Review Article

Valorization of Coffee By-Products through Biorefinery Approaches for a Sustainable Bioeconomy

Mohamed Adam Adam Abakar
Department of Chemistry, Faculty of Sciences, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia

Osman Ahmed
Department of Astronomy and Space Science, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia

Elizabeth Jayex Panakkal, Nida Arshad, Nichaphat Kitiborwornkul, Neelu Raina and Malinee Sriariyanun*
Biorefinery and Process Automation Engineering Center, Department of Chemical and Process Engineering, The Sirindhorn International Thai-German Graduate School of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

Roungdao Klinjapo
Theophane Venard School of Food Biotechnology and Innovation, Assumption University of Thailand, Bangkok, Thailand

V. Ponnumsami
Biomass Conversion and Bioproducts Laboratory, Center for Bioenergy, School of Chemical & Biotechnology, SASTRA Deemed University, Thirumalaisamudram, Tamil Nadu, India

Muhammad Ayub Khan
Institut für Textiltechnik of RWTH Aachen University, Aachen, Germany

* Corresponding author. E-mail: macintous@gmail.com
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Abstract
This review explores the concept of coffee biorefineries as a feasible approach for producing value-added products while promoting sustainability and the circular bioeconomy. Coffee, one of the most widely consumed commodities worldwide, generates substantial quantities of by-products during processing—such as coffee pulp, husk, and spent grounds—which are often discarded as waste. This review highlights several biorefinery strategies that utilize these by-products to produce high-value substances, including biofuels, antioxidants, and functional compounds for food, pharmaceutical, and cosmetic applications. The study analyzes statistical data on research related to coffee biorefineries conducted over the past 15 years, along with global coffee production data from the top ten exporting countries. The advantages of adopting coffee biorefinery technologies are discussed from both economic and environmental perspectives, emphasizing waste reduction, carbon emission mitigation, and the creation of new revenue streams. The conceptual framework of biorefineries highlights the potential of coffee as a feedstock for generating value-added outputs, and includes a statistical analysis to map recent research trends in coffee-based biorefinery systems. Furthermore, this review underscores the diverse applications of coffee and the valorization of its processing by-products while examining various pretreatment methods and their effects on enhancing the yield of value-added products.

Keywords: Biomass, Biorefinery, Coffee, Functional compounds, Sustainability, Value-added Products

1 Introduction

A biorefinery is a process that converts any kind of biological material, such as agricultural waste, into fine chemicals, energy, and alternative fuels. To develop biofuels capable of competing with conventional petroleum-based gasoline, first-generation biorefineries focused on utilizing sugar-rich crops and oil-bearing feedstocks as primary renewable resources [1]. New generations of biorefineries can incorporate novel biowaste materials from various sources. Integrated and cascading biorefineries are cornerstones of the Circular Bioeconomy (CBE), enabling closed-loop systems that maximize resource efficiency, minimize waste, and sustainably convert biomass into diverse value streams [2]. Spent coffee grounds (SCGs), the primary byproduct of coffee processing, are currently discarded as low-value waste, and their potential for recycling, despite offering a promising renewable resource, remains underexplored. SCG can be utilized as a feedstock in a biorefinery concept to fabricate a variety of bio-based goods and bioenergy through a closed-loop system [3]. SCG pellets have gained attention as a renewable alternative to conventional solid fuels, notably due to their competitive lower calorific value of 21.08 MJ/kg [4].

The world population is anticipated to expand from 8.1 billion in 2024 to 10 billion by 2055, potentially leading to the depletion of natural resources. On the other hand, human annual use of biomass materials is approximately 72 gigatons, and it is expected to reach 100 gigatons by 2030 [5]. This dual pressure threatens to outpace the planetary regeneration capacities, demanding innovation in sustainable technologies. Within the circular bioeconomy framework, biorefineries integrate chemical and bioprocessing platforms to transform biomass into diverse products ranging from high-value saccharides and antioxidants to bioethanol, thereby enabling to cascade resource utilization and minimizing waste generation [6], [7]. In recent years, the business has been impacted by swinging oil prices, high levels of pollution associated with greenhouse gas (GHG) emissions, the development of new technologies and competition from emerging markets are in need [8], [9].

The loss of food as global waste is predicted to be about 0.99 billion tons in 2022, accounting for waste created and lost in many sectors of the economy, including agricultural production, postharvest, processing, distribution, and consumption. According to United Nations (UN) 2022 data, 14% of food produced is lost between harvest and retail, underscoring the urgent need for circular bioeconomy strategies (such as biorefineries) to valorize unavoidable waste streams into biofuels, biochemicals, or nutrient-rich materials, thus reducing systemic losses and enhancing resource efficiency [10].

Coffee is one of the most consumed non-alcoholic beverages globally. Coffea is a genus of plants in the Rubiaceae family that has about 120 species globally [11]. It is primarily cultivated as *Coffea arabica*, which accounts for about 75% of total production, and *Coffea canephora* (Robusta), which makes up the remaining 25%, with post-harvest processing carried out using either dry or wet methods. This generates by-products (such as pulp and husks) that hold untapped potential for CBE applications, such as biorefinery conversion into biofuels, bioplastics, or functional food additives, thereby reducing agro-industrial waste. Arabica coffee is generally thought to be superior to robusta coffee due to its delicate scent, high acidity, and winey flavor [12]. Coffee, the world's second most traded commodity after oil, has an annual production exceeding seven million tons, with global demand growing steadily at 3.5 % per year since 2008, highlighting both its economic significance and the urgent need to sustainably manage its by-products (husk, pulp, and spent grounds) through biorefinery approaches, supporting a zero-waste circular bioeconomy [13]. It is produced in around 60 tropical and subtropical nations, and its infusion, made from roasted and ground beans, makes it a significant food extract on a global scale [14].

Biorefinery solutions for coffee waste are gaining popularity to reduce environmental effects while increasing commercial value [15]. In a coffee-based biorefinery concept, coffee waste might be valorized to derivatize a variety of value-added compounds, such as polyhydroxyalkanoates (PHAs) and biofuels [16]. Coffee is one of the most widely used and valued drinks in the world and is significant to the global economy, which, nowadays, is linked to sustainability, health, and enjoyment. Coffee has been shown to possess anti-obesity, antioxidants, and anti-inflammatory properties in addition to its well-liked flavor, which helps prevent metabolic syndrome and related illnesses [17], [18]. Coffee consumption has also been reported to selectively enhance the growth of probiotic strains, thereby exerting a prebiotic effect [19]. Aside from probiotics, there are plenty of chances for coffees supplemented with prebiotics, synbiotics, and postbiotics, which could go beyond the probiotics by using microbial metabolites, dual combos, and fibers to meet trendy patterns of wellness [20], [21]. Additionally, research indicates that buyers are prepared to pay a premium for coffee made using sustainable practices. It is estimated that this large industry produces a significant quantity of waste, with SCG being one of the primary byproducts. The amount of SCGs available alone from coffee manufacturers in the European Union (EU) amounts to around 330,000 tons annually [16], one-half ton for each citizen [22]. In many countries that deal with daily difficulties and high waste disposal costs, recycling such waste into fuels and value-added by-products through biorefineries is a possible solution [23]. SCGs can be efficiently upcycled into high-value oligosaccharides and mannooligosaccharides (prebiotic compounds) through a two-stage enzymatic hydrolysis process, with subsequent fermentation yielding bioethanol at 3.1% efficiency, showcasing SCGs as a promising biorefinery feedstock for cascading production of functional food ingredients [24]. In recent years, there has been an upsurge in the hunt for bio-based raw materials as a substitute for materials based on fossil fuels. Due to this tendency, biomass derived from coffee has the potential to be used as a raw material to create energy vectors and value-added goods like bulk and fine chemicals.

To better review the distribution of research interest in coffee biorefinery for the manufacture of value-added products, the time frame of the last 15 years (2010 - 2024) was used as a search filter (Figure 1). Data were sourced from databases such as Web of Science, Scopus, PubMed, and Google Scholar using keywords like 'Biorefinery', 'Coffee', and 'Value-added Products' in both singular and plural forms. A total of 15,652 publications have been identified in the aforementioned field of research. In the year 2024, it peaked to reach 3695 published papers, which means research interest in this field rose to ~ 13 times more than it was just 9 years earlier (in 2016), and about 3.5 times higher than the average in Figure 1. Reports from various sources indicate that between 2010 and 2024, the majority of research on coffee biorefineries has been conducted by academic institutions in countries such as Denmark, the United Arab Emirates, South Korea, Norway, Oman, Vietnam, Saudi Arabia, and Pakistan. To turn coffee waste into useful goods and advance sustainability, these nations have shown a strong commitment to furthering research on coffee biorefineries. The main countries for coffee production are typically known as the "coffee belt," located between the Tropics of Cancer and Capricorn. The top producers include Brazil, Vietnam, Colombia, Indonesia, Ethiopia, Uganda, Mexico, along with other producers and exporters [25], [26] (Figures 2). Brazil has been the dominant nation in coffee harvesting and exporting since the early 1800s due to its vast land, high yield, ideal climate, sophisticated mechanization, and excellent infrastructure.

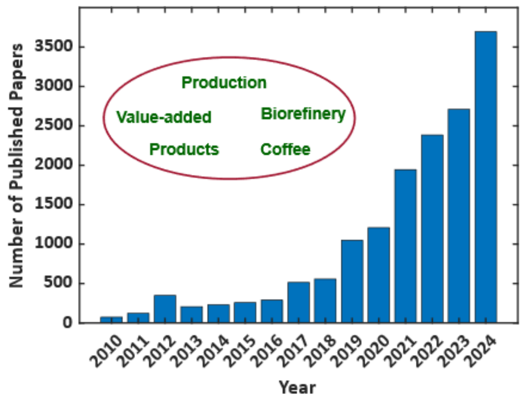
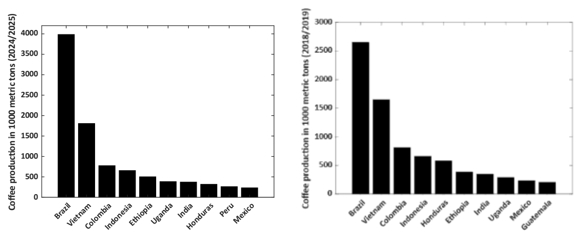


Figure 1: Published research on coffee biorefinery for the production of value-added products during 2010 and 2024.



Figures 2: Distribution of global coffee production by country for the seasons of 2018/2019 (right) and 2024/25 (left).

The goal behind this study is to showcase the biorefinery concept of coffee as a sustainable approach to yield value-added products by highlighting the importance of both coffee and coffee waste as a renewable resource for the production of a huge and diversified array of added-value products. The review extends to exploring a variety of coffee processing methods, coffee plant composition, and addressing global environmental and socioeconomic issues. Moreover, the review also focuses on the 3R concept of reduce, reuse, and recycle in coffee waste management, and challenges with the scalability of coffee biorefineries. Consequently, the present work emphasizes biorefinery-based approaches of coffee waste to generate value-added products with a degree of sustainability in the fabrication process.

2 Coffee Biomass: Composition, Characteristics, and Processing

The coffee fruit, berry, or cherry is a 10 mm bean made up of exocarp (pulp), mesocarp (mucilage), silver skin, and hulls or endocarp (parchment), which form a coating around the two seeds (endosperm). Table 1 depicts various components and their percentage weights in coffee cherry. After harvesting and processing, two major byproducts are created: coffee husk and coffee pulp, which depend on the post-harvest procedure used to turn the cherry into green beans [27]. Even though the content of a coffee plant can vary based on factors such as *Coffea arabica* or *Coffea canephora*, growth conditions, and processing methods [28]. It is expected that each kilogram of coffee produced generates the same amount of residue. In Brazil alone, 3 billion tons of coffee husks were generated in 2020.

Table 1: Components of the coffee plant.

Component	Amount (%wt)	Refs
Beans (Seeds)	2 – 4	[29]
Husks	20 – 30	[30], [31]
Pulp	40 – 50	[10], [32]
Silver skin	1 – 2	[30], [33]
Parchment	1 – 1.5	[23], [34]
Mucilage	15 – 22	[35]
Endosperm	-	[17]
Moisture	50 – 60	[17]
Roots	10 – 15	[36]
Whole fruit	96 – 98	[28]

Coffee processing produces a liquid fraction as a byproduct of coffee pulp, which could be employed as a substrate for anaerobic digestion to produce biogas, and the solid fraction could be turned into ethanol or other bioproducts such as xylooligosaccharides (XOS) [37]. SCG can be recycled in a biorefinery to manufacture biofuels and value-added products, thereby avoiding environmental issues, harmful emissions, and disposal expenses [38]. The variety of lipids found in SCGs makes them a promising resource for several uses, such as the extraction of valuable bioactive compounds and the manufacture of biofuel. The main lipids present in SCG are triglycerides, which are made up of three chains of fatty acids that have been esterified to a glycerol backbone [39]. The source and processing of beans have a significant impact on the elemental compositions of SCGs [40]. Table 2 below highlights some of the reported bioactive compounds and nutrients present in coffee pulp waste.

Table 2: Compositions of coffee pulp waste.

Component	Composition (%wt)	Refs
Cellulose	25.88 – 64.00	[36]
Chlorogenic acids	2.30 – 3.00	[41]
Free amino acids	0.15 – 3.33	[42]
Lignin	9.40 - 20.07	[43], [44]
Lipids	3.00	[45]
Amino acids	~ 21.24	[42]
Caffeine	0.81	[44]
Hemicellulose	1.24 – 3.60	[43], [44]
Total sugars	9.18	[43]

Coffee has over 1,000 components that contribute to its flavor, aroma, color, antioxidant properties, cholesterol level, and physiological effects [46], [47]. There are now several processing techniques that are utilized to refine coffees. Some of the techniques used to process coffee have been depicted in Table 3. Among the various coffee processing techniques, supercritical CO_2 extraction and ultrasound-assisted extraction are well-known green extraction techniques that can extract antioxidants, oils, caffeine, and phenolics from coffee [48], [49].

Table 3: Different types of coffee processing techniques and their effects on the coffee industry.

Processing Method	Description	Effect	Refs
Dry processing	Placing coffee beans in the sun or an air dryer	Enhances sweetness and body	[50]
Wet processing	Adding solvent	Produces cleaner, high-quality coffee	[51]
Honey processing	Coffee beans are spread out on beds	Balances between washed and natural methods	[52]
Fermentation	Fruit is removed, and mucilage is subject to fermentation in water	Enhances complexity and aroma	[53]
Mechanical demucilation	Use of mechanical dryers	Reduces water usage	[54]
Steam explosion	Generate solid and liquid fractions	By product valorization	[55]
Enzymatic Hydrolysis	Use of cellulases and hemicellulases	Modifies coffee composition and extractability	[56]

Table 3: (Continued).

Processing Method	Description	Effect	Refs
Decaffeination	Remove caffeine from coffee beans using a percolation battery	Reduces caffeine	[57]
Thermal + Acid	Heating at 90 °C and 10 % v/v acetic acid treatment	Alters chemical composition	[58]
Aging and monsooning	Beans are exposed to the monsoon in India	Reduces acidity, duplicate color, and taste	[59]
Other techniques	Various processes (chemical, physical, etc.)	Effects properties such as aroma, taste, and color	[59]
Supercritical CO_2	CO_2 acts as a solvent, selective and efficient	Preserves aroma and bio-actives	[49]
Ultrasound-assisted	Ultrasound waves are used	Faster, higher yield	[48], [60]
Enzyme-assisted	Enzymes are used	Higher yields and time saving	[48]

Fermentation is a biological process in which bacteria or fungi break down complex components into simpler compounds [61]. There are also other processing techniques for the coffee pulp industry. For instance, a biological route was used to process coffee pulp employing Basidiomycetes, and microbes, that can generate solid residue with the same enzymatic digestibility [62]. Wet technique is the most prominent technique for coffee pretreatment, applied to about half of the coffee harvested globally [62]. However, in the biorefinery, pretreatment, hydrolysis, fermentation, purification, and product recovery are the primary conversion processes employed to valorize coffee waste [63]. These steps require optimization for better bioconversion of coffee waste (Figure 3). Kovalcik *et al*. proposed that removing hazardous co-contaminants from SCG hydrolysates through detoxification procedures could boost waste utilization [64].

The coffee chain produces over a couple of billion tons of solid residues annually, which leads to several disposal issues, environmental concerns, and particular problems with each form of residue. Despite the possibility of obtaining more bioactive compounds, landfilling is typically the final destination for these wastes [17], [47]. The residues can be mixed and fed into pyrocracking and hydroformylation operations, which convert ammonia, protein, isoprene, lignin, and oils into renewable gas. Any residual waste can be thermo-converted into biochar, which can then be used to improve the soil humus [65]. Pyrolysis is a frequently used process for converting biomass into value-added products. This treatment, carried out at high temperatures in the absence of oxygen, decomposes the biomass (hemicellulose, cellulose, and lignin) into liquid, gas, and solid components [66]. The integration of several technologies for treating coffee waste has the potential to improve economic and environmental sustainability.

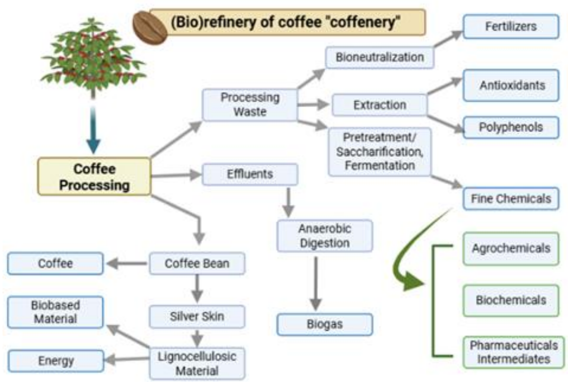


Figure 3: A schematic diagram depicting a biorefinery for coffee processing to receive added-value products (e.g. electricity, bioethanol, energy, fine chemicals, etc.).

However, the utilization of coffee waste is hindered by the recalcitrant lignocellulosic structure formed from the complex and intact arrangements of cellulose, hemicellulose, and lignin [67], [68]. To reduce the recalcitrance and for the ease of bioconversion, the coffee waste has to be pretreated using physical, chemical, or biological processes to disrupt the lignin-carbohydrate complex in the biomass [69]. Although pretreatment is more expensive in the biomass transformation process, it can boost output, which makes it simpler to transform the biomass into products with added value in later steps. The fundamental purpose of pretreatment is to pre-extract hemicellulose, dissolve the lignin linkage, and obtain full access to cellulose [70]. The pretreated biomass will be further saccharified to release sugar monomers from the carbohydrate polymers [69]. These sugar monomers are fermentatively converted to the desired end products, and the final product is recovered as part of the biochemical route of biomass biorefinery. The economics of producing value-added products using a biorefinery technique are highly influenced by location, feedstock, pretreatment technology, intended end-products, and catalysts used [71], [72]. Yet, the biorefinery technique is gaining robustness because biomass exploitation is a possible solution for meeting increasing energy and product demands while also promoting the transition from a fossil-based to a renewable-based economy [73], [74].

3 Coffee By-Products as Raw Materials for Sustainable Biorefineries

A growing amount of research has been published recently on the value-adding of coffee waste through biorefineries, which extract food ingredients, oil, bioenergy, and plant nutrients and use them to clean up environmental pollution. However, there is currently little use of SCG in a cascade of operations. This could impede the advancement of procedures that guarantee both economic and environmental sustainability and enable the realization of the circular bioeconomy [74].

Coffee by-products are unavoidably utilized in multiple highly beneficial industries with various applications spanning lots of areas of businesses from beverages and agrochemicals to power and energy. Utilizing biorefineries to process biowastes is a crucial stage of enhancing the economic performance of crop-centered derivatization and adding value to process byproducts [75]. The potential of coffee husks is demonstrated as a feedstock for ethanol production. Up to 8.49 g/100 g ethanol was obtained by fermenting whole coffee husks with *Saccharomyces cerevisiae* under optimal conditions of 30 °C and a yeast concentration of 3 g/L [76]. Biobased polymers, specifically PHAs from SCG extract, are increasingly being used because they are biodegradable and have thermoplastic and elastomeric qualities that can be controlled [77]. The improved synthesis of carotenoids was previously studied in pulp and husk extract. Carotenoids produced have antioxidants and antibacterial properties against pathogenic bacteria like *Salmonella*, *Escherichia coli, Staphylococcus aureus*, and *Listeria monocytogenes*, as well as toxic fungi, such as *Aspergillus flavus, A. parasiticus, A. carbonarius, and A. ochraceus* [78]. *Cascara*—the dried husk of coffee cherries—is the first by-product generated during coffee processing and it is recognized for its medicinal properties [79]. *Cascara* serves as a natural tonic and laxative, rich in polyphenols, caffeine, and dietary fiber [80].

Pretreatments, followed by recovery methods, result in value-added by-products such as natural antioxidants, vitamins, enzymes, cellulose, starch, lipids, proteins, and pigments that are of great importance to the pharmaceutical, cosmetics, fertilizer, and food sectors [81], [82]. The coffee husk and coffee ground have been used to produce *Trichoderma* formulations for biofertilizer application. The coffee husk-based formulation has reported to promote plant growth and disease resistance in plants [83]. Biofuels made from waste biomass also help to avoid the economic, environmental, and social effects associated with the production and use of energy crops like sugarcane, maize, and palm oil [84].

The most prevalent class of phenolic chemicals found in green coffee beans is chlorogenic acids. 5-O-caffeoylquinic acid (5-CQA), to which the term chlorogenic acid (CGA) commonly refers, is its principal representative. This substance may be used as a food preservative, antioxidant, and in a number of medicinal procedures. Additionally, it has already found commercial use in the form of dietary supplements for weight loss that contain extract from green coffee beans, such as Svetol [85], [86]. CGA is the primary phenolic component present in SCG. Strong antioxidants and 1,1-Diphenyl-2-picryl-hydrazyl (DPPH) radical scavenging properties of CGA may shield against free radicals and lower the risk of cancer and degenerative illnesses [87]. Condensed and hydrolysable tannins are other active polyphenols present in SCG, although the most notable ones are phenolics and diterpene alcohol esters. Melanoidins are high molecular weight end products of the Maillard reaction with variable composition, typically incorporating phenolic compounds derived from SCG. Numerous biological activities, such as prebiotics, antioxidants, and antibacterial properties, are linked to melanoidins. Dietary melanoidins circumvent the gastrointestinal tract's digestion processes, acting as substrates for gut bacteria to produce short-chain fatty acids (SCFAs) before influencing the microbiota [88]. SCG waste stream was demonstrated to produce PHAs and carotenoids, which are high-value compounds with a variety of uses in different fields [89]. Figure 4 presents a scheme for the simultaneous production of CGA and bioethanol from SCG.

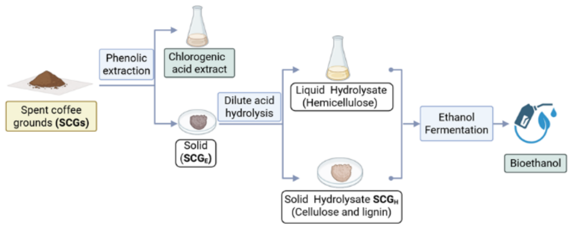


Figure 4: Process scheme shows that chlorogenic acids and bioethanol can be extracted from SCG.

Globally, bioethanol is the most popular biofuel for transportation. One viable substitute biomass source for bioethanol production is coffee residual waste, which makes up approximately 37–42% of the coffee waste [90]. A previous study on bioethanol generation from various coffee waste fractions has investigated using acid or acid and enzymatic hydrolysis followed by fermentation [90]. The fermentation was carried out using two distinct yeasts, baker's yeast and *S.cerevisiae* GSE16-T18, which increase bioethanol output [91], [92]. Coffee Extract Residue (CER) has high cellulose and hemicellulose content and low ash content. Due to the small size of coffee particles, direct hydrolysis and fermentation (DHF) were used to produce ethanol from SCG [11]. In the study on ethanol production from coffee husks, Gouvea *et al*. reported optimal conditions at 30 °C using whole husks. Under these optimized conditions, ethanol production reached 8.49 g per 100 g dry biomass, a yield considered noteworthy when benchmarked against values reported for other agricultural residues, including hydrolyzed wheat stillage, barley straw, and maize stalks [76].

Biochar is a carbon-rich material created through pyrolysis, which involves heating organic biomass in a low-oxygen environment. It is comparable to charcoal but is mostly utilized for agricultural and environmental purposes. The activated carbon obtained by slow pyrolysis of coffee pulp and parchment has been reported to be used in enhancing the properties of solid-state hydrogen storage, specifically, magnesium hydride [93]. Anaerobic digestion, hydrogenation, esterification, transesterification, fermentation, or pyrolytic reactions are some of the other methods used to valorize coffee grounds and SCG to produce various biofuels, including biochar, bioethanol, biodiesel, biogas, renewable diesel, and hydrocarbon fuels [94].

Xylose (2–7 units) makes up the majority of XOS, which are indigestible oligosaccharides with strong prebiotic potential [95]. XOS can pass through the upper gastrointestinal tract undigested because of their physicochemical properties that make them extremely resistant to gastric acids and gastrointestinal enzymes. Once they reach the lower intestine, probiotic bacteria, primarily from the *Bifidobacterium* and *Lactobacillus* genera, metabolize them [96]. XOS is typically produced from xylan-rich lignocellulosic materials such as coffee husks using chemical, enzymatic, or a combination of these methods. Chemical methods for producing XOS include steam, diluted mineral acids, and alkaline solutions [97].

4 Challenges with Economic Aspects, Global Warming, and Coffee Biorefinery Scalability

The economic viability of coffee biorefineries is greatly impacted by various cost factors, including the availability of feedstock, processing technologies, and operational scale. Raw material expenses play a crucial role in determining the economic feasibility of these biorefineries, often influenced by the availability of coffee by-products. By-products such as SCG, coffee husks, and coffee pulps are generally plentiful and easily accessible, making them a cost-efficient feedstock option. SCGs produced in large volumes from coffee consumption are rich in bioactive compounds and oils, which can be transformed into valuable products like biofuels, biochemicals, and nutraceuticals. However, the costs associated with collecting and transporting SCGs can pose a challenge, particularly for smaller operations. Research indicates that implementing centralized collection systems and integrating with existing coffee processing facilities may help reduce these costs [98].

The choice of processing technology plays a crucial role in shaping the total cost of biorefinery operations. Pretreatment often stands out as one of the highest operational costs in the processing of lignocellulosic and coffee-based biorefineries, typically representing 20–40 % of total processing expenses [99]. This is due to its high energy intensity and direct influence on product yields, equipment requirements, and downstream efficiency [99]. Thus, selecting appropriate pretreatment methods is vital for achieving substantial cost savings and ensuring the economic feasibility of coffee biorefineries. The integration of multiple processes within a biorefinery can enhance efficiency and reduce costs. For instance, producing biodiesel from SCG oil can be integrated with the extraction of bioactive compounds, creating a circular economy loop [100]. The adoption of digital technologies, including process simulation and automation, is transforming the coffee biorefinery industry. These tools allow for real-time monitoring and optimization of operations, increasing efficiency and lowering operational costs. The operational scale of a biorefinery is another vital aspect in cost analysis. Larger biorefineries take advantage of economies of scale, which help lower per-unit production costs. Nevertheless, smaller operations can thrive economically by concentrating on high-value products like nutraceuticals and specialty chemicals [101].

Despite having no economic use, the coffee pulp business is thought to be the main source of environmental pollution in the rivers and lakes that are close to the coffee processing facilities. Developing field-adaptable methods to recover valuable byproducts from coffee pulp at a commercial scale could convert this environmental challenge into a viable economic opportunity [102]. Bigdeloo et al. 2021 examined the circular economy concept and its application in reducing waste generation, as well as waste reduction measures. The concept indicates minimizing waste generation at the source to reduce recycling costs, rather than relying on extensive recycling efforts after large volumes of waste have already been produced [103]. A circular economy involves reducing, reusing, and recycling resources (3R concept) to form a closed-loop system that reduces waste and resource consumption. In Indonesia, waste banks can incorporate a variety of waste streams, including coffee waste and plastic, into a closed-loop system [104]. Composting of coffee biomass residues also serves as an effective strategy to enhance the physico-chemical properties of soil while simultaneously mitigating environmental concerns.

Coffee extract was reported to be composed of more than 1500 chemical components, 850 of which are volatile and 700 of which are soluble [105]. Due to this big numbers of possible products, the development of an environmentally sustainable biobased economy will rely on making the right decisions on several levels. This should involve selecting suitable biomass, removing pretreatment process bottlenecks, lowering costs, using genetic and metabolic engineering to boost the yields of the biocatalysts, and concurrently addressing social, economic, and environmental sustainability. Similar to crude oil refineries, a variety of environmentally friendly and sustainable methods can be used to turn coffee waste into traded chemicals and energy. Indeed, the sustainability of coffee production and consumption cannot be considered in isolation from their socioeconomic implications. Coffee husk processing and disposal pose a significant resource and environmental challenge due to their high moisture content and low bulk density [3]. The tremendous diversity within the coffee components complicates the handling, processing, and use of coffee husk. Its fibrous structure and low compactability can impede efficient extraction and inclusion into items with added value. Polyethylene terephthalate (PET) plastic and aluminum are two of the important materials used in packaging coffee. However, the package is not being utilized to its maximum capacity. Rather, when it is discarded, it creates a societal and environmental cost and burden to handle it. A significant amount of biofuel synthesis has occurred on a laboratory scale. Various kinetic models have been created and tested in response to the growing demand for industrial-scale production of alcoholic fermentation in biorefineries. Kinetic models are examined in terms of product generation, microbial growth, and substrate consumption [106]. Though commercial biofuel production has proven to be extremely difficult.

Together with huge volumes of wastewater and cultivation residues, the global coffee agro-industries extract more than ten million tons of solid residues annually [107]. Wastewater generated from coffee processing is hitherto a cause of contamination to our environment. However, it is quite likely that in the future, research on industrial water treatment will solve this dilemma permanently or at least lessen its severity. Galanakis (2017) claims that when coffee washing water is discharged into receptive water bodies, it rapidly creates anoxic zones due to its anaerobic stabilization, giving methane, phenols, and hydrogen sulfide as byproducts of the breakdown of organic material, all of which emit unpleasant odors. Furthermore, the growth of plants like cattail, water hyacinth, and algae, due to the nutritional enrichment of these waters, leads to eutrophication and can be detrimental to the aquatic ecosystem [108].

In a study conducted by Babu *et al.*, Exhausted Coffee Grounds (ECGs) as a bio-adsorbent were used to decontaminate water polluted by lead (II) & fluoride with up to 90 % removal efficiency [109]. Others used an extracted bacterium, *Klebsiella pneumoniae* Kpn555, isolated from coffee waste pulp, showing high resistance to lead, with a minimum inhibitory concentration of 900 mg/L [110]. Also, activated SCG can absorb heavy metal ions like Cd (II), Mn(II), Pb (II), and hence contribute to the detoxification of the environment [111]. Quyen *et al.* (2021) mentioned that the use of coffee husks as raw materials for adsorbents to remove both organic and inorganic contaminants has been the subject of numerous investigations. Comprehensive studies on coffee waste–derived adsorbents, particularly those assessing their regeneration, reusability, and performance with real industrial effluents, remain limited or largely absent in the literature.

5 Conclusions

This review highlights the potential of coffee biorefineries to promote sustainability and transform the global coffee industry. It underscores the feasibility of valorizing coffee waste through biorefinery approaches, offering a long-term and cost-effective means to produce value-added products such as biofuels, biopolymers, pharmaceuticals, and functional foods. To fully harness coffee waste as a renewable resource, advancements in extraction, processing, and industrial integration are essential. Future studies should address scalability, life cycle impacts, and regulatory frameworks to enable commercialization. Although producing biodiesel solely from spent coffee grounds is not yet economically feasible, sustainable processing can enhance the value of coffee by-products. Aligned with the circular economy and its 3Rs—reduce, reuse, and recycle—coffee biorefineries can minimize waste, conserve resources, and drive innovation in bio-based industries worldwide.

Author Contributions

M.A.A.A.: Conceptualization, Investigation, Writing- Original draft; O.A.: Writing- Original draft; E.J.P.: Data curation, Writing - Review & Editing; N.A.: Visualization, N.K.: Data Curation; V.P.: Conceptualization, Writing - Review & Editing; N.R.: Writing - Review & Editing; M.A.K.: Writing - Review & Editing; M.S.: Conceptualization, Investigation, Writing - Review & Editing, Funding acquisition

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Declaration of competing interest

The authors declare that there are no known financial or personal conflicts of interest that could have influenced the work presented in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript and Dimension AI tool to extract data from research database in Figure 1.

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