A review on enhanced biofuel production from coffee by-products using different enhancement techniques

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Abstract
Coffee by-products are a renewable, plentiful, cost-effective, and mostly untapped resource that could be used as a biofuel feedstock. However, the energy efficiency and biofuel yields are mostly determined by the biofuel production technologies. Pretreatment procedure, hydrolysis methods, fermentation methods, oil to biodiesel conversion techniques, binders employed, applying pressure and temperature are the main factors to improve the biofuel yields from coffee by-products. This paper examines state-of-the-art methods for increasing biogas, bio-ethanol, biodiesel, briquettes, and pellets outputs from coffee by-products. Pretreatment and co-digestion of coffee by-products with other low carbon to nitrogen ratio animal manure boost the biogas yield of coffee by-products, which is also discussed. A yield of bio-ethanol from coffee by-products was also improved using advanced pretreatment procedures, production processes, and the use of genetically modified yeast strains that ferment the majority of sugar monomers. Additionally, oil extraction methods from spent coffee grounds were reviewed, as well as optimizing biodiesel yield from spent coffee grounds oil. The process of making briquettes and pellets, as well as the types of binders utilized, are discussed. The main novelty of this review is on improving biofuel yields such as biogas, bio-ethanol, biodiesel, briquettes, and pellets from the entire dry cherry coffee beans processing residues, wet coffee (coffee pulp or peeled) beans processing residues, and optimizing oil and biodiesel yield from spent coffee grounds.

Keywords Biofuel · Biomass · Coffee husk · Lignocellulosic biomass

Introduction
Due to the depletion of fossil fuel reserves and the need to reduce global warming, biofuel production from renewable resources has gotten a lot of attention in recent years [1, 2]. Agricultural leftovers are one of the most abundant, affordable, and renewable biofuel sources [3, 4]. Agricultural industries generate billions of metric tons of biomass each year, which comprises liquid, solid, and gaseous waste, [5, 6]. Second-generation biofuels can be made from a variety of crop and plant residues, fruit and vegetable waste, grass, forest residues, livestock manure, and other agricultural wastes [7–9]. When not adequately managed, many of these leftovers can pollute the environment [10, 11]. Biofuel production from residues with no commercial value can minimize feedstock costs, land constraints, and crop competitiveness for fuel [7, 9, 12].

Coffee is one of the most important agricultural commodities in the world, employing nearly 125 million people [13, 14]. The global coffee production potential varies year to year due to global climate change and land use change [15, 16]. The amount of coffee by-products (coffee husk, coffee pulp, mucilage, parchment, and spent coffee grounds) produced each year is determined by the year’s coffee production potential [17, 18]. Coffee processing produces 42–50 wt% of the cherry as by-products [19, 20]. The dry and wet methods can be used to process coffee beans [19, 21]. The entire cherry is dried in the dry process, providing dry coffee beans [21]. The wet method produces coffee beans that have been pulped, demucilated, and peeled [19]. Coffee processing produces 10–15 million tons of coffee by-products each year around the world [22, 23].

Coffee by-products from coffee processing used for various purposes because they are rich in carbohydrates and other nutrients [24]. Coffee pulp is used as fertilizer and fuel for direct combustion in some parts of the world, and...
spent coffee grounds (SCGs) before or after oil extraction are an appropriate resource for garden fertilizer, feedstock for bio-ethanol, biogas, fuel pellets, and bio-oil production [25–27]. SCGs have a high calorific value of about 24.9 MJ/kg (dry weight), making them an ideal substrate for use in industrial boilers [28]. In addition, some coffee husk has been mixed with fodder for animal feed [29], but direct use of coffee by-products for animal feed has proved impossible due to anti-physiological and anti-nutritional ingredients (e.g., tannins and caffeine) [29–31]. A significant portion of coffee production waste is now underutilized due to a lack of comprehensive uses, resulting in considerable environmental deterioration, health difficulties, and toxic phenolic chemical release into wetlands [32–36].

The valorization of coffee by-products and the production of biofuels from it is one of the most important ways for minimizing waste, human health concerns, and environmental pollution from coffee by-products [1, 30, 37, 38]. Delignification of coffee by-products is essential prior to biofuel production, particularly for bio-ethanol and biogas production, because the biofuel yield is minimal without it [39–41]. There are different pretreatment methods to produce biofuel from coffee by-products, such as thermal, physical, chemical, and biological pretreatments [4, 39, 42–44]. Researchers have been looking for advanced technologies in recent years, including biological delignification (the ability of some organisms to naturally degrade lignin), a combined pretreatment method to improve biofuel yield, fermentation of pentose sugar monomer, and process optimization for biofuel production from lignocellulosic biomass. Pretreatment technologies for delignification of lignocellulosic biomass currently available are neither cost-effective nor environmentally friendly and each has its own set of benefits and drawbacks [2, 40, 45–48]. The main novelty of this review is on improving biofuel yields such as biogas, bio-ethanol, biodiesel, briquettes, and pellets from the entire dry cherry coffee beans, pulp beans processing residues, and spent coffee grounds.

Lignocellulosic composition of the coffee by-products

Crop varietals, growing location, processing style, cultivation compound, and soil type significantly affect the lignocellulosic composition of coffee by-products [14, 49]. According to Chala et al. [17], there are certain differences in the lignocellulosic composition of coffee by-products. Hemicellulose contents in parchment, husk, pulp, and mucilage were as follows: 20, 15, 8 and 1 wt%, respectively, and cellulose contents in pulp, husk, and mucilage were roughly the same (32 wt%), while the parchment had a greater hemicellulose content (45 wt%) [17]. On the other hand, the lignin content in the parchment was about two times higher than for husk and pulp [17]. Furthermore, according to Oliveria et al. [49], the approximate composition of the coffee husk is 26.5 wt% cellulose, 25.5 wt% hemicellulose, 33.5 wt% lignin, 0.2wt% ashes and 6.7wt % extractives (Table 1). A few bacteria and fungi can breakdown lignin for biogas and bio-ethanol production because its structure is complicated and inhibits microbial growth [42, 50, 51]. Hemicellulose has a faster hydrolysis rate than cellulose and is easier to digest, but it can also lead to excessive acid buildup [51]. Co-fermentation of cellulose and hemicellulose could boost cellulose conversion while preventing hemicellulose over-acidification, resulting in efficient and steady biogas production [51].

| Coffee by-products | Cellulose (wt%) | Hemicellulose (wt%) | Lignin (wt%) | Extractives (wt%) | Ash content (wt%) | References |
|--------------------|----------------|--------------------|-------------|------------------|------------------|------------|
| Husk               | 26.5           | 25.5               | 33.5        | 6.7              | 0.2              | [49]       |
| Husk               | 25.7           | 14.6               | 17.6        | –                | –                | [52]       |
| Pulp               | 35             | 46                 | 19          | –                | –                | [53, 54]   |
| SCGs               | 13             | 42                 | 25          | –                | –                | [55]       |
| Husk               | –              | 47.29 holocellulose| 27.14       | 20.53            | 3.55             | [56]       |
| Pulp               | 35             | 46                 | 19          | –                | –                | [57]       |

Biogas production from coffee by-products

Thermochemical, biochemical, and chemical conversion processes are among the technologies utilized to generate power from biomass [58, 59]. The anaerobic digestion (AD) process is one of the recommended options for energy valorization of high moisture wastes such as food, organic leftovers, and wastewater sludge among technologies used.
to convert biomass to biofuel [43, 60, 61]. The presence of lignin in lignocellulosic biomass makes it difficult to hydrolyze properly and inhibit facultative bacteria and fungi for fermentation, as well as lowering methane potential [43, 51, 62, 63]. Pretreatment of lignocellulosic biomass is required to make cellulose and hemicellulose accessible to enzymes [43, 62, 64]. Physical, chemical, thermophysical, thermochemical, and biological pretreatment methods have been used to enhance methane yield from lignocellulosic biomass [4, 39, 42–44, 65]. Biomass becomes more porous after pretreatment, but it may produce inhibitory substances for anaerobic microbes [66, 67]. Pretreatment methods have benefits and drawbacks, and their over use may reduce methane yield. Additionally, a single procedure can not be used for all types of biomass [8, 66]. In addition, anaerobic digestion can be affected by various operational parameters such as temperature [68], initial pH [69], inoculum/substrate ratio [70], carbon/nitrogen ratio (C/N) [71], trace elements [72, 73] and feedstock’s particle size [63].

Pretreatment of coffee by-products before biogas production can increase methane yield [39, 41, 44, 50, 65, 74]. Biogas yield from untreated coffee waste was reduced due to the presence of lignin, which limits bacterial growth that fermenters sugar monomers, and insufficient hydrolysis of cellulose and hemicellulose [39, 75]. Pretreatment of coffee husk by steam explosion at 120 °C for 5 to 60 min enhances the removal of cellulose, hemicellulose, and lignin from the hydrolysate from 14.1 to 28.9%, 7.6 to 21.5%, and 16 to 38.9%, respectively [76]. When the temperature of the steam explosion raises over 120 °C, the amount of acetic acid in the substrate raises, resulting in lower methane yield, due to the production of furans and soluble lignin fragments, which are known to be fermentation inhibitors. Using steam explosion at 120 °C for 60 min and a substrate to inoculum ratio of 0.7 g COD L−1 VS−1 for a retention duration of 20 days produced the highest methane yield of 144.96 NmL CH₄ g COD−1 [76]. Ulsido et al. [44] found that the thermophilic condition (55 ± 2 °C) completed the bioreaction process in 20 days, which is half lower than the retention time required by the mesophilic condition (37 °C ±2), and methane yield from coffee husk were 124.63 ± 6.74 ml and 131.67 ± 5.75 ml from a gram of volatile solid at thermophilic and mesophilic condition, respectively. According to Ulsido et al. [44], the quality of methane gas in the thermophilic condition is lower than in the mesophilic condition. Furthermore, Due et al. [74], found that the addition of Fe²⁺, Co²⁺, and Ni²⁺, individually or in combination, during anaerobic digestion of coffee husks, could stimulate biogas production and increase methane content and the contribution of Fe³⁺ was higher than the other elements. Chala et al. [17], found that the average methane yields from the husk, pulp, parchment, and mucilage are 159.4 ± 1.8, 244.7 ± 6.4, 31.1 ± 2 and 294.5 ± 9.6 L/Kg−1 volatile solid respectively, and the anaerobic performance of parchment was very low, and not to be suitable for anaerobic fermentation. In addition, Valente et al. [41], found that heat pretreatment for an hour at 90 °C improved the anaerobic process and reduced retention time from 21 to 15 days, as well as increased biogas production (0.92 L/g vs with methane content of 79.8%). Furthermore, Girotto et al. [28], found that the anaerobic digestion of spent coffee grounds (SCGs) prepared with 8% NaOH for 24 h produced 24% more methane than the untreated substrate. Santos et al. [77], reported a maximum lignin, hemicellulose and cellulose removal from coffee husk using an oxidative ozone pretreatment method with a solid to liquid ratio of 15ml/g, pH 11 and a specific ozone load of 19.14mg oz/g coffee husk. Furthermore, adding powdered activated carbon or using a two-stage anaerobic digestion procedure minimizes hydrolysate toxicity while increasing biogas output [77].

The carbon to nitrogen ratio of lignocellulosic biomass is one of the most important factor for the production of biogas from it [44, 65, 78, 79]. Chandra et al. [80] reported that the recommended carbon to nitrogen ratio (C/N) of lignocellulosic biomass for methane production is 20–30. The carbon to nitrogen ratio of coffee husk is 93.49 [44] and a high amount of carbon to nitrogen ratio decreases methane yield [43, 44, 80]. There is a potentiality to increase biogas yield from high C/N ratio lignocellulosic biomass through co-digestion with low C/N ratio biomass [81]. Co-digestion of lignocellulosic biomass with animal waste can balance a carbon to nitrogen ratio to optimize biogas yield at a commercial level because mono-digestion produces a low biogas yield due to digester instability [81]. In addition, Luz et al. [78] reported that the biogas production from SCGs liquid fraction mixed with fresh cow manure produces high methane concentration and the produced biogas contains more than 50% of CH₄ with peaks of about 60% when SCGs is used. Selvankumar [79], also reported that co-digestion of coffee pulp with an appropriate quantity of cow dung produced a high biogas yield. Using the process condition of water displaced after 96 h at 40 °C, the co-digestion of coffee pulp and cow dung at a 1:3 ratio provided a maximum biogas output of 144 ml/kg [79]. Furthermore, Orfanoudaki et al. [82] found that co-digestion of SCGs with liquid pig dung enhances the carbon to nitrogen ratio, improve the pH value of liquid pig manure, nutritional balance, and microorganism synergistic effects [82]. According to Orfanoudaki et al. [82], the liquid pig manure produced approximately 22 L biogas per day before the addition of SCGs and 240 L biogas per day after the SCGs addition. Biological pre-treatment is increasingly being advocated as an environmentally friendly process with low energy input, low disposal costs, mild operating conditions, and minimal by-product.
formation [1, 42]. Biogas yield of coffee by-products are comparable with commonly used agricultural residues for methane gas production (Table 2).

**Bio-ethanol production from coffee by-products**

The polymer of cellulose and hemicellulose should be broken down first for effective hydrolysis and to raise sugar content in lignocellulosic biomass for the production of bio-ethanol [42, 89, 90]. Many pretreatment approaches have been tried to permit a better yield of bio-ethanol, including chemical pretreatment [91, 92], ozonolysis [93], ammonia [94], hydrothermal treatment such as steam explosion [95], and hot-water process [96] and physical treatment [97]. Among the pretreatment methods dilute sulfuric acid-based chemical pretreatment is the most popular method for bio-ethanol production from lignocellulosic biomass via enzymatic hydrolysis [62, 98, 99]. After undergoing a pretreatment process, the components of a biomass are drastically altered. In lignocelluloses, for example, the cellulose fraction grows from 43 to 85%, whereas hemicellulose and lignin decrease from 34 to 22% and 6 to 9%, respectively [57, 100]. The lignin and hemicelluloses are a physical barrier to cellulose hydrolysis, and it is critical to use a suitable pretreatment to remove the lignin and hemicellulose present in the lignocellulosic biomass in order to achieve successful enzymatic hydrolysis of the cellulose present in the biomass [101]. Using H2SO4 concentration range of 3.6–4.38% v/v and a process duration range of 40–51 min is the best hemicellulose removal from coffee husk [52.03%] [101]. The optimum lignin removal of 49.79% from coffee husk was determined using a 35.75 h pretreatment duration with peroxide alkaline pretreatment at a 9.62:1 v/w solid to liquid ratio [101].

The production of bio-ethanol from lignocellulosic biomass involves the following four major steps: (i) lignocellulosic biomass pretreatment; (ii) pretreated biomass enzymatic saccharification to generate sugar monomers; (iii) fermentation of hydrolyzed sugars to bio-ethanol by fermenting organisms; and (iv) distilling. When saccharification occurs, the process is known as separate hydrolysis and fermentation (SHF) [102]. Separate hydrolysis and fermentation are not economically viable due to the high cost of biomass-hydrolyzing enzymes (cellulases and hemicellulases) and pretreatment methods, and the yeast cells are subjected to various stresses such as high sugar and bio-ethanol concentrations, low nutrient concentrations, and pH changes [102]. In the absence of feedback inhibition, saccharification and fermentation are carried out simultaneously, allowing the hydrolyzed sugars to be continuously converted into bio-ethanol and boosting enzymatic saccharification efficiency [102, 103]. As a result, microbes that can ferment both pentose and hexose sugars are needed in the simultaneous saccharification and fermentation process, and the bio-ethanol output is 26% higher than when the hydrolysis and fermentation processes are carried out separately [103, 104]. With fed-batch fermentation, simultaneous saccharification and fermentation can be carried out at high water-insoluble solid content, resulting in easier mixing and better bio-ethanol output. It also aids in the maintenance of low glucose levels, allowing for efficient co-fermentation of glucose and xylose [105]. The main limitation of simultaneous saccharification and fermentation is operating temperature for biomass hydrolyzing enzymes is 45–50 °C and the optimum temperature for fermenting organisms is 30 °C [102].

The type of yeast strains used for fermentation has a significant impact on bio-ethanol yield because most yeast strains can not ferment xylose to bio-ethanol and are not thermotolerant during bio-ethanol processing [102–104]. During the fermentation of biomass feedstock, bacteria and fungi (yeast microorganisms) are commonly used [106, 107]. *Saccharomyces cerevisiae* (*S. cerevisiae*), often known as baker’s yeast, is frequently used to convert the glucose from coffee processing residues to bio-ethanol [19, 106–108]. It is well known for its excellent catalytic ability to convert hydroxymethyl furfural (HMF) and furfural to non-inhibitory compounds during alcoholic fermentation [109]. The *S. cerevisiae* yeast strain’s main disadvantage is that it cannot ferment one of the most prevalent xylose sugar monomers in hydrolysate and has low fermentation efficiency at high temperatures [102, 110, 111].

Coffee husk contains 62.55 ± 0.56% total sugar, with glucose accounting for 35.33% and xylose for 21.89% of the total sugar monomer [24]. The yield of 13.6 0.5 g bioethanol/L from the coffee husk was determined using Saccharomyces cerevisiae yeast, which is good when compared to bio-ethanol yield from other agricultural residues [106] (Table 3). Rychtera et al. [112], reported bio-ethanol yield of 13.57 ± 0.45 g bio-ethanol/L from coffee husk fermentation with Saccharomyces cerevisiae yeast at 30 °C and 3 g yeast/L substrate. Shenoy et al. [113], found the bio-ethanol

| Residues             | Biogas yield | References |
|----------------------|--------------|------------|
| Wheat straw          | 274 ml CH₄/g vs | [83]       |
| Corn cob             | 270.6 ml CH₄/g vs | [84]       |
| Corn stalk           | 222.6 ml g⁻¹   | [85]       |
| Barely straw         | 0.312 m³/kg vs | [86]       |
| Spent coffee grounds | 0.314 L CH₄/g vs | [87]       |
| Coffee pulp          | 244.7 ± 6.4 L/kg⁻¹ vs | [17]       |
| Sugarcane bagasses   | 0.44 L CH₄/g vs | [88]       |
| Coffee husk          | 159.4 ± 1.8 L/kg⁻¹ vs | [17]       |
yield of 0.46 g/g of sugar by digesting coffee pulp with 2% sulfuric acid and subjecting to high-pressure (15 psi) cooking at 120 °C for 10 min followed by another one and a half hour pressure cooking at 90 °C to solubilize the pulp and filtrate yeast (Saccharomyces cerevisiae) dilution of 5 g/L was added and fermented for 48 h at 30 °C in a shaker incubator at 120 rpm. Shenoy et al. [113] determined that the bio-ethanol yield from coffee pulp was comparatively higher than barley hay and straw, pearl millet hay, sweet sorghum hay, and wheat straw. Kefale et al. [114] reported that the bio-ethanol yield from coffee pulp using distilled water hydrolysis for 4 h by keeping boiling temperature with reflux, and fermentation for 24 h held at 30 °C with baker yeasts. In addition, Dadi et al. [40] reported that the optimum bio-ethanol yield of 47.9 g/L from spent coffee grounds and 36.6 g/L from coffee husk using lignocellulosic yeast GSE16-T18 and fermentation for 12 h. In comparison to the other fractions of coffee waste, the authors [40] reported that the coffee husk hydrolysis using acid and cellulolytic hydrolysis and fermentation with lignocellulosic yeast GSE16-T18 followed by pervaporation temperature up to 50 °C is the best process for producing the highest bio-ethanol yield compared to the other fractions of coffee waste. In addition, Orrego et al. [89] reported that the optimal conditions for coffee mucilage microbial fermentation are at a temperature of 28 °C, pH 4, and filtrate yeast concentration of 3 g/L, which resulted in 0.46 g bio-ethanol/g sugars and bio-ethanol concentration with 90%, which is a theoretically achievable value. Furthermore, Choi and Menezes [115, 116] determined that removing lignin using an alkali pretreatment during the hydrolysis process enhances the production rate and total yield of fermentable sugars. For the processing of bio-ethanol from coffee residues, Choi et al. [115] used popping equipment. During a 10 min reaction time, different reactor pressures were applied, ranging from 0.49 MPa to 1.96 MPa [115] and they have reported that a higher pretreatment pressure is required to degrade the coffee residue waste cell wall and improve hydrolytic enzyme accessibility, as well as subsequent fermentation. Menezes et al. [116] compared sodium hydroxide (NaOH) and calcium hydroxide [Ca(OH)₂] at 121°C for removing lignin from coffee pulp and to improve the accessibility of cellulose to enzymatic hydrolysis to provide fermentable sugars for bio-ethanol production. With a satisfactory conversion of 60% cellulose to glucose conversion was reported using 4% NaOH and a retention time of around 25 min and NaOH alone was more suited than [Ca(OH)₂] to remove lignin from coffee pulp [116]. Harsono et al. [117] reported that acid pretreatment is important to increase fermentable sugars content in the coffee processing waste, and to apply inoculum for the efficient performance of the fermentation and determined 77.29 wt% of bio-ethanol yield. In addition, Woldesenbet et al. [35] revealed that the optimum yield of bio-ethanol (78 wt%) from coffee pulp by hydrolyzing using 0.4 M H₂SO₄ for an hour at 100 °C hydrolysis temperature and following fermentation for 24 h with an initial pH of 4.5. Longer hydrolysis times resulted in higher bio-ethanol concentrations, which began to fall after an hour of hydrolysis [35]. The bio-ethanol concentration raises as the hydrolysis temperature raises and then begins to fall after 100 °C. After 24 h of fermentation, the maximum bio-ethanol concentration of 6.12 g/L was found [35]. The decrease in bio-ethanol content after 24 hours of fermentation could be due to microorganisms consuming the sugar, or the hydrolysate could contain high quantities of metabolic inhibitors [35]. Tehrani et al. [108] determined that adding more yeast enhanced the bio-ethanol output, as did expose the cell walls of biomass with small particle sizes for direct hydrolysis and fermentation. According to Tehrani et al. [108] the best conditions for the synthesis of bio-ethanol from coffee residue extract is fermentation temperature at 30°C and 30 mg baker’s yeast per gram of coffee residue extract and a mixed aqueous phase after heating and solid residue fermentation after pretreatment. Fermentation time affects bio-ethanol concentration: for example, a shorter fermentation time (48 h) yields more bio-ethanol than a longer fermentation time (72 h) [108]. Mussatto et al. [107] compared three different yeast microorganisms namely, Pichia stipitis, S. cerevisiae, and Kluyveromyces fragilis for bio-ethanol production from spent coffee grounds (SCGs) and coffee silverskin (CS) hydrolysates and found that S. cerevisiae consumed faster the sugar compounds from SCGs hydrolysate comparing to the other strains, with almost total depletion after 24 h fermentation at 30°C [107]. Furthermore, S. cerevisiae produced the most bio-ethanol yield from the SCGs hydrolysate (11.7 g/L, 50.2% efficiency). However, all of the tested yeast strains produced small amounts of bio-ethanol (less than 1 g/L) from CS hydrolysate. Coffee silverskin has a low sugar content, which could lead to low bio-ethanol yield [107]. In addition, Gurram et al. [19] reported that...
88% of bio-ethanol yield with bio-ethanol content of 92.5% and a net energy value of 32.2 MJ/L from coffee pulp under bio-ethanol processing conditions of enzymatic hydrolysis at 50°C for 3 days using fermentation of sugar 150 g/L. Martinez et al. [101] compared enriched culture (culture composed of 5 g/L KH₂PO₄, 2 g/L (NH₄)₂SO₄, g/L MgSO₄ 7H₂O, and 2 g/L yeast extract) and non enriched (only g/L yeast extract) for production of bio-ethanol from coffee husk using yeast extract enzyme concentration of 6% w/w and a solid to liquid ratio of 1:6 w/w. The enriched culture produced bio-ethanol concentrations of 48.19±0.7 g/L and non enriched produced 29.02±0.43 g/L [101]. Biomass to bio-ethanol conversion could be considerably enhanced by developing polymicrobial biofilms from novel strains, one of which can consume lignin while the other does fermentation [42].

**Biodiesel production from spent coffee ground’s oil**

For instance, about 330–450 g of instant coffee drink is produced from 1 kg of Robusta coffee, while 550–670 g of instant coffee known as SCG (Spent coffee grounds) is generated [25]. Approximately 5,817,500 tons of SCGs are generated world wide every year as a municipal solid waste [122]. The spent coffee grounds (SCGs) have lately received interest as a viable source for biodiesel synthesis due to their high oil content (10–20%) and abundant availability [122, 123]. SCGs oil can be extracted using both mechanical and chemical extraction methods, but mechanical method oil extraction from SCGs is not economically viable due to a low oil content [124, 125]; therefore, chemical method oil extraction is the best method for oil extraction from SCGs [124, 125]. Burton et al. [124] reported 10 wt% oil yield from dry grounds using n-hexane as the organic solvent for oil extraction, while the authors [124] determined 98.5 wt% biodiesel yield from dry grounds oil using enzyme catalysis approach. Hamamre et al. [126] reported oil yield of 15.3 wt% of the dry SCGs using n-hexane as extraction solvent after 30 min of extraction time. Furthermore, employing a two-step transesterification method, Bedmutha et al. [127] achieved a biodiesel yield of 99 wt%. On the other hand, Caetano et al. [128] reported 21.1 wt% oil yield using hexane/isopropanol 50:50 v/v after 3 h extraction time, with a higher heating value of 36.4 MJ/Kg and the oil to biodiesel conversion of 58.8–62.2 wt% [128]. Romeiro et al. [129] reported that pyrolysis of the coffee ground at low-temperature (380°C) is good and the oil can be used as an alternative fuel with the improvement of the viscosity. On the other hand, Primaz et al. [130] determined that pyrolysis of the SCGs in a fixed bed reactor and varying the final temperature (400, 450, 500, 550, and 600°C); higher amount of crude bio-oil yield of 30.51 wt% was obtained at pyrolysis temperature of 500 °C with the flow of N₂ in 100 ml/min, and the oil has potential for liquid fuel. Liu et al. [131] reported that direct transesterification (in-situ) of SCGs without the need for oil extraction and esterification steps using process parameters of reaction temperature at 70 °C, 20 wt% sulfuric acid, 12 h reaction time, and 28.87 ml methanol/g oil, and determined the biodiesel yield of 17.08 ± 0.70 wt%, which was equivalent to an oil-to-biodiesel conversion rate of 98.61 wt%. On the other hand, Tuntiwiwattanapun et al. [132] reported that direct transesterification of industrial SCGs oil at 50 °C provided 77wt% biodiesel yield at 3 h reaction time. According to Atabani et al. [25] the average oil content of SCGs is 13 wt%, and the oil is constituted of a low degree of unsaturated fatty acids. This low degree of unsaturated fatty acid composition implies that biodiesel produced from SCGs oils has strong oxidation stability. Furthermore, compared to biodiesel made solely from SCGs oil, biodiesel made by combining SCGs oil with waste cooking oil at a 50:50 v/v ratio enhances unsaturation and improves fuel characteristics [133]. Nguyen et al. [125] used a soxhlet extraction method to compare the oil content of fresh coffee grounds and spent coffee grounds using 250 ml of hexane for 15 g of fresh coffee grounds and spent coffee grounds. The higher amount of oil (18.7 wt%) was determined from fresh coffee grounds due to the fresh coffee ground could contain more moisture than spent coffee grounds. In addition, Nguyen et al. [125], determined the biodiesel yield of 89.2 wt% from spent and fresh coffee grounds oil and the fuel properties of the biodiesel indicated that it is a good alternative to diesel. In addition, Uddin et al. [134] reported that the oil content of coffee grounds is between 10 and 15 wt% (on a dry weight basis), and that biodiesel from coffee ground oil is composed of 37.61% saturated and 62.27% unsaturated fatty acids, and that biodiesel from it has good physical and chemical fuel properties, including higher heating value of 39.67 MJ/kg. The biodiesel physicochemical properties such as density, flash point, cetane number, and acid value meets ASTM D6751 or EN14214 biodiesel standards, but the pour point and cloud point are insufficient; however, they might be enhanced with the addition of additional chemicals [134]. In addition, Atabani and Al-Rubaye [26] reported that biodiesel made from spent coffee grounds oil met ASTM D 6751 biodiesel standards. The biodiesel made from spent coffee grounds oil has the physicochemical properties of 54.23 cetane number, 3.73 mm²/s kinematic viscosity (at 40 °C), 137.5 °C flash point, 891.9 kg/m³ density (at 15 °C), 5.53 h oxidation stability, and a higher heating value of 39.37 MJ/kg. According to Kamil et al. [123], the oil yield of SCGs is 14.12 wt% when extracted with hexane at 60 °C for 4 h at a 6:1 hexane to SCGs ratio. The authors [123] found that the transesterification method at a reaction temperature
of 60 °C, 6:1 alcohol to oil molar ratio, and 1 wt% catalyst mass fraction for 90 min reaction duration, they could convert 90 wt% biodiesel from the oil. The B2 blend has a similar brake mean effective pressure (BMEP) magnitude to the standard diesel at 50% load and even outperforms it at particular speeds (3200 rpm) [123]. In addition, Nguyen et al. [135], reported a maximum biodiesel yield of 97.18 wt% from wet SGCs using DBU (1,8-diazabicyclo [5.4.0] undec-7-ene) of 14.46 ml/g of wet SCGs as a solvent and catalyst of reaction, methanol to wet SCGs ratio of 6.25ml/g, temperature of 60.2 °C, for 28.65 minutes. The biodiesel production from SCGs is environmentally and ecologically outstanding, economically viable, and plentiful available [123, 136], and also compared with the benchmark diesel, the biodiesel blends have a lower tailpipe emission [123].

**Briquettes and pellets production from coffee by-products**

Biomass pelleting and briquetting involves increasing the bulk (or apparent) density to create a denser and more durable form, which lowers transportation, handling, and storage costs and improves shape and size uniformity. It also lowers moisture content, which increases combustion efficiency and reduces smoke during combustion [137–140]. The quality of briquettes and pellets is greatly influenced by the kind and nature of binders employed, compaction pressure, and particle sizes [139, 140]. Corn/potato flour, cassava starch, cow dung, molasses, biosolids, microalgae, saw dust, and wood ash are all common binders used in the making of briquettes and pellets [139–142]. However, some binders cause issues during the conversion of fuel briquettes to energy, such as an increase in ash content, poor combustion qualities, or a decrease in briquette compaction [143, 144]. According to the EU standards, binders that enhance pellet’s quality, reduce emissions, or improve the burning efficiency of the pellets can compose only 2% of the pellet’s total mass [145, 146].

Coffee by-products are a valuable resource for densification, which is used to make briquets and pellets [23, 25, 147]. Coffee parchment and coffee parchment pellets have higher heating values of 18.6 MJ/kg and 28.0 MJ/kg, respectively [148]. According to Wondemagegnehu, [148] both parchment and parchment pellets are suitable alternative energy sources in cement kilns. SCGs and coffee husk are also promising feedstocks for making agropellets with a calorific value of 21.6 MJ/kg for energy production [149–151]. The physicochemical properties of briquettes and pellets can be improved by blending 5% SCGs with other coffee by-products and other biomass [149, 151]. In the cause of mixing SCGs with wood biomass, Brunerova et al. [149] reported that a lower mass ratio of SCGs should be employed, such as 1:1 (50 w/w% of SCGs) or 1:3 (25 w/w% of SCGs). The apparent density and mechanical compressive strength of the briquettes were dramatically altered by reducing the coffee husk particle size [56]. Setter et al. [56] used a densification system at 120 °C and 15 MPa for 15 min to compare the effects of coffee husk particle size on mechanical properties of briquettes in the range of larger than 1.8 mm, in the range of 1.8–1.2 mm, and smaller than 1.2 mm, and the author [56] reported that the briquettes made with particles size less than 1.2 mm had better physicomechanical and energy characteristics due to smaller particles size promote a better accommodation during compaction. In addition, Ndindeng et al. [147] found that briquettes made with tiny particles (0.3 mm) were harder than those made with medium-sized particles (0.9 mm) and that the density of the finer particle size (605 kg/m³) was higher than that of medium-sized particles (506 kg/m³). Furthermore, briquettes dried at room temperature were tougher than those dried at 70 °C (oven-dry). Limosusy et al. [152, 153] reported that SCGs may be used to make briquettes, pellets, and compressed logs, but that blending SCGs with another biomass, such as wood sawdust, improves biomass cohesion and supports increased combustion time and heat release while retaining fuel. Furthermore, due to low moisture content, high calorific value, high lignin content, and low volatile matter content, various authors [23, 147, 154, 155] claimed that residual biomasses from the coffee production chain might be classed as a viable feedstock for densification procedures.

**Summary and future work**

Coffee by-products are ideal prospects for bioenergy production, due to their high cellulose, hemicellulose content, high calorific value, and low ash content. Pretreatment of biomass to remove lignin and hemicellulose is essential to ensure optimal enzymatic hydrolysis of the cellulose present in the biomass, especially for the production of bio-ethanol and biogas. When lignin is present in the hydrolysate, it inhibits microorganisms that ferment sugar monomers and decreases bio-ethanol and biogas yield. The cellulose fraction increased after pretreatment, but the hemicellulose and lignin fractions declined. High-temperature pretreatment produces furans and shards of soluble lignin, which are known to inhibit fermentation. Furthermore, in the production of biogas from coffee by-products, co-digestion with animal manure with a low carbon to nitrogen ratio improves biogas yield by reducing digester instability and regulating the optimum acid level in the fermentation process. The bio-ethanol yield of coffee by-products was considerably increased after pretreatment and using a simultaneous saccharification and fermentation method, as well as using yeast strains that are thermotolerant and ferment the sugar monomer of xylose.
The bio-ethanol yield from coffee husk was increased using cellulolytic hydrolysis and genetically modified lignocellulosic yeast strains (lignocellulosic yeast GSE16-T18) for fermentation and pervaporation temperature up to 50 °C. Biodiesel made from spent coffee grounds oil has a high calorific value and meets ASTM D 6751 and EN14214 biodiesel standards. The calorific value of biodiesel made from spent coffee grounds oil is composed of 37.61% saturated fatty acids and 62.27% unsaturated fatty acids, and it flows well at moderate temperature. Blending biodiesel made from spent coffee grounds oil with biodiesel that contains a high percentage of unsaturated fatty acids can improve biodiesel flow properties. Briquettes and pellets with a high caloric value and good physicochemical properties are made from coffee by-products using an optimum particle size, pressing pressure, and using the right amount of appropriate binder. The physicochemical properties of briquettes and pellets can be improved by blending 5% SCGs with other coffee by-products and biomass from agricultural and forest residues. The following research area could be important for increasing biofuel yields from coffee by-products:

1. Pretreatment methods for producing bio-ethanol and biogas from coffee by-products are inefficient and environmentally unfriendly. As a result, enhanced pretreatment research is needed to increase bio-ethanol and biogas yield from coffee by-products and to make the process environmentally friendly, and to improve biofuel yield.

2. Lignin is one of the most abundant components in coffee by-products and has a high calorific value; more research is needed to determine how to use it for energy purposes.

3. Coffee by-products have a total sugar content of 62.5%, with xylose accounting for 21.89% of the total sugar content. However, only a few yeast strains ferment xylose, so more research is needed to develop yeast strains and microorganism that ferment xylose sugar monomere to improve bio-ethanol and biogas yield.

4. The use of binders in the production of briquettes and pellets is currently one of the most challenging issues. Binders are now largely made from food materials and are used for a various purposes. They are also expensive. More research is needed to improve binders so that briquettes and pellets can have improved physicochemical properties while also being economically viable.

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**Declarations**

**Conflict of interest** There is no conflict of interest on publication and the authorship of this paper.

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