environmental impacts and enhance its integration into sustainable resource systems.

The chemical composition of SCGs is a complex interplay of multiple factors, including the species of the coffee plant, its age, geographical location, and climatic conditions [32]. Moreover, the chemical makeup of SCGs can vary significantly based on the type of analysis conducted [18]. Additionally, it contains a diverse range of sugars, including galactose, arabinose, glucose, and mannose. SCGs also consist of carbon, oxygen, nitrogen, and hydrogen, while sulfur is found in lower concentrations [33]. In addition to macronutrient content, SCGs also contain phenolic compounds, caffeine, and a range of minerals including potassium, calcium, magnesium, and phosphorus, as well as trace metals (such as copper, zinc, and iron, with occasional traces of lead or cadmium) that can exert phytotoxic effects if applied raw to soil [16,19,34]. The intricate composition of SCGs highlights their tremendous potential as a valuable resource for various applications. Careful analysis and management of its chemical properties can unlock a wealth of sustainable opportunities for this abundant waste product. The composition of SCGs can be represented in several ways, by elements or by chemical components, as shown in detail in Table 2.

Table 2. Elemental and chemical composition of SCGs from different geographical sources and coffee types.

Location/Coffee Type	C	H	N	O	S	Reference
			wt%			
Italy	48.67	6.54	2.27	40.03	0.15	[35]
Malaysia/Arabica	47.63	6.57	2.93	45.80	0.47	[19]
UK. 80% Arabica and 20% Robusta	53.94	7.06	2.29	36.72	-	[36]
Canada	50	6.7	2.5	39.0	0.9	[10]
United Arab Emirates	48.9	6.80	2.88	41.2	0.250	[37]
Greece	47.96	1.57	6.42	44.05	- *	[32]
Mexico	43.09	9.03	2.15	45.21	0.52	[38]
Germany	56.3	7.7	1.8	-	0.47	[39]
Taiwan	49.37	7.37	2.26	39.47	0.085	[40]
Italy/30% Arabica and the green beans	68.52	11.04	1.40	-	-	[34]
Italy	48.67	6.54	2.27	40.03	-	[41]

Location/Coffee Type	Cellulose	Hemicellulose	Extractives	Lignin	Protein	Fat	Ash	Reference
				wt%				
Spain	16.3	27.7	12.4	39.2	9.4	9.9	0.1	[42]
Malaysia/Arabica	16.78	48.22	19.42	34.94	-	-	-	[19]
China	12.3	38.4	-	22.9	-	-	-	[43]
Thailand	10.6	41.5	-	44.5	-	-	-	[44]

* '-' Indicates that the data were not reported in the cited reference.

It is important to note that SCGs' complex chemical composition provides both opportunities and challenges for valorization: while it enables multiple avenues for resource recovery, it also imposes constraints on certain technologies. For instance, the high moisture and oil content of fresh SCG can impede efficient combustion or anaerobic digestion unless pre-dried or defatted. Likewise, the presence of residual caffeine and polyphenols (which are beneficial antioxidants) means that raw SCGs can be toxic to microbes or plants, limiting their direct

use in fermentation or soil amendment without pretreatment. These factors must be carefully managed to achieve effective valorization across different processing pathways.

Beyond these opportunities and constraints, specific components of SCGs strongly influence their valorization pathways and environmental implications. The substantial lignin content renders them unsuitable for animal feed, and bioactive substances like residual caffeine can influence microbial ecosystems. Importantly, the physical and chemical characteristics of SCGs—such as moisture content, volatile matter, and fixed carbon—play a decisive role in determining the yield and distribution of pyrolysis products, including biochar, bio-oil, and syngas [33].

3. Valorization Processes

SCGs are rich in organic compounds such as cellulose, proteins, tannins, fibers, carbohydrates, and residual caffeine [45]. In addition, more than 700 volatile compounds remain insoluble and unextractable in SCGs during the thermal water extraction process, making them candidates for valorization through various pathways. These compounds possess significant organic content, favorable physical properties, and high energy potential, all of which support their utilization in value-added applications [45]. Various biological, chemical, and thermochemical methods have been explored to convert SCGs into high-value products (Table 3).

Table 3. Overview of valorization processes applied to SCGs, their typical products, temperature ranges, and critical operational parameters.

Valorization Process	Products	Temperature Range (°C)	Effective Parameter	Ref.
Pyrolysis	Biochar, bio-oil, syngas	300–700	Reaction temperature	[46]
Anaerobic digestion	Biogas	35–60	Carbon-Nitrogen ratio	[47]
Chemical activation	Activated carbon	400 to 900	Chemical agent	[48]
Physical activation	Activated carbon	800–1100	Reaction Temperature	[49]
Hydrothermal carbonization	Hydrochar	180–250	Reaction temperature	[50]
Gasification	Biochar, syngas	above 700	Gasification agent	[40]

3.1. Biological Processes

Biological treatment techniques present a promising approach for SCG valorization due to their environmentally friendly nature, operational simplicity, and minimal chemical requirements. These methods typically operate under mild conditions and do not demand complex setups. While thermal, physical, and chemical approaches have demonstrated broad applicability in SCG valorization, they often involve higher energy inputs, harsher operating conditions, or more complex processing requirements. In contrast, biological processes may appear more economically favorable in theory as they operate under milder operational conditions [51]. However, in practice, these processes face notable limitations, including slower reaction rates, narrower ranges of optimal conditions, and low catalyst recyclability [51]. Additionally, large-scale exploitation of biomass through biological methods requires significant land, labor, and financial resources [52]. The effectiveness of biological treatments is also highly dependent on the survival and performance of microorganisms, which require carefully controlled environmental conditions [53].

Anaerobic Digestion

Anaerobic digestion (AD) is one of the most widely used biological processes for recycling organic waste. It efficiently converts SCGs and other biomass into biogas and digestate—the latter of which can be utilized as a nutrient-rich biofertilizer [54]. AD can be categorized into two types based on operating temperature: mesophilic and thermophilic. The process offers several advantages, including the production of inorganic nutrients,

humus-like fertilizers, and biomethane, thereby offering both environmental and economic benefits. The efficiency of AD depends heavily on the carbon-to-nitrogen (C/N) ratio, which ideally ranges from 25 to 30. A low nitrogen level can limit microbial growth, while excess nitrogen may lead to ammonia accumulation, inhibiting microbial activity and slowing carbon degradation. Additionally, pH levels play a crucial role in microbial metabolism during different AD stages [55]. Carbon serves as an energy source, while nitrogen supports microbial biomass development [47]. Sumantri et al. [47] studied the co-digestion of SCGs with cow manure and the addition of Effective Microorganisms-4 (EM-4) to enhance biomethane production. Cow manure is a widely available substrate in anaerobic digestion, known for its potential in producing biogas and its digestate for use as high-quality organic fertilizer. The manure typically contains 25.2% cellulose, 20.2% lignin, and 18.6% hemicellulose, along with 0.3% nitrogen, 0.2% phosphate, 0.15% potassium oxide, and 0.2% calcium oxide, yielding an approximate C/N ratio of 20–25%. EM-4 is a liquid microbial consortium composed of photosynthetic bacteria, actinomycetes, lactic acid bacteria, and yeast. It enhances the breakdown of hemicellulose, lignin, and cellulose into simpler compounds for biogas production. In the referenced study, cow manure was naturally fermented into compost and analyzed for composition, revealing total nitrogen and carbon contents of 0.34% and 9.3%, respectively, corresponding to a C/N ratio of 27.34. SCGs were first dried and then delignified using 1.5 N sodium hydroxide, yielding a material with 49.9% carbon and 2.70% nitrogen (C/N ratio = 17.87). A substrate blend of 500 g was prepared by mixing 19.37 g SCG with 480.63 g cow manure. Optimal biogas production was achieved at pH 7 (neutral) with a 9% addition of EM-4. Due to its composition, SCGs tend to elevate the pH of the digester, thereby improving microbial activity and gas yield when used in combination with EM-4.

3.2. Thermochemical Processes (Pyrolysis, Gasification, and Hydrothermal Carbonization)

Thermochemical conversion pathways have gained significant attention as efficient and flexible technologies for biomass valorization. These methods offer the ability to manage diverse feedstocks and produce multiple valuable products such as bio-oil, biochar, and syngas [52]. Among the various thermochemical routes, pyrolysis, gasification, and hydrothermal carbonization (HTC) are particularly prominent due to their efficiency and adaptability to different biomass types.

3.2.1. Pyrolysis

Pyrolysis refers to the thermal decomposition of organic materials in an oxygen-free (or inert) environment, typically under a nitrogen atmosphere, to prevent oxidation and promote the breakdown of volatile components [5]. The process generally involves temperatures ranging from 300 °C to 700 °C, though higher temperatures can be used depending on the desired product [56]. Pyrolysis yields three primary products: biochar (solid), bio-oil (liquid), and non-condensable gases (gas phase). The distribution of these products is highly dependent on processing conditions such as temperature, heating rate, and vapor residence time.

Different types of pyrolysis—slow, intermediate, fast, and flash—are categorized based on heating rate, vapor residence time, and operating temperature. For instance, slow pyrolysis at lower temperatures and longer residence times favors biochar production, while fast or flash pyrolysis with rapid heating and short residence times increases bio-oil yield [57].

The pyrolysis process involves multiple thermal stages, each contributing to the breakdown of biomass into useful products [58].

- Drying phase (100–120 °C): Moisture is removed from the biomass, preparing it for thermal decomposition.
- Volatilization (~275 °C): Light gases such as CO_2, CO, N_2, methanol, and acetic acid begin to evolve as temperature increases.
- Exothermic decomposition (280–350 °C): Complex mixtures of chemical substances (i.e., ketones, aldehydes, phenols, esters), CO_2, CO, CH_4, C_2H_6, and H_2 are removed through breaking the weakest chemical bonds.
- Evaporation and residual carbon formation (~350 °C): Remaining volatiles are driven off, resulting in increased yields of H_2, CO, and fixed carbon. The solid residue becomes biochar. The thermal decomposition of more stable biomass components, such as lignin, may continue at higher temperatures.

In practice, the performance of pyrolysis varies with reactor design, temperature profiles, and residence time. For instance, in experiments conducted by Primaz et al. [59], SCG pyrolysis was performed using a quartz reactor with nitrogen gas flow (150 mL/min), a heating rate of 100 °C/min, and final temperatures ranging from 400 °C to 600 °C. Bio-oil yields peaked at 30.51% at 500 °C. Further studies using fluidized bed reactors revealed how different temperatures affect product distribution. Fast pyrolysis of SCGs at 550 °C yielded 54.85% bio-oil, outperforming yields at 400 °C and 600 °C [23]. In fixed-bed systems, 500 °C yielded 30.51% bio-oil and 51.61% total liquid product (including aqueous phases). Higher temperatures (550–600 °C) increased gas production and decreased biochar yields, due to intensified secondary cracking and volatilization of organics.

Atabani et al. [23] also evaluated screw-conveyor pyrolysis reactors, which offer advantages such as avoiding the need for inert gas or heat carriers like sand. Maximum oil yield (61.7%) was obtained at 500 °C with a 23 s residence time, while peak char yield (20.6%) occurred at 429 °C. These results suggest that screw-conveyor systems outperform fluidized beds in terms of oil yield. Modeling results identified 505 °C as the optimal temperature for maximum bio-oil production. Reactor design plays a critical role in determining pyrolysis efficiency [56].

Following pyrolysis, an additional activation step is essential to enhance the adsorptive and surface properties of the resulting biochar, yielding AC. To manufacture AC from SCGs, two crucial methods must be performed. Carbonization (pyrolysis) is the first step, which is explained previously, while activation is the second. The production of AC from biomass is beneficial in two ways: first, it can avoid the production of CO_2 by fixing the carbon, and second, the AC can organically enter the soil [57]. The carbon composition of the carbonaceous material (biochar) is produced at carbonization step by eliminating the volatile matter via thermal degradation. Because the obtained biochar has a poor adsorption ability, an activation procedure is required to increase the pore volume, pore width, surface area, physical characteristics, adsorption capacity, and pore density [57]. Chemical and physical activation are the most common types.

3.2.2. Chemical Activation

Chemical activation is commonly used in a single or two processes for cellulose-containing raw materials. Prior to thermal treatment in an inert atmosphere, the precursor is impregnated with chemical activating agents. AC is eventually created by repeatedly washing the resultant mixture [60]. These agents, which function as dehydrating chemicals, influence pyrolytic decomposition by increasing AC content, minimizing bitumen formation, and promoting the development of porous carbon materials. The chemicals penetrate deep into the carbon structure and induce the formation of micropores, thereby improving surface area. Various activating agents have been tested, including sulphuric acid (H_2SO_4), alkaline groups, metal salts, and other chemicals. Advantages of this process include low

cost, low activation temperature, shorter processing time, improved carbon efficiency, and the potential for one-step furnace production. However, the method requires extensive washing to remove chemical residues, generating potentially harmful wastewater [60].

Wirawan et al. [61] mentioned the production of AC from Robusta coffee waste using chemical activation. SCGs were synthetically prepared by soaking 50 g of grounds in 1.5 L of hot water. After rinsing until colorless, the grounds were oven-dried at 105 °C for 3 h and carbonized at 500 °C in a muffle furnace under limited oxygen for 45 min. The carbonized sample was then activated by soaking in 2 M H3PO4 for 24 h, filtered, rinsed, and dried. The resulting AC was tested for Rhodamine B adsorption at pH 2.5 with a 90 min contact time.

Chiu and Lin [62] developed a one-step activation method that combines carbonization and activation using chemicals like KOH, NaOH, HCl, H3PO4, ZnCl2, and FeCl3. Waste coffee grounds were treated in 1 M KOH at 40 °C for 6 h, filtered, and dried. The resulting powder was exposed to activating agents for 15 min before AC fabrication. The KOH-AC electrode exhibited enhanced electrocapacitive performance due to reduced hydrophobic groups, increased surface area, and favorable pore characteristics.

3.2.3. Physical Activation

In physical activation, two sequential steps are followed: pyrolysis, and then activation using gases like steam or CO_2. Several studies have suggested that physical activation can outperform chemical activation in terms of cost, environmental impact, and pore development—particularly for mesopores and micropores. For the preparation of AC, carbon-rich precursors such as hybrid willow biomass or SCGs are commonly used.

Steam activation is an endothermic post-pyrolysis treatment where volatile compounds are removed from the adsorbent surface, enhancing the material's adsorption capacity. It is considered more environmentally friendly than chemical methods. The mechanism involves four steps: chemisorption of water-derived oxygen onto biochar, gasification to form CO_2, water-gas shift reaction generating hydrogen (H_2) and CO_2, and activation of the carbon surface [48].

CO_2 activation also proceeds via endothermic reactions, wherein CO_2 serves as a mild oxidizing agent that creates new pores and expands existing ones. It is often favored over steam due to its lower reactivity, which allows for more controlled pore development [48]. Chiang et al. [63] demonstrated that SCG-derived biochar activated with CO_2 at 550–950 °C yielded AC with a surface area of 2407 m^2/g, low ash content (0.46 wt%), and strong dye adsorption capacities (678 mg/g for a cationic dye and 612 mg/g for methyl orange).

Table 4 summarizes various experimental parameters and results reported in the literature for the chemical and physical activation of SCG-derived biochar, highlighting the diversity in activation agents, temperatures, surface areas, and yields.

Table 4. Summary of experimental parameters and performance metrics for AC production from spent coffee grounds using chemical and physical activation methods.

Activation Type	Agent	Activation Temperature (°C)	Reaction Time (h)	Surface Area (m^2/g)	Yield (wt.%)	Ref.
Chemical activation	KOH	800	4	1199	-	[64]
	H_3PO_4	350–500	1	300–1209	40	[65]
	$CaCO_3$	850	1	167	41.0	[39]
	K_2CO_3	600–800	1 or 5	2337	28.4	[66]
	NaOH	80	- *	2.3	-	[67]
	$ZnCl_2$	800	2	367	15	[68]

Table 4. *Cont.*

Activation Type	Agent	Activation Temperature (°C)	Reaction Time (h)	Surface Area (m^2/g)	Yield (wt.%)	Ref.
Physical activation	Steam	700	-	400–1300	-	[69]
	CO_2	700	-	630	-	
	Steam	800	0.83	1181	9.6	[70]
	Steam	700	2	641	13.4	[71]
	CO_2	700	1	593	-	[72]
	Steam	800	1	981.12	-	

* '-' Indicates that the data were not reported in the cited reference.

3.2.4. Gasification of Spent Coffee Grounds: Process Mechanisms, Reactor Designs, and Performance Drivers

Gasification is a thermochemical process that transforms solid biomass, including SCGs, into a gaseous mixture known as synthesis gas or syngas [73]. The syngas typically contains CH_4, H_2, CO, and CO_2, along with a solid carbonaceous residue called char [74]. SCGs are characterized by a relatively high volatile matter fraction and a favorable calorific value (23 MJ/kg), which make them a suitable feedstock for gasification. These properties facilitate efficient thermal decomposition and enhance the potential for energy recovery and carbon utilization through gasification [75].

Stages of the Gasification Process

The gasification process occurs in distinct but interconnected stages.

- Drying: Biomass moisture levels directly influence gas quality and energy efficiency. For optimal gasification, SCGs should be dried to a moisture content of 10–20%. Lower moisture levels (below 2%) improve thermal conversion by reducing energy losses during evaporation [74]. Solar drying is cost-effective but slow and weather-dependent, whereas electric dryers offer faster rates at higher energy costs [76].
- Pyrolysis: In this stage (125–500 °C), SCGs undergo thermal decomposition in an oxygen-limited environment. Volatile compounds are released, leaving behind char, liquid tars, and gases. Pyrolysis of SCGs has been shown to yield significant carbon-rich gases and tar, necessitating careful process control [76].
- Oxidation (combustion): A limited amount of oxygen or air is introduced to partially combust the biomass, generating the heat required for subsequent endothermic reactions. Operating at 1100–1500 °C, this stage produces CO, CO_2, H_2, and H_2O and provides thermal support to pyrolysis and reduction zones [74]. Inert gases such as N_2 and CO_2 moderate system temperature and impact syngas quality [76].
- Reduction: Char reacts with steam, CO_2, and H_2O to produce CO and H_2 in a highly endothermic zone (800–1000 °C). The reduction zone also plays a critical role in tar reforming, addressing one of the key limitations of SCG gasification—its high tar yield [74]. Key reactions include the water–gas shift, CH_4 reforming, and Boudouard reaction [76].

Reactor Configurations for SCG Gasification

All stages of biomass gasification occur within a dedicated reactor called a gasifier. The design of a gasifier directly influences process efficiency, product composition, tar formation, and scalability. Key design parameters include fuel availability and properties (e.g., particle size, moisture, and ash content), desired syngas quality, and the intended end-use of the product gas. Based on operational principles, gasifiers are broadly categorized into fixed bed, fluidized bed, and advanced or emerging configurations [76].

Fixed Bed Gasifiers

Fixed bed gasifiers are among the earliest and most commercially available gasification systems. They feature a simple, compact design and are well suited for small-scale, decentralized biomass conversion (typically up to 10 MW) [77]. Variants include updraft (handles moist feed, high tar), downdraft (low-tar syngas, but limited to dry fuels), and cross-draft (fast heating, CO-rich gas, low H_2). Operating pressures range from 0–7 MPa [74].

Fluidized Bed Gasifiers

Biomass particles are suspended in a rising gas stream, enabling excellent mixing and carbon conversion up to 95%. They accept varied feedstocks and produce less tar than updraft beds, though high temperatures (650–950 °C) must be controlled to prevent bed agglomeration. Fluidized beds are increasingly applied for medium-scale SCG gasification (500 kW–50 MW) [74,76].

Advanced Gasifier Designs

To overcome limitations of conventional systems, advanced options include entrained flow (near-complete carbon conversion at >1000), dual fluidized beds (better tar reforming), supercritical water gasifiers (suited to wet biomass like SCGs), and plasma gasifiers (high-quality syngas but very costly) [74].

A comparative summary of gasifier types—including their operational strengths and limitations—is presented in Table 5.

Table 5. Comparative overview of gasifier types, key advantages, and limitations for biomass valorization.

Gasifier Type	Advantages	Limitations	References
Updraft (Fixed Bed)	High thermal efficiency; simple design; handles high-moisture feed; low pressure drop	High tar content; poor response time; sensitivity to feed quality	[76]
Downdraft (Fixed Bed)	Simple and low-cost; syngas with <0.1% tar; suitable for engines	Limited to dry feed; high exit gas temperatures; unconverted carbon (~5%)	[78]
Cross-draft (Fixed Bed)	Fast heating; high CO concentration in gas output	High exit temperature; low H_2 and CH_4 content	[76]
Bubbling Fluidized Bed	Excellent fuel mixing; handles high ash feed; flexible operation	Lower carbon conversion; moderate tar levels	[74]
Circulating Fluidized Bed	Intense gas–solid contact; high carbon conversion; scalable; suitable for large-scale use	Agglomeration risk; material back-mixing; complex and costly setup	[74,76]
Entrained Flow	High carbon conversion (~100%); short residence time; suitable for any feedstock	High operating temperature; material limitations due to ash melting	[74]
Dual Fluidized Bed	Improved temperature control; enhanced tar reforming	Still under development; higher cost and design complexity	
Supercritical Water	Converts wet biomass; eliminates drying step; energy-efficient	High-pressure operation; limited commercial availability	
Plasma Gasifier	High-temperature operation; full decomposition of organics; vitrified slag from inorganics	Very high capital and operational costs; complex thermal management	

Key Parameters Influencing Gasification Efficiency

Gasification of spent coffee grounds (SCGs), due to their high moisture and lignin content, is highly dependent on a set of process parameters. The following key factors significantly influence syngas yield, energy content, and byproduct formation (e.g., tar, char).

Temperature

Elevated gasification temperatures improve syngas quality by enhancing reaction kinetics and tar cracking. However, temperatures above 900 °C raise costs and thermal stress. Optimal operation lies in the moderate-to-high temperature range [74,78].

Pressure

While most SCG gasification is done at atmospheric pressure, elevated pressures are beneficial for downstream synthesis (e.g., Fischer–Tropsch), though equipment cost is a limitation [76,77].

Gasifying Agent

The choice of gasifying medium significantly affects the thermodynamic pathways and final syngas composition. Common agents include air, oxygen, steam, CO_2, and supercritical water [73].

- Air is the most economical option but yields low-calorific syngas due to nitrogen dilution.
- Steam and oxygen mixtures produce syngas with higher heating values.
- Steam alone improves H_2 yield and facilitates tar reforming, especially in lignin-rich biomass such as SCGs.
- Supercritical water enables gasification of wet biomass without the need for drying, offering energy savings.

These agents also influence whether the overall reaction is endothermic (steam, CO_2, supercritical water) or potentially exothermic (air, oxygen), allowing fine-tuning of heat balance by adjusting oxidant flow [76].

Air–Fuel Ratio and Equivalence Ratio (ER)

A lower ER results in syngas with higher calorific value, while a higher ER reduces tar but also energy content. Fine-tuning ER is essential to balance energy yield and emissions content [74,76]. Higher ERs also lower tar content, but at the expense of syngas quality.

Residence Time

Longer times enhance tar reforming and carbon conversion. However, excessive duration can reduce system throughput. SCGs' high lignin content requires an optimized balance [74].

Kibret et al. [40] investigated SCG gasification in a semi-fluidized bed reactor at 700–900 °C under both reactive and non-reactive atmospheres using steam, CO_2, and their combinations as gasifying agents. The study revealed that co-gasification using steam and CO_2 significantly improved carbon conversion and gas efficiency. According to their experimental results, increasing the temperature from 700 °C to 900 °C led to a consistent rise in carbon conversion, and LHV (from ~9 to 12.8 MJ/Nm^3), indicating clear thermal enhancement of the gasification process. Further optimization was achieved by adjusting the steam-to-biomass (S/B) ratio. Raising the S/B ratio from 0.14 to 0.53 increased LHV from 12.8 MJ/Nm^3 to 13.5 MJ/Nm^3, with corresponding improvements in carbon conversion and gasification efficiency. These findings highlight steam's critical role in facilitating tar reforming and hydrogen-yielding reactions, ultimately improving both the quality and efficiency of syngas production.

Complementing these insights, Rodrigues et al. [79] conducted a detailed study on steam/CO_2-enhanced gasification of SCGs. Increasing the CO_2-to-biomass ratio (CO_2BR) from 0.09 to 0.27 decreased CH_4 and CO_2 content while raising CO concentrations up to 45.6 vol. An optimum CO_2BR of 0.18 was found to yield the highest H_2/CO ratio (0.83), representing a favorable balance between reforming activity and product composition. Simultaneously, increasing the S/B ratio from 0.5 to 1.2 elevated hydrogen formation by up to 40% while reducing CH_4, CO, and CO_2 fractions. Although CO_2 addition can moderately reduce syngas LHV due to its dilution effect, increasing the steam input effectively counteracts this trend. In the same study, LHV improved from 10.8 to 12.1 MJ/Nm^3 as S/B

increased, confirming that steam addition enhances both hydrogen production and energy content, even in CO_2-rich environments.

3.2.5. Hydrothermal Conversion of SCGs: Principles and Applications

Hydrothermal conversion involves decomposing biomass in hot, pressurized water to yield solid (hydrochar), liquid (bio-crude), and gaseous products, alongside aqueous byproducts [80,81]. A major advantage over conventional thermal processes is its ability to process wet biomass like SCGs without pre-drying, making it attractive for sustainable energy and material production [82]. Based on operating conditions, hydrothermal processes are classified into hydrothermal carbonization (HTC), liquefaction (HTL), and gasification (HTG) [83].

Hydrothermal Carbonization (HTC)

HTC operates at 180–250 °C and 1–5 MPa, producing hydrochar (35–80 wt% yield), CO_2, and an aqueous fraction [50,80]. It is particularly suitable for wet feedstocks (70–90% moisture) and yields a hydrophobic, carbon-rich solid with oxygenated functional groups. Hydrochar is applicable as fuel, adsorbent, soil amendment, or precursor for advanced materials [80,84]. Its properties are governed by temperature and residence time: higher values enhance aromaticity and reduce hydrochar yield, while shorter times limit conversion [80]. HTC has been successfully applied to SCGs, producing stable hydrochar under mild conditions [85].

Hydrothermal Liquefaction (HTL)

HTL is carried out at 280–370 °C and 10–25 MPa, producing bio-crude oil, hydrochar, aqueous products, and light gases [80]. The key advantage is handling high-moisture feedstocks without drying, in contrast to pyrolysis. Bio-crude typically contains 8–20% oxygen, lowering its energy density relative to petro-crude, but upgrading (e.g., hydrodeoxygenation) can improve quality. Process efficiency depends on temperature, pressure, and catalysts, which influence product distribution and minimize repolymerization [86,87].

Hydrothermal Gasification (HTG)

HTG involves the conversion of biomass at temperatures exceeding 350 °C in the absence of oxidants, producing flue gas enriched with H_2 or CH_4. The process can be performed in either batch or continuous mode. While batch systems enable controlled studies of varying concentrations and catalysts, continuous systems are better suited for investigating reaction kinetics and industrial scalability [81].

HTG is typically classified into three main forms [81].

- Aqueous Phase Reforming (APR): Conducted at 215–265 °C in the presence of a heterogeneous catalyst to produce H_2 and CO_2. However, this process is generally unsuitable unless H_2 is consumed in situ, such as for biomass hydrogenation [81].
- Catalytic Gasification in a Near-Critical State: Operates around 350–400 °C using a catalyst to convert CO into CH_4 and CO_2. Methanation reactions play a key role under these conditions.
- Supercritical Water Gasification (SCWG): Carried out at 600–700 °C using supercritical water, with or without a catalyst. This method yields primarily H_2 and CO_2 and is particularly effective for biomass with >30% moisture content, including very wet feedstocks (up to 90 wt%).

SCWG requires high energy input, but heat exchangers can recover part of it, improving feasibility. It also avoids additional gas pressurization and reduces tar and coke

formation. Compared to conventional gasification, HTG generates cleaner syngas with fewer contaminants, lowering downstream filtration costs [81].

A detailed comparison of HTC, HTL, and HTG is provided in Table 6, summarizing their operational conditions, product yields, and applicability for high-moisture feedstocks like spent coffee grounds.

Table 6. Comparative summary of hydrothermal valorization processes (HTC, HTL, and HTG) based on reaction conditions, feedstock moisture tolerance, product distribution, and process suitability for spent coffee grounds. Data compiled from Kumar et al. [81], Lachos-Perez et al. [80], and Basar et al. [86].

Feature	HTC (Hydrothermal Carbonization)	HTL (Hydrothermal Liquefaction)	HTG (Hydrothermal Gasification)
Typical Temperature Range	180–250 °C	250–370 °C	>350 °C (up to 700 °C for SCWG)
Pressure Range	1–5 MPa	10–25 MPa	Up to 25 MPa (supercritical: >22 MPa)
Medium	Subcritical water	Sub-/supercritical water	Supercritical or near-critical water
Main Products	Hydro-char (solid), CO_2-rich gas, aqueous byproducts	Bio-crude oil, aqueous phase, light gases	H_2/CH_4-rich syngas, minimal tar
Feedstock Moisture Tolerance	High (70–90%)	High	Very high (>30%; up to 90%)
Catalyst Use	Not essential, optional for tuning	Optional (alkaline catalysts for corrosion resistance)	Often required for selectivity and gas yield
Energy Recovery	Low–moderate	Moderate–high (via crude upgrading)	High (especially with heat exchangers)
Carbon Retention	High (in solid hydro-char)	Medium (in liquid bio-crude)	Low (converted to gas)
Drying Requirement	None	None	None
Applications	Fuel, soil amendment, adsorbents, supercapacitors	Liquid fuels, fuel upgrading	Clean syngas, hydrogen production

4. Products and Applications

In alignment with circular economy principles, modern sustainable industries increasingly recognize organic residues as valuable feedstocks rather than waste. Among these SCGs have gained considerable attention due to their abundance and biochemical richness. Valorizing coffee by-products not only contributes to pollution reduction and waste minimization but also enables the generation of high-value products that support sustainable development goals [30]. This review categorizes and evaluates the range of products derived from SCGs into three primary groups—solid, liquid, and gaseous—and discusses their corresponding applications in industrial, agricultural, and domestic contexts.

4.1. Solid Phase

4.1.1. Biochar and Applications of SCG-Derived Biochar

Biochar is a carbon-rich solid material produced through the thermochemical decomposition of biomass under limited oxygen conditions, typically via pyrolysis. Due to its porous structure, high carbon content, and surface functional groups, biochar exhibits beneficial properties such as high adsorption capacity, enhanced soil amendment potential, and suitability for renewable energy applications [10,87]. SCGs have emerged as a promising feedstock for biochar production due to their availability and favorable chemical composition.

SCG-derived biochar properties vary with pyrolysis temperature, which strongly influences adsorption capacity and soil performance. For example, Oliveira et al. [88] reported that biochar produced from SCGs at 300 °C exhibited superior performance in adsorbing lead ions, outperforming biochar generated at higher and lower temperatures. Similarly, Hechmi et al. [16] demonstrated that pyrolysis in the 270–400 °C range not only reduces phytotoxic compounds like polyphenols but also improves pH and electrical

conductivity, enhancing its effectiveness in soil applications. These findings emphasize the importance of optimizing pyrolysis parameters to tailor biochar properties for targeted uses. A variety of studies have evaluated different thermal conditions, residence times, and heating rates to optimize yield, carbon content, and functional characteristics. Table 7 summarizes the yield, pyrolysis conditions, and resulting carbon content of SCG-derived biochar across different experimental studies.

Table 7. SCG Biochar Yield and Properties Under Different Pyrolysis Conditions.

Pyrolysis Type	Yield (wt%)	Temp (°C)	Residence Time (min)	Heating Rate (°C/min)	Carbon Content (wt%)	Specific Surface Area (m^2/g)	Total Pore Volume (cm^3/g)	Ref.
Slow	5–35	300–700	50	5	- *	-	-	[88]
Slow	-	850	60	10	75.3	492	0.238	[89]
Slow	36	350	240	10	66.4	-	-	[90]
Slow	33	600			68.6			
Slow	35.1	350	45	-	63.9	-	-	[91]
Slow	28	450	180	50	76.2	1.1	-	[92]
	31.3	400			51.3	179	0.13	
Slow	-	500	60	5	59	311	0.24	[10]
	25.4	600			64.3	539	0.32	
Slow	23.5	500	120	10	47.5	40.1	0.019	[93]
Slow	24.1	600	60	10	65.0	-	-	[94]
Slow	20	350	60	-	65.40			[95]
	23.95	450						
Fast	21.93	500	-	-	-	-	-	[96]
	23.77	550						

* '–' indicates data not reported in the cited reference.

Adsorption Applications

SCG-derived biochar has been widely investigated for its ability to adsorb nutrients and contaminants. For instance, magnesium-impregnated biochar (Mg-biochar) produced from SCGs demonstrated high phosphate recovery efficiency from wastewater and functioned as a slow-release fertilizer, with phosphate bioavailability ranging from 8.74% to 43.2% [97]. Nguyen et al. [98] showed that SCG-derived biochar pyrolyzed at 500 °C achieved an adsorption capacity of 39.22 mg/g for tetracycline, outperforming several other biochars.

Energy Storage Applications

SCG-based biochar is also a potential material for supercapacitor electrodes due to its surface area and pore structure. Andrade et al. [89] reported a specific surface area of 379 m^2/g and a pore volume of 0.238 cm^3/g (with 77% micropores), leading to a specific capacitance of up to 200 F/g without any additional activation. Wang et al. [99] synthesized nitrogen-doped porous carbon from SCGs and KOH through pyrolysis at 600–800 °C, achieving specific capacitances of 475 F/g at 0.1 A/g and 175 F/g at 1 A/g in 6 M KOH. These results highlight SCG biochar's promise in energy storage systems such as supercapacitors.

4.1.2. Activated Carbon (AC)

Activated carbon (AC) is a porous carbonaceous material with a large surface area and a high degree of microporosity, making it highly effective in adsorbing a wide range of contaminants from gases and liquids. Its surface is typically functionalized with chemical groups such as lactone, carbonyl, phenol, and carboxyl, which contribute to its reactivity and adsorption efficiency [64,100]. These properties make AC widely applicable in industries including water treatment, air purification, food processing, pharmaceuticals, and chemical manufacturing [60]. The performance of SCG-derived AC is strongly influenced by the choice of activation method. Factors such as specific surface area, pore size distri-

bution, elemental composition, and yield are determined by the type of activating agent and thermal conditions. Tables 8 and 9 summarize the physicochemical characteristics and production parameters of AC from SCGs across various studies, providing insight into optimal conditions for different applications.

Table 8. Physicochemical properties of activated carbon produced from SCGs using various activation methods.

Activation Method	Chemical Composition (wt%)				Properties			Ref.
	C	H	N	S	BET Surface Area (m^2/g)	Pore Size (nm)	Total Pore Volume (cm^3/g)	
H_3PO_4 chemical activation	72.08	8.77	4.75	0.64	1420	2.1	0.747	[101]
Solid-state chemical activation with K_2CO_3	82.66	0.59	1.55	0.17	2337	above 1.0	1.15	[66]
Hydrothermal carbonization followed by physical activation	85.4	0.9	0.7	0.1	981	4.2	1.03	[102]
Thermochemical activation using KOH	- *	-	-	-	400–1050	5–6.5	0.23–0.51	[103]
Chemical activation using KOH	-	-	-	-	1566	1–2	0.694	[104]
Co-calcination with $CaCO_3$	84.0	1.38	2.6	0.3	167	-	0.14	[39]
Chemical activation with KOH	84.48	-	-	0.44	-	-	-	[105]
Carbonization	-	-	-	-	1056	5–6.5	0.507	[103]
Pyrolysis + chemical activation using KOH	-	-	-	-	1372	-	0.998	[106]
Chemical activation with H_3PO_4 followed by pyrolysis	-	-	-	-	300–2118	2.6–3.4	0.038–0.127	[65]
HTC followed by KOH activation	88.75	-	2.35	-	1835	-	1.81	[107]
Carbonization + post-treatment with NaOH and acetic acid	-	-	-	-	43.18	3–6	-	[108]
Pyrolysis	-	-	-	-	89.55–99.19	2.98–2.95	0.0168–0.0183	[109]
Carbonization under Ar, activation with CO_2	93.00 (at%)	-	2.38 (at%)	-	2497	2.11	1.28	[110]
Pyrolysis + CO_2 physical activation	92.0	1.2	2.8	-	1224	1.70	0.63	[111]
Pyrolysis + chemical activation	82.9	1.7	2.57	0.2	464	0.57	0.197	[112]
KOH activation followed by carbonization	87.54	-	2.36	-	164.33	-	0.08021	[113]
Chemical activation with $ZnCl_2$ followed by carbonization	53.9	1.7	7.9	-	1039	-	0.481	[114]

* '–' indicates data not reported in the cited reference.

Table 9. Processing parameters and yield outcomes for activated carbon derived from SCGs under different activation conditions.

Product Type	Activation Agent	Carbon Content (wt%)	Temp (°C)	Time (min)	Heating Rate °C/min	Yield (wt%)	Ref.
AC	CO_2	93	900	180	15	41.3	[110]
	KOH		800	120	10	6.11	[115]
	$CaCO_3$	84	850	60	5	9.1	[39]
	CO_2	76.2–77.5	750 750 800 800	30 60 30 60	10	16.7 16.6 12.7 8.9	[116]
	KOH	- *	800	240	-	-	[64]
	CO_2	-	600 700 800	120	10	63.8 60.2 55.3	[111]
	CO_2		400 475 550	60 65 120		20.12–23.61	[117]
	$ZnCl_2$,	90.2	500	120	10	35 to 50	[114]
	KOH	70.01 88.75 89.44	800	60	5		[107]

* '-' Indicates that the data were not reported in the cited reference.

Adsorption Applications

AC derived from SCGs has demonstrated strong adsorption capacity for removing dyes, heavy metals, and other contaminants from aqueous environments. Its efficiency is largely attributed to its high surface area, hierarchical pore structure, and surface chemistry tailored through activation processes. For instance, chemically modified AC with KOH has been shown to achieve an acid yellow dye removal efficiency of 88.7% at a concentration of 35 ppm, with an adsorption capacity of 2.58 mg/g and a contact time of 2.5 h [118]. In another study, calcium alginate–SCG composite beads significantly outperformed pure calcium alginate beads in heavy metal removal, exhibiting adsorption capacities of 20.96 mg/g for Ni^{2+} and 91.18 mg/g for Cd^{2+} [119]. These findings highlight the potential of SCG-based AC not only as a low-cost and abundant adsorbent but also as a platform for composite material development to enhance contaminant removal in environmental applications.

Supercapacitor Applications

SCG-derived AC has been investigated for its potential use in supercapacitor electrodes due to its tunable surface area, pore structure, and electrochemical stability. The choice of activation agent and carbonization conditions plays a critical role in determining capacitance performance. Choi et al. [120] produced nitrogen-doped AC by blending dry coffee powder with melamine and using KOH as the activating agent. The process yielded a high surface area of 1824 m^2/g, although the resulting specific capacitance was relatively low at 74 F/g. In contrast, Yun et al. [121] achieved a surface area of 1945.7 m^2/g and a higher capacitance of 121 F/g by increasing the carbonization temperature to 1200 °C.

Liu et al. [122] reported a multistep activation process involving catalytic carbonization using $FeCl_3$ and KOH activation, which further enhanced porosity. However, it is important to note that a higher surface area does not always guarantee better capacitance. For example, bamboo-derived AC with a surface area of 1250 m^2/g yielded only 65 F/g, while flax-derived carbon with a much lower surface area of 645 m^2/g achieved a specific capacitance of 325.8 F/g [123]. This discrepancy emphasizes the role of pore size distribution, surface functional groups, and conductivity in optimizing electrochemical performance. SCG-based AC offers a low-cost and renewable alternative for electrode fabrication in energy storage devices. However, issues such as electrode swelling, oxygen functional group interference, and structural instability during cycling remain challenges to be addressed in scaling up these systems [124].

Battery Applications

AC derived from SCGs has also shown promise in energy storage technologies, particularly as a sustainable electrode material in lithium-ion and redox flow batteries. Its advantages include cost-effectiveness, high surface area, and tunable porosity.

In lithium-ion batteries, researchers have synthesized composites of amorphous carbon from SCGs with germanium nanoparticles using GeO_2 as a precursor. These composites function effectively as negative electrodes due to their conductivity and structural compatibility. In vanadium redox flow batteries (VRBs), steam-activated SCG AC has been employed to enhance electrode microporosity. Prolonged activation increased the surface area from 541 to 1113 m^2/g and expanded pore volume, but also reduced voltage efficiency from 97–99% to 91–96%, likely due to structural disorder from excessive microporosity [125]. Despite this, the coulombic efficiency remained high at 99–100%, indicating stable charge retention. These findings suggest that SCG-derived AC, with proper activation and structural tuning, is a viable and sustainable material for advanced battery systems, particularly when cost, availability, and environmental impact are taken into account.

Sensor Applications

SCG-derived carbon materials have shown considerable potential in the development of sensors for environmental monitoring, human–machine interfaces, and biomedical applications, owing to their conductivity, stability, and surface reactivity.

In a more advanced application, Li et al. [126] fabricated a triboelectric nanogenerator (CG-TENG) from waste coffee grounds. This device not only served as a flexible power source but also functioned as a self-powered sensor capable of detecting physiological signals, human gestures, and tactile feedback. Its adaptability and low cost make it a promising technology for wearable electronics, smart prosthetics, and interactive devices.

Additionally, Gissawong et al. [127] developed an electrochemical sensor for ciprofloxacin detection using gold nanoparticles deposited on SCG-derived AC and modified with a supramolecular solvent. The sensor exhibited excellent electrocatalytic activity, with a detection limit as low as 0.20 nM and successful application in complex matrices such as milk, achieving recovery rates between 78.6% and 110.2%.

These studies confirm that carbon materials derived from SCGs can be tailored for high-sensitivity sensor platforms in both environmental and biomedical fields.

Microbial Fuel Cells

Microbial fuel cells (MFCs) are bioelectrochemical systems that utilize the metabolic activity of microorganisms to convert chemical energy in organic substrates into electrical energy. One of the key limitations in MFC development is the high cost and limited performance of conventional electrode materials. AC derived from SCGs offers a cost-effective and sustainable alternative due to its high surface area, good electrical conductivity, and favorable pore distribution.

Hung et al. [113] demonstrated that SCG-based AC used as an anode in *Escherichia coli*-driven MFCs achieved a power density of 3927 mW/m^2—over four times higher than commercial AC (975 mW/m^2). This enhancement was attributed to the optimized pore structure that facilitated both bacterial adhesion and rapid electron transfer. In terms of cathode performance, Bose et al. [128] investigated SCG-derived carbon as a replacement for platinum-based catalysts in the oxygen reduction reaction (ORR). The system achieved an open-circuit voltage of 580 mV, a peak power density of 110 mW/m^2, and a COD removal efficiency of approximately 64%, suggesting strong dual-functionality in both energy production and wastewater treatment. These studies collectively highlight SCGs as a viable and efficient material for electrode development in MFC systems, particularly for decentralized energy production and environmental remediation.

4.1.3. Compost and Organic Fertilizers

SCGs are rich in organic matter and nutrients, making them a promising candidate for agricultural use when properly pretreated or valorized. However, direct application of raw SCGs to soil—particularly in concentrations above 20% (v/v)—has been associated with phytotoxic effects due to the presence of caffeine, tannins, and polyphenols. These compounds can suppress seed germination and limit nitrogen availability to plants [16,129].

Pre-treatment methods such as composting, vermicomposting, or co-application with animal manure have been shown to mitigate these negative effects and enhance the agronomic value of SCGs. For instance, Bomfim et al. [130] reported that applying 10% (v/v) SCGs to lettuce cultivation improved chlorophyll content by up to 37%, with only a minor decrease in organic nitrogen (4.4%). Hechmi et al. [16] emphasized that pre-treated SCGs significantly improved soil pH, C:N ratio, and microbial activity compared to raw SCGs, which tended to reduce seedling growth and nutrient uptake in early stages.

When combined with other organic amendments such as horse or cat manure, SCGs offer additional benefits:

- Free from harmful heavy metals, SCGs reduce the risk of soil contamination.
- Their high water-holding capacity helps maintain soil moisture and regulate temperature when used as mulch.
- SCGs can immobilize pesticide residues and heavy metals, reducing their mobility in the soil.
- Improvements in leaf development, rosette diameter, and nutrient bioavailability have been observed in various crops.

Bomfim et al. [130] showed that a 10 kg/m^2 SCG addition to horse manure increased soil carbon and nitrogen by 25% and 45%, respectively, and reduced the C/N ratio to 10. When used with cat manure, SCGs enhanced spinach productivity and suppressed harmful soil elements, though they did not significantly improve nutrient levels compared to cat manure alone. Moreover, SCG applications at 5–10 kg/m^2 resulted in improved C and N content and up to 50% weed suppression.

Overall, the co-application of SCGs with other organic materials and the use of pretreatment methods are essential for unlocking their full potential as a soil amendment, while avoiding phytotoxicity associated with raw material use.

4.1.4. Bio-Based Materials: Subgrade Materials, Plastics, Composites, and Adsorbents

Subgrade and Construction Materials

SCGs have been widely explored as a sustainable additive in construction materials, particularly for subgrade applications. Arulrajah et al. [131] investigated various SCG-based mixtures using recycled glass, bagasse ash, fly ash, and slag to enhance the ultimate compressive strength (UCS) of the resulting materials. Their results indicated that while the SCG–ash mixture achieved a UCS of approximately 1.5 N/mm^2, blending SCGs with recycled glass significantly enhanced strength to nearly 11 N/mm^2 [131–134]. Kua et al. further demonstrated that a mixture containing 70% SCGs and 30% slag produced favorable UCS values around 2 N/mm^2, whereas a 50/50 blend exhibited reduced strength, indicating slag as a more effective binder than fly ash [132,135,136]. Other enhancements using rice husk ash have also shown UCS improvements up to 2 N/mm^2 [137]. These findings collectively highlight the potential of SCGs as a cost-effective and environmentally friendly additive for low-strength construction materials.

Bioplastics and Polymer Composites

SCGs have been effectively incorporated into composite materials and bioplastics to enhance mechanical properties and sustainability. Wu et al. demonstrated that oil-extracted SCGs improve interfacial adhesion, mechanical strength, and water resistance when used with polypropylene [138]. Similarly, Zarrinbakhsh et al. found coffee chaff to outperform SCGs in heat stability and density but acknowledged SCGs' viability as a reinforcing agent [139]. Garcia-Garcia et al. produced wood-plastic composites using 20% SCGs and 80% polypropylene, reporting minor flexural improvements and enhanced heat stability [140].

In PLA-based composites, maleic anhydride-grafted PLA and crosslinked SCGs improved processability and biodegradability [141]. Hydrolyzed SCGs have also been blended with polyethylene to form antioxidant films with enhanced thermal and photo-oxidative stability [142]. Lee et al. created polyvinyl alcohol/SCG nanocomposites with enhanced tensile strength and Young's modulus, showing potential for replacing carbon black in flexible materials [143].

Biodegradable Polymers: PHAs and PHBs

Beyond traditional composites, SCGs have been utilized as feedstock for producing biodegradable polymers such as polyhydroxyalkanoates (PHAs) and polyhydroxybutyrates (PHBs). Obruca et al. [144,145] demonstrated that oil and sugar extracted from SCGs can serve as carbon sources for PHA production using *Cupriavidus necator* H16 and *Bacillus megaterium*. Furthermore, SCG hydrolysates enhanced PHA yields when polyphenols were removed. The residual SCG after extraction retained calorific value, supporting its use for energy recovery. Cruz et al. [146] used supercritical CO_2 to extract SCG oil for biopolymer synthesis. Wu [147] also developed SCG-PHA membranes for cell-based assays, demonstrating their compatibility for biomedical applications.

SCG-Based Adsorbents for Water Purification

SCG-derived materials have demonstrated excellent adsorptive properties for removing metal ions, dyes, and organic contaminants. Their effectiveness in removing As, Cu, Cd, Pb, Ni, and Hg has been well-documented [29,148]. Pretreatments like solar degreasing or ion exchange modeling have further enhanced performance [149,150].

Studies have shown that SCG biochar outperforms untreated SCG for heavy metal adsorption, while remaining calorific value supports its reuse in energy applications [145,151]. Composite foams combining SCGs and silicone elastomers achieved strong removal efficiencies for Pb and Hg [152]. Other studies compared SCGs with banana peels, piassava, and water hyacinth, with SCGs emerging as the more practical and scalable option due to their particle size and availability [153].

Kim and Kim [154] demonstrated SCGs' superior cadmium adsorption capacity (19.32 mg/g) compared to zeolite (13.91 mg/g), attributed to their high organic matter content (94.65%). The adsorption capacity was highest at pH 6, with ionic strength and solid-to-solution ratios playing significant roles in performance. At a solid-to-solution ratio of 1:10, the highest Cd removal efficiency was achieved. Similar findings were reported by Azouaou et al. [155] for Cd removal kinetics and by Nam et al. [156] for arsenic removal, showing improved performance under acidic and alkaline pH conditions.

SCGs also showed high efficiency in removing pharmaceutical pollutants like caffeine, diclofenac, and salicylic acid. Zungu et al. [157] produced biochar from SCGs via pyrolysis, achieving adsorption capacities of 40.47 mg/g for salicylic acid, 38.52 mg/g for diclofenac, and 75.46 mg/g for caffeine. Additional studies confirmed dye removal including acid orange 7, methylene blue, and safranin O [29,148]. SCG-derived hydrochar with Fe_3O_4 nanoparticles [158,159] showed improved efficiency for Acid Red 17 removal.

Advanced Nanomaterials and Photocatalytic Applications

The versatility of SCGs extends to the synthesis of advanced nanomaterials and photocatalysts, offering sustainable alternatives in environmental remediation. For instance, Xu et al. [160,161] converted SCGs into fluorescent carbon quantum dots using a microwave-assisted hydrothermal method. These dots exhibited high oxygen content, tunable fluorescence, and good water dispersibility. When embedded into membrane systems, they showed strong performance in removing both organic pollutants and heavy metals from aqueous solutions. Recent developments also include the fabrication of nanoporous membranes and hybrid materials using SCG-based nanostructures [160,162], which demonstrated promising electrochemical stability and photocatalytic activity under real wastewater conditions. These materials expand the potential for SCG applications in next-generation water treatment systems.

Overall, the integration of SCG-based nanomaterials into environmental technologies exemplifies a high-value pathway within the circular economy. These advancements not

only enhance pollutant removal capabilities but also reduce the reliance on high-cost, non-renewable materials in water purification and sensing applications.

4.2. Liquid Phase

4.2.1. Bio-Oil

Bio-oil derived from the pyrolysis of SCGs is a complex dark-colored mixture with a distinct aroma. Its composition includes over 300 compounds such as hydrocarbons, aldehydes, alcohols, ketones, carboxylic acids, esters, phenols, furans, and nitrogen-containing molecules [32]. While slow pyrolysis tends to produce bio-oil with higher energy density (20–37 MJ/kg), it yields less oil than fast pyrolysis, which can yield up to 54–56% due to minimal secondary cracking [96,163]. Fast pyrolysis offers advantages such as biomass densification, compatibility with multiple feedstocks, and lower capital costs. However, it produces oxygen-rich bio-oil, necessitating upgrading steps. Pre-treatment of SCGs, including removal of acidic glycerides, improves the quality and reduces corrosivity of the resulting bio-oil [164].

Bio-oil derived from pyrolysis has multiple promising applications. It can be directly utilized or co-fed with fossil fuels as a boiler fuel or in heavy-duty engines. Compared to heavy fossil fuels, bio-oil combustion results in significantly lower emissions of CO_2, NO_x, and SO_x, aiding in pollution control and possibly eliminating the need for additional NO_x/SO_x removal systems. For example, co-feeding 2.5 wt% bio-oil with heavy fuel oil led to a 2.6% reduction in NO and a 7.9% decrease in SO_2 emissions. These environmental advantages are mainly attributed to the inherently low nitrogen and sulfur content in biomass. Nevertheless, bio-oil's high water content (20–30%, compared to just 0.32 wt% in fossil fuels) diminishes its heating value (13–19 MJ/kg versus 40.63–42.39 MJ/kg) [165].

To enhance bio-oil properties for fuel applications, hydrodeoxygenation—a catalytic process conducted under elevated pressures and temperatures—is employed to remove excess oxygen, thus improving its energy density and stability. Another pathway is using bio-oil for H_2 production, either through direct steam gasification of biomass or steam reforming of the bio-oil itself. H_2, with an energy content of 120.7 MJ/kg and zero GHG emissions upon combustion, is considered a highly attractive energy carrier [165].

Bio-oil is also a potential source for industrial chemicals. Given the environmental and economic concerns of fossil-based chemical production, research has focused on extracting valuable compounds from bio-oil using diverse separation and synthesis techniques. Lastly, bio-oil can be used to produce carbonaceous materials applicable across industries. Biomass-derived carbons are favored over coal-based alternatives due to their lower sulfur and nitrogen contents, making them more sustainable and environmentally benign [165].

4.2.2. Bioactive Extracts

SCG extracts are a rich source of natural antioxidants, flavors, and pigments. Ethanol and water extracts of SCGs have demonstrated strong 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity. Hot ethanol extraction (80 °C for 1 h) was found to be the most effective in preventing lipid oxidation in meat emulsions [166]. However, efficacy in preserving cooked meat declined after three days, indicating the need for optimized extraction and delivery methods.

SCGs have also been applied in beverage production. Sampaio et al. [167] used hydrothermal treatment, fermentation, and distillation to create spirits with pleasant coffee aroma. Machado et al. [168] used microwave-assisted extraction, followed by fermentation and distillation, to produce beverages with up to 40% ethanol. Gas chromatography-mass spectrometry identified 60 volatiles contributing to flavor, including esters and alcohols. Liu et al. [169] showed that using non-Saccharomyces yeasts and enzymatic hydroly-

sis enhanced succinic and lactic acid production along with flavor-active compounds. Masino et al. [170] developed coffee-flavored liquors using SCG extract with ethanol, caramel, and glucose syrup.

In addition to antioxidants and flavors, SCGs are a source of natural pigments such as flavonoids, anthocyanins, and carotenoids. These pigments have antioxidant and antimicrobial properties and are used in food, cosmetic, and pharmaceutical industries [171,172]. Fermentation of SCG hydrolysates by microorganisms like *Sporobolomyces roseus* enables the production of carotenoids [29,145].

4.3. Gas Phase: Biogas and Syngas

SCGs can be converted into energy-rich gases via three primary pathways—anaerobic digestion (producing biogas), pyrolysis, or gasification (both producing syngas). Although numerous studies have investigated these conversion processes and characterized gas yields and composition [40,79,173], real-world applications of SCG-derived gases remain limited. This gap highlights an important area needing further exploration in terms of practical deployment, techno-economic analysis (TEA), and scalability of SCG-derived gaseous fuels.

5. Comprehensive Sustainability Assessment of Spent Coffee Grounds Valorization

5.1. Comparative Life Cycle Assessments (LCAs)

Life Cycle Assessment (LCA) is an essential tool for evaluating the environmental performance of SCG valorization pathways. The reviewed literature consistently reveals that SCG processing routes differ markedly in their environmental burdens depending on the technology used, energy inputs, and product outputs. This section critically compares the environmental implications of several SCG reuse scenarios, particularly focusing on biofuels, biochar, building materials, and biogas generation.

Several studies have highlighted that thermal valorization processes like pyrolysis outperform transesterification (biodiesel production) in terms of both environmental and economic sustainability. Gu et al. [174] conducted a comparative LCA between pyrolysis and transesterification of SCGs and reported that transesterification emits 6.92 times more CO_2 and costs 3.49 times more per GJ than pyrolysis. Although the biodiesel route produces a slightly higher heating value (40.1 MJ/kg vs. 32.2 MJ/kg), the necessity of feedstock pretreatment and chemical use in transesterification significantly elevates its impact and cost. Similarly, Kisiga et al. [175] assessed six valorization routes—biodiesel, anaerobic digestion (AD), gasification, fermentation, hydrothermal liquefaction (HTL), and fast pyrolysis—and found that anaerobic digestion had the lowest overall environmental burden. HTL, on the other hand, had the highest total weighted score due to its heavy electricity consumption, especially from coal-based sources. This aligns with Schmidt Rivera et al. [176], who evaluated SCG biodiesel against disposal methods and found it to be the least environmentally sustainable, while incineration with energy recovery and direct land application showed net-negative impacts in most impact categories.

Forcina et al. [177] further confirmed these insights through a comparative LCA of composting, biodiesel production, and brick-making. They found that brick incorporation of SCGs reduced air emissions by 76%, composting by 18%, and biodiesel by only 1% compared to landfilling. A sensitivity analysis revealed that transport distances play a crucial role, with break-even distances of 150 km for biodiesel and 1800 km for bricks.

SCG valorization systems producing multiple outputs often offer better environmental returns. For instance, Yang et al. [178] compared two routes: biodiesel extraction followed by HTL of residue, and direct HTL of raw SCGs. The latter resulted in 65% fewer GHG

emissions due to the elimination of solvent-based pretreatment. This reinforces the importance of process integration and solvent avoidance. Pradhan et al. [179] used simulation modeling to assess SCG pyrolysis, showing that increasing temperature from 300 °C to 600 °C reduced the carbon footprint of biochar by 59%, though emissions from bio-oil and syngas increased due to CO_2 content. These findings indicate a trade-off between product composition and environmental performance.

Comparative LCAs indicate that anaerobic digestion generally performs better environmentally than biodiesel production. Pyrolysis and integrated pathways (e.g., residue HTL) offer favorable outcomes when energy use and solvent inputs are minimized. HTL shows strong product potential, but its environmental performance is constrained by high electricity demand. Overall, process integration, efficient energy management, and minimization of pretreatment requirements are the key factors that shift SCG valorization toward environmental sustainability.

5.2. Techno-Economic and Feasibility Analyses

The techno-economic feasibility of SCG valorization is highly dependent on the type of process employed, product yields, energy requirements, and regional factors such as feedstock availability, market conditions, and plant location. Across the literature, integrated biorefinery concepts, energy-efficient technologies, and waste-to-product diversification consistently improve economic performance.

SCG biodiesel production presents mixed economic outcomes. Thoppil and Zein [180] performed a TEA for a biodiesel plant in Seattle processing 31.2 kt/year of SCGs. Despite producing 2.6 kt/year of biodiesel, the study concluded that the project was not profitable under baseline conditions, with high capital investment (~USD 123 million) and insufficient returns. Sensitivity analysis revealed that the price of biodiesel significantly affects Net Present Value (NPV).

SCG pyrolysis systems generally exhibit better economic metrics. Pradhan et al. [179] reported annual profits ranging from USD 14–22 million and a payback period of just 3.4 years for pyrolysis plants modeled using PIS-V2.0 in multiple countries. Key findings included that increased temperatures improve biochar quality and reduce its carbon footprint but raise energy demands. Similarly, Gu et al. [174] showed that pyrolysis had a much lower production cost (USD 8.8–12.4/GJ) than transesterification (USD 30.8–43.7/GJ). Even after optimizing extraction efficiency, the transesterification route remained significantly more expensive. Matrapazi and Zabaniotou [32] proposed a city-scale SCG pyrolysis system using rotary kilns in Greece, collecting 2566 t/year from local coffee shops. The model yielded EUR 47/t profit, a return on investment (ROI) of 0.24, and a payback time (PBT) of 2.6 years—demonstrating the viability of distributed, community-level valorization systems.

Integrating SCG valorization into biorefineries with multiple outputs enhances both economic and environmental outcomes. Valencia-Isaza et al. [181] compared four scenarios including the recovery of oil, prebiotics, melanoidins, and hydrochar. Scenario 3, excluding oil and melanoidin separation, emerged as the most economically and environmentally viable, while Scenario 2 (including oil) offered higher profitability due to oil's market value. Mukherjee et al. [182] simulated AC production via slow pyrolysis and CO_2 activation. All three production scenarios yielded positive NPVs, with Scenario 1 producing AC at just USD 0.15/kg—significantly lower than commercial AC prices (~USD 0.45/kg). This result demonstrates the competitive advantage of SCG-derived AC.

Biogas production from SCGs via anaerobic digestion (AD) is another economically viable route. Mahmoud et al. [54] reviewed studies reporting CH_4 yields of 0.27–0.34 m^3/kg, with defatted SCGs performing better. Co-digestion with waste activated sludge or food waste can enhance yields. The authors advocate for techno-economic and

LCA studies to support future SCG-AD-based biorefineries. Yeoh and Ng [183] evaluated four SCG biorefinery scenarios combining biodiesel with either electricity or high-value chemicals. Scenario C (on-site, large-scale, using SCGs from a coffee factory) produced a positive NPV of GBP 3.1 million, with GHG emissions 13% lower than conventional rapeseed biodiesel. Product pricing and energy integration were key sensitivity factors. It should be noted that although agricultural applications of SCGs are widely practiced, dedicated TEA on their scalability and environmental impacts are scarce. Future studies should prioritize integrated evaluations of these applications to better assess their role in sustainable waste management and circular economy transitions.

Key Techno-Economic Takeaways

- Profitability improves significantly when SCG valorization systems integrate co-products (e.g., activated carbon, biogas).
- Pyrolysis and biogas routes consistently show higher returns and lower risk than biodiesel under current market assumptions.
- Energy integration and process efficiency—particularly in drying, heating, and solvent use—strongly influence feasibility.
- On-site processing and consistent feedstock supply (e.g., coffee factories vs. retail establishments) lower transportation and variability costs.

These analyses confirm that SCG valorization becomes financially attractive when implemented as part of an integrated, scalable, and circular biorefinery system designed to maximize product diversity and minimize energy inputs.

5.3. Socio-Economic and Policy Considerations

The implementation of SCG valorization technologies is not solely dictated by techno-economic metrics but is also significantly influenced by socio-economic conditions, regulatory frameworks, public perception, and logistical feasibility. As countries pursue circular economy and sustainability targets, SCG valorization offers a viable path for waste reduction, local job creation, and green innovation, but policy and social infrastructure must evolve accordingly.

Matrapazi and Zabaniotou [32] proposed a city-scale eco-social innovation model in central Greece based on slow pyrolysis of SCGs collected from urban coffee shops. Their model emphasized zero-cost feedstock acquisition, local employment generation, and the use of recovered biochar for municipal gardening. The study concluded that proximity to feedstock sources, logistical efficiency, and public–private partnerships are essential for successful upscaling. Similarly, Saeli et al. [184] demonstrated the application of SCGs in green geopolymer construction materials as a low-cost, energy-saving solution. Their simulations showed that integrating SCGs into building blocks and plasters could yield up to 19% annual energy savings, reduce costs by up to 37%, and provide performance superior to conventional materials in colder climates. The authors emphasized the importance of aligning such innovations with European Minimum Environmental Criteria (MEC) and pursuing certifications like LEED or ReMade in Italy, showing how regulatory endorsement can support commercial viability.

Several studies warned of the inconsistencies between existing waste hierarchy regulations and life cycle evidence. Schmidt Rivera et al. [176] found that incineration with energy recovery was more environmentally sustainable than biodiesel or composting for SCGs, contrary to prevailing assumptions under EU waste hierarchy guidance. The authors recommended revising guidelines to align policy with life cycle sustainability metrics. Likewise, Kisiga et al. [175] emphasized the importance of energy source considerations in SCG valorization. They showed that AD, while lowest in overall environmental burden, emitted more CH_4 and CO_2, raising concerns under global warming potential (GWP) indi-

cators. Switching from coal-based to natural gas-based electricity significantly improved overall sustainability, suggesting that regional energy policy and grid mix directly affect the viability of SCG-to-fuel projects.

Banu et al. [185] and Zabaniotou and Kamaterou [186] highlighted that the transition from mono-processing (e.g., only oil or bioethanol extraction) to cascade biorefinery systems is hindered by low technology readiness level, fragmented regulatory frameworks, and lack of standardized economic and sustainability assessments. Both studies advocate for national-level incentives, harmonized regulations, and technical standards for SCG valorization. Yeoh and Ng [183] reinforced these findings, identifying product pricing volatility and lack of on-site energy integration as major commercial risks. In their UK-based scenarios, biorefineries relying on consistent feedstock from industrial coffee factories were significantly more viable than those sourcing from smaller retail establishments. This aligns with broader policy themes on industrial symbiosis and urban circular economy planning.

Effective SCG valorization requires more than infrastructure—it necessitates public awareness and behavior change. Matrapazi and Zabaniotou [32] stressed the importance of engaging consumers and coffee shop operators in the collection and segregation of SCG waste, noting that citizen participation is crucial for maintaining a steady feedstock supply in decentralized systems. Additionally, Ahmed et al. [187] emphasized SCGs' potential in bio-based plastics, adsorbents, and cosmetic sectors, noting that such products may be better accepted by the public due to their association with waste reduction and sustainability. However, success depends on clear communication, regulatory approval, and branding strategies that emphasize environmental benefits.

5.4. Integrated Sustainability Assessments and Future Prospects

Integrated sustainability assessments synthesize environmental, economic, and social dimensions to holistically evaluate SCG valorization routes. Across the reviewed literature, multi-criteria frameworks such as TEA, life cycle assessment (LCA), and socio-environmental modeling offer crucial insights into the feasibility and long-term benefits of SCG-derived products.

Several studies employed simultaneous TEA and LCA frameworks to compare SCG valorization pathways. For example, Gu et al. [174] modeled biodiesel (via transesterification) and pyrolysis routes, showing that although transesterification offered slightly better CO_2 emission profiles under optimal conditions, its production cost remained 3.49 times higher than that of pyrolysis. The unit cost of pyrolysis ranged from \$8.82–12.35/GJ, while transesterification reached up to \$43.71/GJ, mainly due to pretreatment inefficiencies and solvent costs. Mukherjee et al. [182] evaluated three AC production scenarios using Aspen Plus simulations and detailed cash flow analyses. All scenarios were profitable, with Scenario 1 (pyrolysis + CO_2 activation + flue gas recycling) delivering the lowest minimum selling price (MSP) (\$0.15/kg) and the highest NPV (\$206 million USD). This study demonstrated the critical importance of integrating process modeling with financial sensitivity analysis, particularly when evaluating bio-based materials competing with petrochemical equivalents.

Building on the techno-economic challenges discussed earlier (Section 5.3), several studies emphasize that transitioning from mono-processing to integrated cascade biorefinery models remains the most promising strategy for SCG valorization. Such systems can exploit multiple fractions (lipids, sugars, polyphenols, residual biomass) for biofuels, chemicals, and energy, aligning with circular economy goals [185,186]. Integration at industrial sites—such as coffee factories—further enhances viability by ensuring consistent feedstock, energy self-sufficiency, and reduced transportation impacts [183].

Future studies must address several gaps to enable large-scale deployment of SCG valorization:

- Many promising processes remain at lab or pilot scale. Studies like Valencia-Isaza et al. [181] stress the need for continuous process design and adoption of green extraction methods to reduce hexane and energy footprints in multi-product biorefineries.
- Matrapazi and Zabaniotou [32] and Kamil et al. [188] identified the lack of coordinated SCG collection infrastructure as a primary barrier to scale-up. Future research should evaluate city-scale logistics, consumer incentives, and decentralized systems.
- Zabaniotou and Kamaterou [186] and Kisiga et al. [175] emphasized the need for national-level guidelines, carbon credit integration, and financial incentives to drive adoption. Without coherent regulatory support, valorization systems risk underutilization despite their technical maturity.
- While most studies focus on GHG emissions and NPV, broader metrics such as ecosystem services, human toxicity, and social acceptance are seldom included. As Schmidt Rivera et al. [176] cautioned, ignoring these can lead to misguided policy and investment decisions.

To facilitate comparison across the various SCG valorization pathways discussed in Section 5, a summary is provided in Table 10. The table combines the key findings by comparing different valorization routes for SCGs based on life cycle environmental performance (e.g., GWP, emissions) and techno-economic metrics (e.g., NPV, MSP, ROI).

Table 10. Summary of environmental and technoeconomic assessments of SCG valorization pathways.

Valorization Pathway	Environmental Impact Summary	Techno-Economic Insight	Refs.
Biodiesel	High GHG emissions, high resource use due to solvents like hexane and methanol	Often economically unviable unless supported by co-products; high production cost	[174–176,180]
Pyrolysis	Moderate GHG emissions; lower than biodiesel; improved with temperature optimization	Generally favorable economic feasibility, especially with biochar or co-products	[32,174,179]
Hydrothermal Carbonization (HTC)	Low carbon footprint, low toxicity, favorable across impact categories	Energy-intensive; less common in large-scale studies but environmentally promising	[175,178]
Anaerobic Digestion	Lowest overall environmental impact in multiple LCAs; mitigates waste emissions	Cost-effective under co-digestion scenarios; high methane yield with DSCGs	[54,175]
Construction Materials (Geopolymers)	Reduces environmental footprint via waste reuse and energy savings	Cost-effective in green building; up to 37% cost savings observed	[184]
Activated Carbon	Low to moderate impact depending on activation method	Profitable across different scenarios with positive NPV	[182]
Biorefinery (Multi-product)	Varies by configuration; improved with waste stream integration	Promising when integrated with value-added products; scalability challenges	[181,183,185,186]

5.5. Alignment with Sustainable Development Goals (SDGs)

The valorization of SCGs into bio-based fuels, materials, and chemicals contributes meaningfully to several of the United Nations Sustainable Development Goals (SDGs), offering a pathway to integrate waste management with global sustainability objectives. SCG-derived biofuels and biogas directly advance SDG 7 (Affordable and Clean Energy) by promoting renewable alternatives to fossil fuels. Multiple studies emphasize the high calorific value and potential of SCGs for energy recovery through anaerobic digestion, pyrolysis, and hydrothermal liquefaction [54,174]. By fostering innovation in bio-based product development—ranging from biodiesel and AC to construction materials and bioplastics—SCG valorization also supports SDG 9 (Industry, Innovation, and Infrastructure). Demonstrations of modular biorefinery designs [183,185] highlight the feasibility of scalable, decentralized infrastructures for SCG processing.

Circular bioeconomy principles underpin the SCG valorization chain, aligning well with SDG 12 (Responsible Consumption and Production). Several life cycle assessments (LCAs) confirm that compared to landfilling or conventional incineration, SCG reuse substantially reduces emissions, energy demand, and environmental toxicity [175,176,181]. Significantly, SCG-based alternatives also contribute to SDG 13 (Climate Action) through GHG reductions. Biodiesel production was found to lower carbon emissions by up to 80% compared to fossil fuel baselines [179,188]. The potential to offset CH_4 emissions from landfilling further reinforces SCGs' role in mitigating climate impacts [54]. Finally, when deployed in community-driven or city-scale applications—as proposed by Matrapazi and Zabaniotou [32]—SCG valorization supports SDG 11 (Sustainable Cities and Communities) through decentralized waste-to-energy models, localized resource recovery, and reduced dependency on landfill infrastructure.

6. Challenges and Recommendations

6.1. Key Challenges in SCG Valorization

Despite the promising advances in valorizing SCGs for biofuels, biochar, chemicals, and materials, several technical, economic, environmental, and systemic challenges persist across the reviewed studies.

Many conversion routes remain technologically immature or under-optimized at scale. For instance, Gu et al. [174] found that the pretreatment efficiency in biodiesel production via transesterification is a critical bottleneck, resulting in high costs and lower energy returns compared to pyrolysis. Similarly, Valencia-Isaza et al. [181] noted that steam consumption during hydrothermal processes is a major contributor to environmental burden and cost, particularly in multi-product biorefinery scenarios. Several other studies [179,182] pointed to energy-intensive operations like drying, hexane recovery, and char activation as process hotspots requiring optimization.

Economic outcomes are highly sensitive to market variables, such as the price of co-products and energy. Thoppil and Zein [180] showed that biodiesel from SCGs in Seattle was not economically viable under baseline conditions, requiring significantly higher product pricing to offset costs. Kamil et al. [188] and Yeoh and Ng [183] similarly reported that profitability depends heavily on co-product valorization (e.g., high-value chemicals) and site-specific factors such as scale and feedstock consistency.

While many SCG valorization pathways offer environmental benefits, several trade-offs remain underexplored. Although anaerobic digestion is the least environmentally burdensome in total weighted impact, it still produces large amounts of methane and CO_2, necessitating further valorization or capture strategies [175]. Additionally, the use of solvents and fossil-derived energy has been identified as a major contributor to life cycle impacts, particularly in biodiesel production [176,189]. Moreover, most studies focus solely on GHG emissions, neglecting impact categories such as human toxicity, eutrophication, and water footprint, leading to incomplete assessments. A major barrier to commercial implementation is the absence of a robust SCG collection network. Especially in urban settings, fragmented supply chains and the lack of coordinated logistics hinder consistent feedstock availability [32,185]. Collection-related emissions can also negate environmental benefits beyond specific transport distances [177].

A lack of standardized policy support, especially in waste valorization incentives and certification schemes, limits investment. National harmonization of policies and the introduction of technical indicators to guide sustainability assessments and industrial planning have been recommended [186].

6.2. Recommendations for Future Research and Policy

Advancing the valorization of SCGs toward sustainable and economically viable pathways requires a multifaceted approach that simultaneously improves technological performance, expands sustainability metrics, strengthens infrastructure, and aligns with policy frameworks.

A primary priority is the optimization of process integration and energy efficiency. Multiple studies have identified key energy-intensive stages, such as drying, pyrolysis, and solvent recovery, which substantially contribute to the overall environmental and economic burden. For example, open-air drying has been shown to offer environmental advantages over thermal drying [189]. Similarly, energy consumption associated with hydrothermal carbonization and hexane recovery significantly increases environmental impacts and operational costs [181,190]. Transitioning to green solvents and adopting continuous-flow or modular systems may offer meaningful reductions in process emissions and costs. Furthermore, there is a pressing need to expand the scope of sustainability assessments. While many LCAs focus on GWP, categories like human toxicity, eutrophication, particulate formation, and water use remain underreported. Studies by Schmidt Rivera et al. [176] and Kisiga et al. [175] advocate for broader environmental indicators and more rigorous use of tools such as ReCiPe and Eco-Indicator 99, which can improve decision-making across valorization pathways.

In parallel, the success of SCG valorization is critically dependent on logistical efficiency and the robustness of collection infrastructure. Even technically promising processes may underperform due to irregular feedstock availability, particularly in urban areas lacking centralized collection systems [32]. Moreover, environmental benefits can be offset by transport-related emissions when supply distances exceed specific thresholds—such as 150 km in the case of biodiesel production [177]. Deploying mobile or decentralized pre-treatment units may enhance feedstock stability and reduce emissions, especially in coffee-dense urban environments.

Policy and regulatory frameworks are critical to enabling SCG valorization at scale. The absence of unified waste valorization standards, economic incentives, and certification protocols remains a major obstacle to commercialization [186]. Integrating SCGs into value-added products such as construction materials could benefit significantly from formal certification systems which would enhance market trust and uptake [184]. In addition, a recurring insight across the literature is the strategic advantage of cascade or integrated biorefinery models. These approaches combine multiple valorization steps—such as oil extraction, biogas recovery, and biochar production—within a unified system, thereby maximizing both material utilization and economic viability [185,186]. Scaling such systems will require comprehensive pilot testing, underpinned by TEA, life cycle sustainability assessment, and market feasibility studies.

7. Conclusions

The growing global production of SCGs presents both a challenge and an opportunity: while its disposal contributes to environmental burdens, its nutrient- and carbon-rich composition makes it an attractive feedstock for energy, chemical, and material applications. This review has synthesized advances across various valorization pathways. Comparative studies indicate that anaerobic digestion consistently achieve lower environmental impacts, while pyrolysis and hydrothermal processes offer promising multiproduct outputs but face energy-intensive bottlenecks. Biodiesel production remains technically feasible but economically less favorable unless strongly coupled with co-products. Activated carbon from SCGs show strong techno-economic potential, though large-scale demonstrations are scarce. Collectively, these findings highlight that integrated cascade biorefinery concepts—

where multiple products are extracted within a single system—represent the most viable path forward. Despite significant academic progress, challenges persist. Low technology readiness level, fragmented supply chains, high energy inputs, and limited standardized policies remain barriers to commercialization. Moreover, sustainability assessments often focus narrowly on GHG emissions, overlooking broader categories such as water use, eutrophication, and human toxicity. Broadened LCAs, combined with TEA, across diverse valorization pathways and their corresponding end-product applications will be crucial for guiding practical implementation and investment decisions. Future research should emphasize scaling pilot plants, optimizing energy integration, and strengthening SCG collection logistics. Policy instruments—including waste valorization incentives, certification systems, and carbon credit integration—are also critical for market uptake. Importantly, SCG valorization aligns with the UN Sustainable Development Goals, particularly SDG 7 (affordable clean energy), SDG 12 (responsible consumption and production), and SDG 13 (climate action). Harnessing this abundant waste through integrated, sustainable, and scalable pathways can transform SCGs from a disposal challenge into a cornerstone of the circular bioeconomy.

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