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Valorisation of Spent Coffee Grounds for Bioenergy Purposes: A review

BACHELOR'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled "Valorisation of Spent Coffee Grounds for Bioenergy purposes" independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged using complete references and according to Citation rules of the FTA.

In Prague, 18th April 2024

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Jana Larbi

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Abstract

The global effort to achieve the UN Sustainable Development Goals has led to a focus on sustainable renewable energy resources, as well as efforts to mitigate climate change and environmental pollution. Spent coffee grounds (SCGs) are a significant waste stream generated by the coffee industry worldwide, prompting increased interest in valorising SCGs to extract value from this abundant waste material. One promising step for this valorisation is the conversion of SCGs into bioenergy, which can contribute to renewable energy targets and simultaneously reduce waste disposal costs and environmental impact. This review was done using articles found in web databases, EBSCO Discovery Service, Google Scholar, and Web of Knowledge, and also includes a case study of successful SCGs valorisation. The study aims to provide a comprehensive understanding of the valorisation processes, technologies, and the economic and environmental considerations associated with SCGs utilisation. It suggests that one potential solution to multiple environmental challenges lies in the conversion of waste materials into valuable sources for bioenergy production. The research assesses the potential of abundant spent coffee grounds as a resource for bioenergy production, although it also acknowledges several challenges that hinder the scaling up of SCGs valorisation, such as feedstock availability, collection logistics, and the optimisation of technologies. Ultimately, it provides a comprehensive review of the valorisation potential for spent coffee grounds for bioenergy purposes and offers directions for future research.

Keywords: spent coffee grounds, bioenergy, valorisation, sustainable development, renewable energy, waste management

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List of the Abbreviations Used in the Thesis

UN	United Nations
SCGs	spent coffee grounds
FFA	free fatty acid
SFE	supercritical fluid extraction
AV	acid value
LCA	life cycle assessment
CHP	combined heat and power

1. Introduction

In recent years, there has been growing interest in the valorisation of waste biomass for bioenergy purposes (Jain et al. 2022; Johnson et al. 2022). This focus on sustainable and renewable energy sources, supported by the UN Sustainable Development Goals, is driven by the need to reduce greenhouse gas emissions, mitigate climate change, and move towards a more environmentally friendly energy landscape. According to Zuorro and Lavecchia (2012), spent coffee grounds, which are a significant by-product of the coffee industry, have emerged as a promising feedstock for bioenergy production.

Global coffee consumption has been on the rise, leading to a substantial increase in the generation of spent coffee grounds (Mussatto et al. 2011). The total amount of SCGs generated annually worldwide is estimated to be about 60 million tonnes (Forcina et al. 2023). Traditionally, these grounds have been treated as waste and either disposed of in landfills or incinerated, contributing to environmental pollution and greenhouse gas emissions. However, recent research has revealed the potential of using wasted coffee grounds for bioenergy purposes, thus transforming them from waste into a valuable resource.

One of the key advantages of using spent coffee grounds as feedstock for bioenergy production is their high energy content (Esquivel & Jiménez 2012). Coffee grounds are rich in organic compounds, including carbohydrates, lipids, and lignocellulosic materials, which can be converted into biofuels through various conversion pathways. This high energy content makes spent coffee grounds an attractive alternative to conventional feedstocks for bioenergy production (Bravo et al. 2013; Serda et al. 2013).

The utilisation of spent coffee grounds for bioenergy purposes aligns with the principles of the circular economy (Passadis et al. 2020). Diverting this waste stream from landfills or incineration can be valuable resources extracted and used for energy production (Buntić et al. 2016). This not only helps to reduce waste generation but also contributes to a more sustainable and efficient use of resources.

Another important aspect to consider is the potential economic benefits associated with valorising spent coffee grounds. According to Banu et al. (2021), the coffee industry generates substantial quantities of spent coffee grounds, which, if effectively managed and processed, can be transformed into a valuable feedstock for bioenergy production. This presents an opportunity for both the coffee industry and bioenergy producers to collaborate, creating a win-win situation where waste is transformed into a valuable resource.

Valorisation of spent coffee grounds for bioenergy production can also contribute to the development of rural economies. Many coffee-growing regions, especially in developing countries, face socio-economic challenges (Carus & Dammer 2018). Establishing bioenergy facilities that utilise spent coffee grounds, these regions can create new job opportunities and generate income, thus improving the livelihoods of local communities.

The valorisation of spent coffee grounds for bioenergy purposes offers a sustainable solution to manage this abundant waste residue. Through various conversion technologies, these grounds can be transformed into biofuels, such as biodiesel, bioethanol, and biogas, thereby reducing reliance on fossil fuels and mitigating climate change (Murthy & Naidu 2012; Semaan et al. 2021; Zabaniotou & Kamaterou 2019). In addition, other potential applications, such as biochar production, provide additional opportunities to use spent coffee grounds. The valorisation of spent coffee grounds presents a viable and environmentally friendly approach to both waste management and energy production (Yeoh & Ng 2022).

2. Aims of the Thesis

This review seeks to assess the possibility of using spent coffee grounds (SCGs) for bioenergy production. The review intends to offer insights into the processes, and economic and environmental factors related to the exploitation of SCGs. It also intends to illustrate the difficulties and potential outcomes of scaling up SCGs valorisation for sustainable bioenergy production.

3. Methods

The present thesis was compiled as a literature review based on scientific articles. The thesis was prepared according to the Faculty of Tropical AgriSciences manual to write for a Bachelor`s thesis, and all literature is cited in accordance with the mandatory faculty rules.

The preparation of the literature review was based on searching articles from web databases such as the EBSCO Discovery Service, Google Scholar, and Web of Knowledge. The journals referenced in the present work were: Bioresource Technology, Renewable and Sustainable Energy Reviews, Waste and Biomass Valorisation, and others. The search for scientific information was done using the keywords spent coffee grounds, bioenergy, valorisation, sustainable development, renewable energy, waste management, etc. The information obtained was processed and analysed.

4. Literature Review

4.1. Definitions of Key Terms

4.1.1. Bioenergy

According to Iyyappan et al. (2022), bioenergy refers to energy derived from biological sources, such as organic matter, waste materials, and crops. It can be done through various processes, including combustion, anaerobic digestion, or biochemical conversion (Iyyappan et al. 2022; Meramo 2022).

In terms of global energy needs, bioenergy plays an important role in meeting the growing demand for clean and renewable energy sources. As countries strive to reduce their dependence on fossil fuels and reduce greenhouse gas emissions, bioenergy offers a promising solution. It accounts for a substantial share of the global renewable energy mix, along with solar, wind, and hydropower (Serda et al. 2013).

According to Wu et al. (2018), bioenergy contributes to energy security by diversifying the energy supply, as it can be produced locally from a variety of biomass resources. This reduces dependence on imported energy sources and creates opportunities for rural development. Also, bioenergy systems can be more flexible than other renewable energy technologies, allowing for intermittent energy generation (Iyyappan et al. 2022).

One of the major environmental benefits of bioenergy is its potential to reduce greenhouse gas emissions. While burning fossil fuels releases carbon dioxide (CO_2) that has been trapped underground for millions of years, bioenergy uses recently captured CO_2 from the atmosphere (van Leeuwen et al. 2021). This results in a closed carbon cycle, where the CO_2 released during combustion is reabsorbed by plants during their growth, creating a carbon-neutral energy source.

Furthermore, bioenergy can help address waste management challenges by using organic waste streams and by-products from agriculture, forestry, and food processing industries (Monteiro et al. 2018). Bioenergy systems contribute to waste reduction and promote a circular economy by diverting these waste materials from landfills and converting them into energy. From an economic point of view, developing the bioenergy sector can create new job opportunities, especially in rural areas where biomass resources are abundant. It can promote local investment, technology development, and innovation in the renewable energy sector (Hillring 2002).

However, it is important to ensure sustainable bioenergy production practices to avoid negative impacts on land-use change, biodiversity, and food security. Responsible biomass sourcing, efficient conversion technologies, and a comprehensive approach to sustainability are essential for maximising the benefits of bioenergy while minimising potential drawbacks.

4.1.2. Valorisation

Valorisation, also known as value creation or enhancement, is a crucial concept in the field of bioenergy production. It refers to the process of maximising the economic, environmental, and social benefits derived from biomass resources (Leder et al. 2020). With the growing interest in sustainable energy options and the urgent need to mitigate climate change, valorisation plays a significant role in the transition to a greener and more sustainable future.

In the context of bioenergy production, valorisation involves utilising biomass, such as agricultural residues, forest waste, and dedicated energy crops, to produce various forms of renewable energy. This can include biofuels, such as biogas, and biomass-based power and heat generation systems (Karmee 2018). The significance of valorisation lies in its potential to address multiple challenges and offer several advantages.

First, the valorisation of biomass resources contributes to energy security and diversification. Countries can reduce their dependence on limited and often imported energy sources by utilising renewable biomass instead of fossil fuels (Long et al. 2013).

Valorisation helps to diversify the energy mix, ensuring a more balanced and resilient energy system.

Secondly, valorisation aligns with the principles of sustainable development. Biomass is considered a carbon-neutral energy source since it results from the natural carbon cycle and does not introduce additional CO_2 into the atmosphere when effectively managed (Destek et al. 2021). Bioenergy production systems can significantly reduce greenhouse gas emissions compared to fossil fuel-based alternatives, thus mitigating climate change.

Thirdly, valorisation supports rural development and brings economic benefits to local communities. Bioenergy production often relies on locally available biomass feedstocks, creating opportunities for farmers, foresters, and other stakeholders (Long et al. 2013). The establishment of biorefineries and decentralised energy systems can stimulate job creation and foster regional economic growth.

Valorisation promotes resource efficiency and waste management. Bioenergy production maximises the value of these materials and reduces waste by using agricultural and forest residues that would otherwise be left unused or burnt (Kumar et al. 2023). This approach also helps minimise the environmental impact associated with waste disposal and contributes to the circular economy by avoiding the use of raw materials.

4.1.3. Spent Coffee Grounds

Coffea, a genus of flowering shrubs in the *Rubiaceae* family, is cultivated primarily for its seeds, which play a crucial role in beverage production (Brunerová et al. 2019; Potip & Wongwuttanasatian 2018). Among more than 100 known species, *Coffea arabica* and *Coffea canephora* (known as Robusta) have global importance and use. Arabica contributes approximately 75 %, while robusta makes up the remaining portion. These seeds have been a key component in beverage production, particularly coffee, for over a millennium, making it a globally celebrated drink (Lachenmeier 2023). Coffee is the second largest commodity traded worldwide, involving more than 80 countries, and has significant economic and political importance for many developing nations (Battista et al. 2020).

The coffee production industry provides several job opportunities, ranging from cultivation to packaging and shipping. However, in the process, a considerable amount of waste is generated, known as spent coffee grounds (SCGs) (Serda et al. 2013). Unfortunately, these wastes lack market value and are typically discarded, contributing to environmental pollution.

Despite their lack of immediate utility, SCGs wastes have been recognised for their calorific value and potential as a fuel source. They can be transformed into biofuels, such as biodiesel, bio-ether, biochar, bio-oil, or biogas, through advanced chemical and biotechnological processes (Karmee 2018; Gardy et al. 2019).

In particular, densified SCGs briquettes or pellets, exhibit fuel characteristics similar to those of fossil fuels, offering a low-cost, highly renewable, and environmentally friendly alternative.

Developing binder-less or 100% raw SCGs briquettes has proven challenging, primarily due to coarse particle morphology and high lipid content (Silva et al. 1998). However, the addition of calculated amounts of binders, moisture content, and other biomasses enhances the durability and utilisation of the briquettes. These eco-friendly briquettes, which incorporate spent coffee grounds, coal fines, and sawdust, produce low toxicity emissions suitable for domestic applications.

Briquettes derived from SCGs-biochar show promise for energy generation as a result of their superior fuel combustion characteristics. Recognising their potential, these SCG-based briquettes could contribute significantly to the growing energy demand, offering a renewable and readily available alternative to the depletion of fossil fuel resources (Colantoni et al. 2021).

4.2. Composition and Properties of Spent Coffee Grounds

4.2.1. Physicochemical Properties of SCGs

4.2.1.1. Moisture Content

Moisture content is a critical physicochemical property of SCGs, as it directly impacts their suitability for various applications. Moisture content is typically expressed as a percentage of the total weight of SCGs (Kotsou & Chatzimitakos 2023).

It is crucial to accurately determine the moisture content because it influences the stability and shelf life of SCGs and affects their behaviour in different processes. The moisture content in SCGs can vary significantly depending on factors such as the coffee brewing method, storage conditions, and environmental humidity. Freshly generated SCGs typically have a moisture content ranging from 45 % to 65 % (Kotsou & Chatzimitakos 2023). However, during storage, SCGs can absorb moisture from the surrounding environment, leading to an increase in their moisture content.

High moisture content in SCGs can be problematic for several reasons. It can promote the growth of moulds and fungi, leading to spoilage and the development of unpleasant odours. The high moisture content reduces the calorific value of SCGs, making them less suitable for energy applications. Moist SCGs are less suitable for use in certain industrial processes, such as the production of biofuels, where a low moisture content is desirable (Oh et al. 2021). To address these issues, researchers and industries have developed various methods for reducing the moisture content of SCGs, such as drying and dehydrating techniques. These processes not only extend the shelf-life of SCGs but also enhance their suitability for diverse applications.

4.2.1.2. Volatile Matter

According to Caillat and Vakkilainen (2013), volatile matter refers to the portion of SCGs that can be vaporised or converted into gas when heated at specific temperatures in a controlled environment. This property is of particular interest in the context of the use of SCGs for energy generation, as it indicates the combustible components present in the material. Volatile matter is typically expressed as a percentage of the total weight of spent coffee grounds (Silva et al. 2023).

Volatile Matter (%) = (Total Weight of SCGs / Weight of Volatile Matter) × 100

The volatile matter content in SCGs consists of organic compounds, such as volatile organic acids, oils, and aromatic compounds (Sermyagina et al. 2021). These compounds can contribute to the energy content of SCGs when they are used as a fuel source. The determination of the volatile matter content is essential for assessing the potential of SCGs as a renewable energy source, especially in the context of biomass combustion or gasification (Kovalcik et al. 2018).

Higher volatile matter content indicates better combustibility, making SCGs a more attractive option for energy production. However, the volatile matter content can also vary depending on the type of coffee bean, the level of roasting, and brewing the method. Therefore, it is crucial to characterise the volatile matter content of SCGs for specific applications accurately.

4.2.1.3. Fixed Carbon

Fixed carbon is the portion of SCGs that remains after the volatile matter has been driven off through heating in a controlled environment. It represents the non-volatile, carbonaceous components of SCGs and is expressed as a percentage of the total weight (Biswal et al. 2020).

Fixed Carbon (%) = (100 - % Volatile Matter - % Ash)

The fixed carbon content is a significant factor in determining the energy potential of SCGs. A higher fixed carbon content implies a higher carbon-to-ash ratio, which is desirable for energy applications (Afolabi et al. 2020). Fixed carbon is responsible for the release of heat during combustion or gasification processes and contributes to the overall energy yield.

The fixed carbon content in SCGs is influenced by factors such as the type of coffee bean, roasting, and the brewing method. SCGs from darker roasted coffee beans tend to have higher fixed carbon content, making them more suitable for energy generation (Chen et al. 2023).

4.2.1.4. Ash Content

The ash content is a crucial physicochemical property of SCGs that represents the inorganic residue left behind after complete combustion or incineration. It is expressed as a percentage of the total weight of SCGs and is primarily composed of minerals and trace elements that were present in the coffee beans. The ash content in SCGs can vary significantly depending on the the origin of coffee bean, as different regions have varying soil compositions. Also, the roasting process can influence the ash content, as minerals may change concentration or chemical composition during roasting.

The high ash content in SCGs can be advantageous and disadvantageous, depending on the intended application. In agriculture, the ash content can contribute essential nutrients, such as potassium and phosphorus, to the soil when SCGs are used as soil conditioners or fertilisers.

In energy production, high ash content can be problematic because it reduces the calorific value of SCGs and can lead to the formation of ash-related issues, such as slagging and fouling in combustion or gasification equipment.

Therefore, it is essential to assess the ash content of SCGs to determine their suitability for specific applications accurately. Ash content can be reduced through washing or other pre-treatment processes (Jeníček et al. 2022).

4.2.2. Chemical Composition of Spent Coffee Grounds and Its Contribution to Their Energy Potential

4.2.2.1. Cellulose

Cellulose is a crucial and abundant component found in various organic materials, including spent coffee grounds (SCGs) (Siriwong et al. 2014; Sung et al. 2017). Comprising a substantial portion of plant cell walls, cellulose is a long-chain polymer composed of glucose units connected together linearly. Its structural integrity is vital for plants as it provides strength and rigidity to their cell walls. However, cellulose can also serve as a valuable resource for biofuel production (El Miri et al. 2015).

The breakdown of cellulose into simpler sugars, such as glucose, is a crucial step in the production of bioethanol, a sustainable and renewable alternative to traditional fossil fuels (Ballesteros et al. 2014). This process is enabled by various biological and chemical methods. One of the most significant transformations involves the chemical reaction represented by $C_6H_{10}O_5$ (cellulose) → $C_6H_{12}O_6$ (glucose).

In this reaction, cellulose, with its complex and rigid structure, is converted into glucose, a simpler sugar that can be readily fermented by microorganisms (Ballesteros et al. 2014; Lu et al. 2014). This enzymatic or chemical transformation is the key to unlocking the energy stored in cellulose and converting it into a biofuel source, specifically bioethanol.

To accomplish this conversion, several steps are typically involved. First, cellulose is broken down into smaller saccharide units through various chemical or enzymatic processes (Lu et al. 2014). These smaller sugar molecules, primarily glucose, are then made available for fermentation by yeast or bacteria. During the fermentation process, microorganisms consume glucose and convert it to ethanol, a process that can be further refined and optimised for bioethanol production.

The production of bioethanol from cellulose-rich sources such as SCGs represents a sustainable and eco-friendly solution to energy needs. This innovative approach not only reduces our reliance on finite fossil fuel resources but also offers a way to repurpose organic waste materials like coffee grounds, providing an environmentally friendly and economically viable energy source (Murthy & Naidu 2012). It also contributes to the reduction of greenhouse gas emissions, making it a valuable component of a greener and more sustainable energy future.

4.2.2.2. Hemicellulose

Hemicellulose is a complex and important polysaccharide found in spent coffee grounds (SCGs), which contributes significantly to the overall composition of these coffee waste by-products (Harrahill et al. 2023). Hemicellulose is a macromolecule composed of various sugar monomers, and through a process known as hydrolysis, it can be broken down into simpler sugars. This hydrolysis reaction, similar to the breakdown of cellulose, converts hemicellulose, with its chemical formula $C_6H_{10}O_5$, into a mixture of different sugars, primarily glucose with a chemical formula of $C_6H_{12}O_6$ (Kavitha et al. 2019).

Hemicellulose plays a crucial role in the bioconversion of SCGs, offering a source of fermentable sugars that can be used for various applications. This depolymerisation of hemicellulose into sugars makes it a valuable resource for industries involved in biorefinery, biofuel production, and the development of sustainable products (Chandel et al. 2020). It should be noted that while the presented equation simplifies the hydrolysis of hemicellulose, hemicellulose is a heterogeneous polymer, and its breakdown can result in a mixture of sugars, including pentoses (such as xylose and arabinose) in addition to hexoses (like glucose) (Laca et al. 2019). This complexity highlights the versatility and potential of hemicellulose as a feedstock for various biotechnological processes, making it an intriguing component of SCGs.

4.2.2.3. Lignin

Lignin is a fascinating and intricate component of spent coffee grounds (SCGs), which, although not used directly for bioethanol production, holds immense potential for the creation of valuable chemicals and biofuels (Johnson et al. 2022). Lignin is a complex, aromatic polymer that can undergo several chemical processes to be transformed into a range of useful products.

The chemical formula of lignin, $C_9H_{10}O_3$, is a testament to its complex nature, composed of a myriad of intricately bonded carbon, hydrogen, and oxygen atoms. Despite its complexity, the intricate structure of lignin can be broken down and converted into a variety of substances, including biofuels and valuable chemicals (Zhao et al. 2022).

The process of converting lignin into biofuels and other chemicals typically involves several steps. Lignin must first be extracted from the SCGs, a process that can be achieved through various methods, such as alkaline extraction or enzymatic breakdown. Once isolated, lignin can then undergo a series of chemical reactions and processes to produce the desired end products.

Biofuels, for example, can be derived from lignin through processes such as pyrolysis, where lignin is heated in the absence of oxygen to break down into bio-oil, which can be further processed to produce biofuels such as biodiesel or bioethanol (Vavilala et al. 2019). The high energy content of lignin makes it a promising source for these sustainable fuels.

In addition to biofuels, lignin can also be transformed into valuable chemicals. Various chemical reactions can modify its structure to produce compounds that have applications in industries ranging from pharmaceuticals to materials science. These chemicals can be used as raw materials for the synthesis of plastics, resins, adhesives, and more, contributing to the reduction of dependence on fossil fuels and promoting a more sustainable and environmentally friendly future (Swetha et al. 2023).

The ability to convert lignin from SCGs into biofuels and valuable chemicals showcases the importance of recycling and utilising waste materials. This not only reduces the environmental impact of waste disposal but also offers a sustainable solution for meeting the growing global demand for renewable energy sources and eco-friendly chemical feedstocks. Lignin, as a resource within SCGs, exemplifies how creative approaches to waste management can contribute to a greener and more sustainable world.

4.2.2.4. Lipids

The lipids and fats present in the spent coffee grounds (SCGs) constitute a valuable resource with diverse potential applications, including biodiesel production

(Kovalcik et al. 2018b). The process involved in the conversion of these lipids and fats into biodiesel is termed transesterification. This chemical reaction holds significant promise for the repurposing of the lipids in SCGs, thus contributing to sustainability and environmental conservation initiatives.

Despite typically containing only minor quantities of lipids and fats, SCGs, the by-product of coffee brewing, is of importance due to the considerable volume generated globally daily. Transformation of these lipids and fats into biodiesel offers a distinctive avenue for the reduction of waste and the utilisation of a readily available resource.

Transesterification involves the reaction of triglycerides (a subtype of lipid) of SCGs with alcohol, which produces two main products: biodiesel and glycerol. The chemical equation that represents this reaction is Triglyceride (lipid) + Alcohol Biodiesel + Glycerol. In this context, triglycerides in coffee grounds, essentially esters of glycerol with three fatty acid chains, undergo a conversion when reacting with alcohol (Barbosa et al. 2022). This reaction decomposes triglycerides into biodiesel, an eco-friendly alternative to conventional fossil fuels, and glycerol, a valuable byproduct applicable in diverse industrial processes.

The significance of this process is noteworthy, aligning with the escalating emphasis on sustainability, renewable energy sources, and the reduction of reliance on non-renewable fossil fuels. By efficiently repurposing SCG lipids and fats into biodiesel, not only is waste minimised, but a concurrent reduction in greenhouse gas emissions and overall environmental footprint is achieved.

Furthermore, the use of spent coffee grounds as feedstock for biodiesel production adds a layer of sustainability to the coffee industry. It underscores the importance of responsible resource management, advocates for circular economy principles, and mitigates the environmental impact associated with one of the world's most widely consumed beverages. This innovative approach exemplifies the potential of finding creative solutions in unexpected sources and demonstrates how science and technology can convert waste materials into valuable assets, fostering a more sustainable future.

4.2.2.5. Proteins

Proteins are macromolecules composed of amino acid chains linked together by peptide bonds. During the fermentation process for bioethanol production, proteins in spent coffee grounds (SCGs) can indeed serve as a source of nitrogen for microorganisms. This nitrogen is essential for the growth and metabolism of microorganisms, such as yeast or bacteria, that are responsible for the conversion of sugars into ethanol.

The breakdown of proteins into amino acids is a crucial step in making this nitrogen available to microorganisms. This process involves enzymatic hydrolysis, where enzymes break the peptide bonds between amino acids. This results in the release of individual amino acids that can then be utilised by microorganisms as a nitrogen source (Karmee 2018). The general representation of this protein breakdown can be expressed as Protein → Amino Acids.

4.2.3. Compositions and Characteristics of SCGs In Relation to Their Utilisation

When considering the utilisation of spent coffee grounds (SCGs), it becomes crucial to comprehend their makeup. It should be noted that, similar to most biological feedstocks, the composition of SCGs exhibits significant variability due to various factors, including the brewing method, the type of coffee and the growing conditions. Nevertheless, most SCGs samples share a common composition. The primary constituent of SCGs consists of polysaccharides, specifically cellulose and hemicellulose, which collectively account for approximately 50 % of the dry mass of the SCGs. Hemicellulose sugars mainly comprise mannose, galactose, and arabinose, while glucose is the primary component of cellulose (Jeguirim et al. 2014).

Following closely in abundance are lignin and protein, each contributing roughly 20 % of the dry mass. Although the study by Ballesteros et al. (2014) in **Table 1** reports unusually low values, it should be noted that SCGs also contain a substantial amount of oil, with more than 15 % recorded in several other studies, based on dry mass measurements. SCGs contain a smaller number of various components, including ash, phenolic compounds, minerals, caffeine, and tannins.

Table 1. Composition of SCGs

Component	Composition (g / 100 g dry matter)
Cellulose	12.40 ± 0.79
Hemicellulose	39.10 ± 1.94
Arabinose	3.60 ± 0.52
Mannose	19.07 ± 0.85
Galactose	16.43 ± 1.66
Lignin	23.90 ± 1.70
Insoluble	17.59 ± 1.56
Soluble	6.31 ± 0.37
Ashes	1.30 ± 0.10
Protein	17.44 ± 0.10
Nitrogen	2.79 ± 0.10

Source: Jeguirim et al. (2014)

4.3. Energy Conversion Methods

4.3.1. Thermochemical Methods

The thermal conversion of biomass into bioenergy encompasses three primary processes: combustion, gasification, and pyrolysis. Each method presents distinct advantages and considerations, particularly in the context of utilising spent coffee grounds for bioenergy production.

Combustion, the most prevalent and widely employed method, entails the burning of biomass in the presence of oxygen to release heat energy. In the case of spent coffee grounds, direct combustion produces heat, which can be used for steam and electricity generation. Although a straightforward process with minimal pre-processing requirements, combustion generates emissions such as carbon dioxide, nitrogen oxides, and particulate matter (Jeníček et al. 2022). Consequently, the implementation of emission control technologies is imperative to mitigate environmental impacts.

Gasification represents a more advanced technique, converting biomass into combustible gases, primarily carbon monoxide and hydrogen, through partial oxidation. The resulting syngas can be utilised for electricity generation or further processed into fuels such as methane or hydrogen. Gasification exhibits enhanced efficiency compared to combustion, as it effectively utilises both carbon-rich and volatile components of biomass. However, its complexity requires sophisticated equipment and precise control of operating conditions. Additionally, the tar content in the syngas poses a challenge, which requires supplementary purification steps (Rodrigues et al. 2022).

Pyrolysis involves the decomposition of biomass at elevated temperatures in the absence of oxygen, yielding bio-oil, char, and gas. Bio-oil can serve as a liquid fuel or undergo further processing into valuable chemicals. Although it offers a diverse range of products and potentially higher efficiency than combustion and gasification, pyrolysis confronts challenges related to the instability and variability of bio-oil produced. Refinements are thus necessary to eliminate impurities and enhance stability (AlMallahi et al. 2023).

In evaluating the conversion of spent coffee grounds into bioenergy through these three methods, considerations must include factors such as efficiency, environmental impact, and product versatility. Combustion, while straightforward and immediately heat-generating, may exhibit higher emissions. Gasification offers increased efficiency and product flexibility but requires more sophisticated equipment and gas purification. Pyrolysis, though providing a broader range of valuable products, necessitates additional refining steps. Table 2 summarises the distinctions between combustion, gasification, and pyrolysis, emphasising their roles in the thermal conversion of biomass. Combustion occurs with sufficient oxygen for complete oxidation, gasification involves incomplete oxidation, and pyrolysis transpires in the absence of oxidising agents. Gasification, positioned between combustion and pyrolysis, entails partial oxidation and partial pyrolysis.

Table 2. Comparison of Combustion, Gasification, and Pyrolysis for Spent Coffee Grounds for Bioenergy Production

	Combustion	Gasification	Pyrolysis
Oxidizing agent	Greater than stoichiometric supply of oxygen	Less than stoichiometric oxygen or steam as an oxidising agent	Absence of oxygen or steam
Typical temperature range with biomass fuels	800 °C to 1200 °C (1450 °F to 2200 °F)	800 °C to 1200 °C (1450 °F to 2200 °F	350 °C to 600 °C (660 °F to 1100 °F)
Principle products	Heat	Heat and combustible gas	Heat, combustible liquid and combustible gas
Principle components of gas	CO_2 and H_2O	Heat and combustible gas	CO and H_2

Source: Carolyn (2010)

4.3.2. Biochemical Methods

4.3.2.1. Oil Extraction from Spent Coffee Grounds

Before commencing the oil extraction process from spent coffee grounds (SCGs), it is imperative to first eliminate the moisture content through a drying process

(Phimsen et al. 2016). This not only ensures the prevention of spoilage and microbial growth but also facilitates the extraction process. The drying of SCGs can be achieved at temperatures of 50 °C or 105 °C ± 5 °C for oil extraction. In certain cases, wet spent coffee grounds with 60 % moisture can be used for direct transesterification (in situ transesterification). It is important to note that moisture in SCGs can exist as unbound or excess moisture as well as bound moisture, which depends on various factors such as the physical nature of the solid, drying temperature, and time. The bound moisture content can influence the drying rate.

Several characteristics of SCGs can be determined, including moisture content, total carbon, total nitrogen, protein, ash, cellulose, and the content of both insoluble (Klason) and soluble lignin.

SCGs are known to contain a high oil content, typically ranging from 11 % to 20 % on a dry weight basis (Jeguirim et al. 2014). The primary fatty acids found in the oil extracted from the spent coffee grounds are linoleic (C18:2), palmitic (C16:0), and oleic (C18:1), which are suitable for the production of diesel fuel. The oil yield can be influenced by the brewing methods used for fresh coffee grounds, such as boiling, drip-filtering, or percolating, leading to varying concentrations of substances in the SCGs (Vu et al. 2018). Additionally, different types of fresh coffee, such as Coffee Arabica and Coffee Robusta, have varying lipid contents, resulting in different lipid fractions in SCGs. Furthermore, the polarity of the extraction solvent can significantly impact the oil extraction yield, with polar solvents extracting higher amounts of free fatty acids (FFA), leading to higher crude oil yields. It is worth noting that the use of polar solvents may result in the formation of a black, gummy material alongside the extracted oil, such as in the case of ethanol, where this material can account for 1.02 % of the SCGs sample. This material may comprise proteins, carbohydrates, and other compounds formed due to complex interactions between fatty acids and carbohydrate breakdown components, which can pose challenges in oil extraction. The oil yield is also affected by factors such as moisture content in SCGs, particle size, solvent quantity, extraction technology, extraction time, and more (Al-Hamamre et al. 2012).

Various methods can be employed to extract oil from spent coffee grounds, including Soxhlet extraction, Supercritical fluid extraction (SFE), Ultrasound extraction, and Microwave extraction. Although organic solvents are commonly used for oil extraction, there is an increasing consideration of alternatives due to environmental and health concerns. Soxhlet extractions are known to be time-consuming and require a substantial amount of solvent and energy, resulting in low productivity. SFE, on the other hand, is a novel technique that uses supercritical fluids as solvents, offering advantages such as efficient extraction and reduced environmental impact. Supercritical CO_2 is a widely used solvent in this method. Ultrasound-assisted solvent extraction is an efficient process and particularly suitable for oil-containing materials with a high moisture content.

When solvents are used in extraction processes, they are typically distilled off in a rotary evaporator under moderate vacuum after the extraction is complete. The recovered solvent can then be reused in subsequent extractions. The quality of the oil is assessed through parameters like the iodine number, saponification, calorific values, acid value (AV), water content, kinematic viscosity, viscosity index, density, and elemental composition. In addition, the heating value of the SCGs was measured after extraction. The acid and saponification values are crucial parameters for evaluating the fatty acid content in the extracted oil. The AV reflects the total acidity, or the amount of free fatty acids in the oil, which can influence its quality. High levels of free fatty acids increase susceptibility to oxidation.

Several studies have explored oil extraction from spent coffee grounds using various solvents, extraction methods, and conditions. The choice of solvent, SCGs-to-solvent ratio, and extraction time can significantly affect the oil extraction rate and solvent recoverability. For example, the use of different solvents and extraction times in Soxhlet extraction led to oil yields ranging from 8.60 % to 15.28 % on a dry weight basis. Researchers have investigated the optimisation of solid-to-solvent ratios and extraction times to achieve higher yields, with response surface methodology assisting in finding optimal conditions for coffee oil extraction (Uddin et al. 2019).

Various extraction methods, including ultrasound-assisted extraction, supercritical fluid extraction, and microwave extraction, have been explored, with different results reported in the literature. These methods offer unique advantages and challenges (or ultrasound-assisted extraction) from SCGs have been reported, and supercritical fluid extraction has been explored for both green roasted and spent coffee forms. Microwave extraction, or microwave-assisted extraction, is another technique worth considering for oil extraction.

4.3.2.1.1 Biodiesel Production from Spent Coffee Grounds

Biodiesel, a versatile and sustainable fuel option, has emerged as a promising solution to address both our energy and environmental concerns (Dang & Nguyen 2019). This renewable and biodegradable fuel can be exploited from an unlikely source, spent coffee grounds (SCGs), through a sophisticated chemical process known as transesterification (Dang & Nguyen 2019). The utilisation of SCGs for biodiesel production has opened a new frontier in sustainable energy, offering numerous advantages.

SCGs, typically considered waste material after brewing your morning coffee, possess a hidden treasure within them: lipids. These lipids, which include residual coffee oils, can be carefully extracted and transformed into high-quality biodiesel.

The optimal approach to producing biodiesel involves the transesterification of oils with various alcohols, such as methanol, ethanol, propanol, and butanol. Transesterification reactions can be carried out using either non-catalytic or catalytic processes.

Non-catalytic transesterification is characterised by slow reaction rates, often requiring high pressures and temperatures to reach completion (Chai et al. 2014). However, the employment of diverse catalysts can enhance the biodiesel production. These catalysts can be broadly classified into three main categories: homogeneous catalysts, heterogeneous catalysts, and biocatalysts (enzymes).

Transesterification reactions typically hinge on various critical parameters, including reaction temperature, reaction time, the free fatty acid content in the oil, the water content in the oil, the type and amount of catalyst, the molar ratio of alcohol to oil, the type or chemical nature of the alcohol, the use of co-solvents, and mixing intensity. These factors have a significant impact on the final conversion and yield of biodiesel.

The biodiesel production process involves a transesterification reaction, a reversible process consisting of three successive steps. In these steps, triglycerides are converted into diglycerides, diglycerides into monoglycerides, and monoglycerides into esters and glycerol, as shown in **Figure 1**. This reaction yields three moles of fatty acid monoalkylester (biodiesel) and one mole of glycerol as a by-product.

Figure 1 illustrates the reactions involved in the transesterification of a triglyceride.

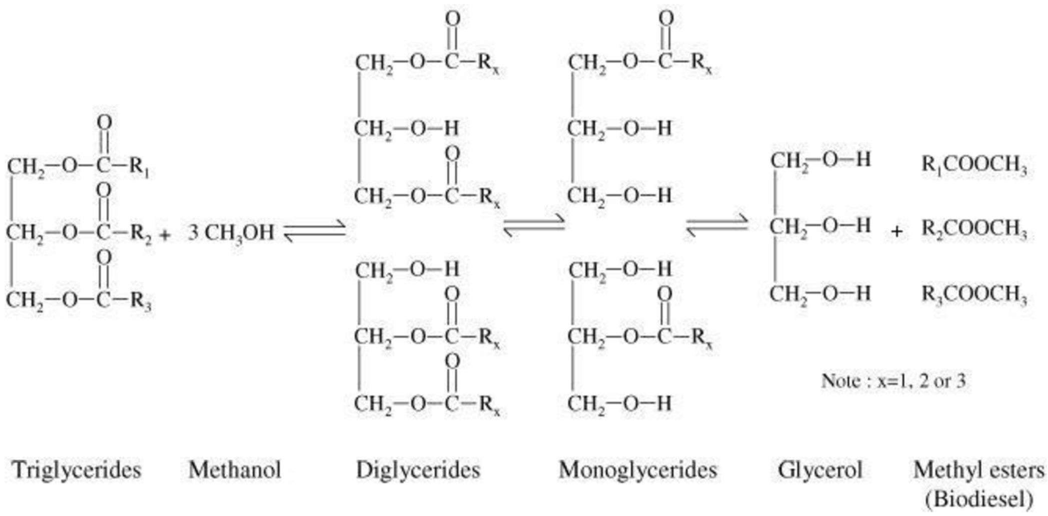

Figure 1. Transesterification of triglycerides

Source: Shereena & Thangaraj (2009)

To what extent the biodiesel production process reaches completion is significantly influenced by the quality of the feedstock oil when biodiesel is manufactured from various types of oils. Biodiesel production methods from spent coffee grounds (SCGs) can be categorised as follows.

1. One-step alkali-catalysed transesterification.
2. Two-step transesterification, which includes:
    - Acid-catalysed pretreatment.
    - Alkali-catalysed transesterification.
3. In situ transesterification.

Figure 2 Schemes for producing biodiesel from spent coffee grounds.

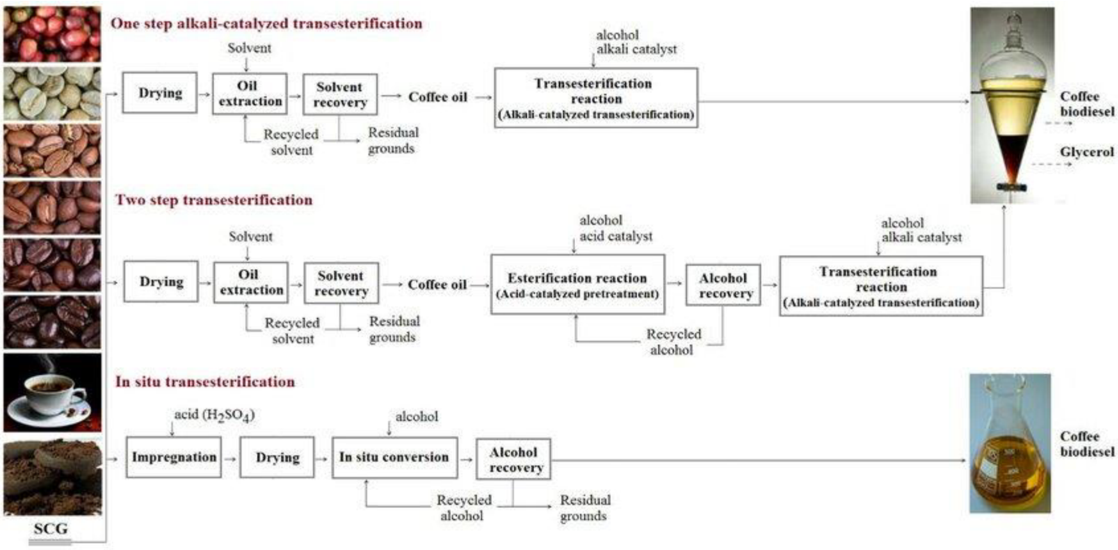

Figure 2. Biodiesel production from spent coffee grounds

Source: Blinová et al. (2017)

Single-Step Alkali-Catalysed Transesterification

The one-step alkali-catalysed transesterification process involves the reaction of alcohol, typically methanol, with triglycerides in the presence of an alkali (base) catalyst. However, this method has a significant limitation—it is highly sensitive to the purity of the reactants, especially regarding water and free fatty acid content. Water can lead to ester saponification under alkaline conditions, and free fatty acids can react with the alkali catalyst, resulting in the formation of soaps and water. Saponification not only depletes the alkali catalyst but also leads to the formation of emulsions, complicating downstream recovery and biodiesel purification. The allowable free fatty acid content for successful one-step alkali-catalysed transesterification typically ranges from 0.5 % FFA which is equivalent to an acid value of 1 mg KOH/g to 1 % FFA corresponding to an acid value of 2 mg KOH/g.

Two-Step Transesterification

When dealing with low-cost oils and fats, such as waste cooking oil and fats or SCGs oil, which often contain substantial amounts of free fatty acids that cannot be converted into biodiesel using an alkali catalyst, a two-step transesterification approach is necessary. In the first step, free fatty acids are initially converted into esters through the reaction of the oil with alcohol, typically methanol, using an acid catalyst (acid-catalysed pretreatment). Acid catalysts are employed when the free fatty acid concentration in the feedstock exceeds 2.0 mg KOH/g of oil (FFA content < 1 % by weight). In the second step (alkali-catalysed transesterification), the remaining triglycerides are transesterified with alcohol using an alkali catalyst to produce methyl esters and glycerol. This method allows for achieving the highest possible conversion rate. Acid catalysts are not practical for converting triglycerides into biodiesel due to their slow reaction rates, but they are effective in converting free fatty acids into esters, making them a suitable choice for pretreatment.

In Situ Transesterification

Biodiesel can also be produced through direct transesterification, known as in situ transesterification. In the wet in situ transesterification process, which integrates oil extraction, esterification, and transesterification into a single step, biodiesel can be directly produced from source materials like SCGs, saving production costs (Park et al. 2016). This approach is not only cost-effective but also environmentally friendly, as it facilitates the recycling of municipal waste and its use as a renewable energy source. In summary, in situ transesterification can yield biodiesel from SCGs that matches the quality of conventionally produced biodiesel through solvent extraction. This process is considerably simpler (Chai et al. 2014).

For in situ transesterification, most studies use an alkali catalyst, such as sodium hydroxide, potassium hydroxide, or sodium methoxide, due to their reduced corrosiveness, shorter reaction times, and lower catalyst usage compared to acidic processes (e.g. H_2SO_4).

In biodiesel production, purification steps are essential to ensure that the product meets stringent international standards and specifications. Various characteristics of biodiesel, such as colour, physical state, acid and iodine values, water content, reaction yield, methyl ester content, density, kinematic viscosity, cetane number, flash point, cloud and pour points, and more, can be evaluated for characterization.

4.3.2.2. Bioethanol Production from SCGs

Bioethanol, a promising biofuel, holds immense potential as a sustainable alternative to traditional gasoline, and one of its most intriguing sources is spent coffee grounds (SCGs). These coffee remnants, typically discarded as waste, can be transformed into a valuable energy resource. The key to this transformation lies in the rich carbohydrate content found within SCGs, which are primarily composed of cellulose and hemicellulose.

The conversion of these carbohydrates into a usable energy source begins with enzymatic hydrolysis. During this process, specialised enzymes break down the complex cellulose and hemicellulose structures within the SCGs into simpler fermentable sugars (Jooste et al. 2013). This crucial step is the gateway to unlocking the energy potential hidden within the coffee grounds.

The next stage of this remarkable bioethanol production journey involves fermentation. The fermentable sugars obtained through enzymatic hydrolysis are now ready to undergo a microbial transformation. Yeast or bacteria are introduced to the mix, where they eagerly consume these sugars and convert them into ethanol, a valuable biofuel (Siahruddin et al. 2023). This fermentation process is akin to the age-old tradition of brewing alcoholic beverages, but here the result is a sustainable, clean-burning fuel.

The conversion of SCGs into bioethanol carries several notable advantages. Primarily, it contributes significantly to the reduction of carbon emissions, a critical factor in the fight against climate change (Karmee 2018). Utilising a waste material that would otherwise be destined for landfills, does not only reduce reliance on fossil fuels but also mitigates the pollution associated with coffee waste disposal. This dual benefit is a significant stride towards a more eco-friendly and sustainable energy landscape.

The process of deriving bioethanol from SCGs showcases the potential for a circular economy, where waste materials are repurposed into valuable resources. Rather than simply discarding SCGs, they can be harnessed as a renewable energy source, aligning with the principles of sustainability and responsible resource management.

4.3.2.3. Biogas Production from SCGs

Spent coffee grounds (SCGs) represent a valuable resource that often goes to waste, but they hold significant potential for sustainable energy production and environmental benefits. By subjecting SCGs to anaerobic digestion, a natural process involving the action of microorganisms in the absence of oxygen, the organic content generated by biogas can be utilised. This biogas, primarily composed of methane and carbon dioxide, holds great promise as a renewable and clean-burning fuel source (Mahmoud et al. 2022).

Four Phases of Biogas Production from SCGs

Phase 1 – Hydrolysis

Complex Biopolymers (proteins, polysaccharides, fats/oils) in the presence of fermentative bacteria become broken-down monomers and oligomers (sugars, amino acids, peptides).

Phase 2 – Acidogenesis

The broken-down monomers and oligomers in the presence of fermentative bacteria become propionate, butyrate, etc. (short-chain volatile organic acids).

Phase 3 – Acetogenesis

The broken-down monomers and oligomers from phase 1, in the presence of fermentative bacteria, can also become acetate or $H_2 + CO_2$. The propionate and butyrate in the presence of Acetogens (H_2 producing or consuming) can also become acetate or $H_2 + CO_2$.

Phase 4 – Methanogenesis

$H_2 + CO_2$ in the presence of CO_2-reducing methanogens becomes $CH_4 + CO_2$. Acetate in the presence of acetoclastic methanogens can also become $CH_4 + CO_2$.

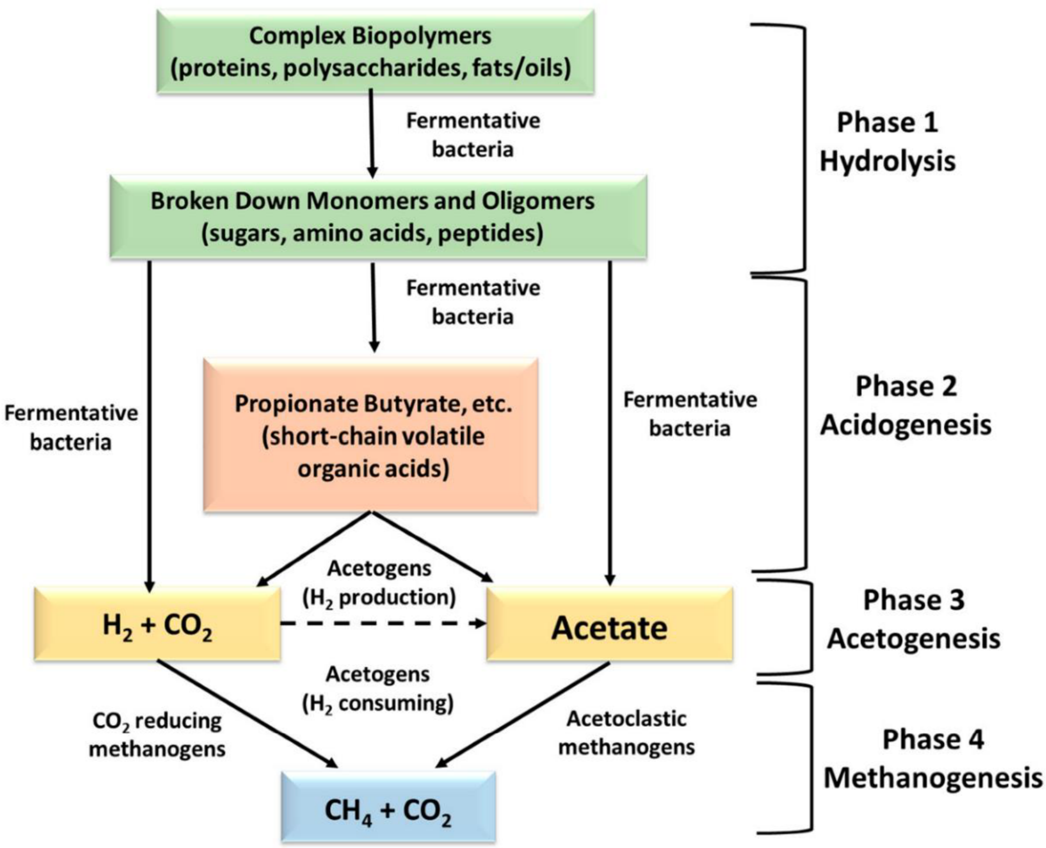

Figure 3. Schematic of four phases of biogas production

Source: Economou et al. (2023)

Anaerobic digestion is a biologically driven process in which microorganisms break down the complex organic compounds present in SCGs. During this decomposition, methane is produced as a byproduct, constituting the main component of the generated biogas (Vanyan et al. 2022). The resulting methane-rich biogas can be harnessed for a multitude of purposes, such as heating applications, electricity generation, and even as a vehicle fuel. This versatility in biogas utilisation makes it a compelling option for replacing traditional fossil fuels and reducing our reliance on non-renewable energy sources.

One of the most significant advantages of biogas production from SCGs is its positive impact on waste management and greenhouse gas mitigation. When SCGs are discarded in landfills, they contribute to the organic load, leading to the emission of methane—a potent greenhouse gas—during their decomposition. By diverting SCGs to anaerobic digestion, we not only prevent the release of methane into the atmosphere but also actively capture and utilise it for productive purposes. This dual benefit not only reduces the organic load in landfills but also helps combat climate change by mitigating greenhouse gas emissions (Czekała et al. 2023).

In essence, the utilisation of SCGs for biogas production exemplifies the circular economy concept, where waste materials are transformed into valuable resources. This approach not only addresses the environmental concerns associated with waste disposal but also promotes sustainable energy production. Furthermore, as the demand for renewable and cleaner energy sources continues to grow, the integration of SCGs into biogas production becomes a compelling solution that aligns with our goals of reducing carbon emissions and transitioning towards a more sustainable and eco-friendly energy landscape.

4.3.3. Physical Methods

Spent coffee grounds (SCGs) possess a remarkable potential for transformation into valuable resources that can significantly contribute to sustainable energy production and waste reduction efforts. One of the most innovative and eco-friendly ways to utilise this potential is by converting SCGs into solid fuels in the form of pellets and briquettes.

The process of turning SCGs into pellets and briquettes involves several crucial steps. First, the SCGs are collected and thoroughly dried to eliminate excess moisture content. This drying process not only makes the material more suitable for fuel production but also extends its shelf life. Once properly dried, the SCGs are subjected to a mechanical compression and densification process. During this step, the dried coffee grounds are compacted into small, uniform pellets, or briquettes.

The resulting pellets and briquettes have numerous applications and benefits. They serve as a renewable and sustainable energy source that can be efficiently burned in various settings, such as stoves, boilers, and power plants. When ignited, these SCGs-based fuels release heat energy that can be used for heating spaces, generating hot water, and even producing electricity through steam turbines. This versatile nature of SCGs-based fuels makes them a valuable resource in a wide range of industries, from residential heating to large-scale energy generation (Colantoni et al. 2021; Atabani 2023).

The advantages of using SCGs-based pellets and briquettes are multifaceted. Firstly, they offer a sustainable alternative to traditional fossil fuels, reducing reliance on non-renewable energy sources like coal, oil, and natural gas. By doing so, they contribute to a substantial reduction in greenhouse gas emissions, helping combat climate change. The utilisation of SCGs in this manner reduces the overall demand for fossil fuels, which can have a positive impact on energy security and price stability.

Figure 4. Production of pellets from SCGs

Source : Colantoni et al. (2021)

4.4. Potential of SCGs Utilisation for Bioenergy Purposes

4.4.1. Case Studies of Successful SCGs Valorisation Projects: Coffee Waste as a Bioenergy Source

Kaffe Bueno, a visionary company established in 2016 in Copenhagen, has used the potential of coffee waste to utilise bioenergy production. This transformation has not only redefined the way we perceive waste but has also significantly contributed to the pursuit of sustainable energy solutions.

Historically, coffee waste has been relegated to the category of trash, a by-product that ends up in landfills, contributing to environmental problems. As the world began to fight with the consequences of unsustainable practices and the urgent need to transition to renewable energy sources, companies like Kaffe Bueno recognised an opportunity within this insignificant waste stream. They embarked on a journey to transform discarded coffee grounds and waste into a valuable and sustainable energy resource.

Kaffe Bueno's bioenergy production has been nothing short of revolutionary. They have effectively closed the loop on coffee consumption by adopting a circular economy approach, ensuring that every part of the coffee-making process contributes to a sustainable energy future. In this quest, coffee waste is no longer a liability but rather an asset.

The process begins at the coffee shop, where used coffee grounds are collected and carefully sorted. Kaffe Bueno has established partnerships with local coffee shops and chains, encouraging them to participate in this eco-friendly initiative by providing designated containers for waste coffee grounds. This approach not only reduces waste disposal costs for these businesses but also aligns with their commitment to environmental sustainability.

Once collected, the coffee waste is transported to Kaffe Bueno's state-of-the-art bioenergy facility, where the process begins. Through an innovative and environmentally friendly process, the coffee grounds are converted into biofuel and biogas, two invaluable resources in the transition towards sustainable energy. This conversion is achieved through a combination of anaerobic digestion and pyrolysis, methods that maximise energy extraction while minimising environmental impact (Serrano et al. 2018).

Anaerobic digestion involves breaking down the organic matter in coffee waste using bacteria in the absence of oxygen. This process results in the production of biogas, a renewable energy source that can be used for electricity generation and heating. Biogas is a clean and versatile energy source, emitting significantly fewer greenhouse gases compared to traditional fossil fuels, making it a crucial component of the sustainable energy mix (Vanyan et al. 2022).

Simultaneously, pyrolysis, another essential step in Kaffe Bueno's bioenergy production process, transforms the remaining coffee waste into biofuel. Pyrolysis involves heating the organic material at high temperatures in the absence of oxygen, causing it to break down into bio-oil, biochar, and syngas. Bio-oil can be further processed to produce biodiesel, a renewable and environmentally friendly alternative to traditional diesel fuel. Biochar has applications in agriculture as a soil conditioner, enhancing crop growth and carbon sequestration. Syngas, a mixture of hydrogen and carbon monoxide, can be utilised as a fuel in various industrial processes (AlMallahi et al. 2023).

The synergy between these two processes, anaerobic digestion, and pyrolysis, ensures that every component of the coffee waste is utilised to its full potential, leaving virtually nothing to waste. Kaffe Bueno's commitment to sustainability extends beyond energy production; it also encompasses responsible waste management and resource optimisation.

The benefits of Kaffe Bueno's bioenergy venture extend far beyond the confines of their production facility. Their innovative approach to coffee waste management has created a ripple effect in local communities and coffee-producing regions. They have encouraged greater participation in sustainable practices and raised awareness about the potential of waste-to-energy initiatives by incentivising the collection of coffee waste.

Kaffe Bueno's bioenergy production aligns with broader environmental goals. The reduction of organic waste in landfills reduces methane emissions, a potent greenhouse gas that contributes to climate change. This reduction in waste disposal also eases the burden on municipal waste management systems, leading to cost savings and a cleaner urban environment.

In addition to its environmental benefits, Kaffe Bueno's bioenergy venture has brought economic opportunities to the regions where it operates. They have created jobs and stimulated economic growth by partnering with local coffee shops and employing individuals in waste collection and processing (Serrano et al. 2018). This localised approach not only strengthens communities but also promotes a sense of responsibility towards the environment.

The story of Kaffe Bueno's journey into coffee waste bioenergy is emblematic of the broader shift towards circular economies and sustainable energy solutions. It highlights the transformative potential of innovation and the power of collaboration between businesses, communities, and individuals in addressing pressing environmental challenges.

As the global demand for sustainable energy sources continues to grow, Kaffe Bueno's efforts serve as a source of hope and inspiration. They have shown that even seemingly wasteful streams can be transformed into valuable resources that contribute to a cleaner, greener future. This is a testament to the importance of reimagining the approach to waste and recognising that, in the quest for sustainability, every coffee cup has the potential to power a brighter tomorrow.

Kaffe Bueno's success story is a reminder that sustainability is not a distant goal but an achievable reality when driven by innovation, commitment, and a vision for a better world. Their bioenergy venture serves as a blueprint for businesses across industries, demonstrating that with the right mindset and practices, waste can become an asset and sustainability can be integrated into every aspect of our lives.

Kaffe Bueno's venture into coffee waste bioenergy represents a remarkable shift in how people perceive and utilise waste materials. Through their innovative approach to waste collection and processing, they have not only reduced the environmental impact of coffee consumption but also significantly contributed to the sustainable energy landscape. Their circular economy model, which maximises resource utilisation and minimises waste, sets a precedent for businesses worldwide to follow.

4.4.2. The Energy Conversion Efficiencies and Environmental Impacts Associated with SCGs Bioenergy Production

Energy conversion efficiency is a critical factor in determining the feasibility and sustainability of bioenergy production processes. In the context of spent coffee grounds (SCGs), this efficiency relates to how effectively the energy contained in coffee waste is transformed into usable energy forms like heat, electricity, or biofuels. Several conversion technologies are employed to harness this energy, including anaerobic digestion, pyrolysis, and combustion.

Anaerobic digestion is a process that takes place in an oxygen-free environment, where microorganisms decompose SCGs and produce biogas, primarily composed of methane and carbon dioxide. This biogas can then be used to generate electricity and heat. The efficiency achieved through anaerobic digestion depends on several factors, including the quality and composition of the SCGs feedstock, process conditions, and system design. Proper optimisation and management can lead to high conversion efficiencies, making anaerobic digestion an environmentally friendly option for SCGs bioenergy production (Czekała et al. 2023).

Pyrolysis, on the other hand, involves subjecting SCGs to high temperatures in the absence of oxygen, resulting in the production of biochar, liquid bio-oil, and non-condensable gases. The efficiency of pyrolysis processes can vary depending on factors such as feedstock properties, temperature, residence time, and reactor design. The bio-oil and biochar produced can be further utilised as renewable fuels or soil amendments, contributing to more sustainable energy systems (AlMallahi et al. 2023).

Although combustion is another viable option for SCG bioenergy production, it is crucial to ensure that the process is efficient and minimises environmental impacts. Combustion typically involves burning SCGs to generate heat or steam for various industrial processes or electricity generation. Efficient combustion systems aim to maximise energy conversion by optimising the combustion process and reducing emissions through technologies like flue gas treatment systems. This helps minimise environmental impacts, including greenhouse gas emissions and air pollution associated with SCGs bioenergy production (Colantoni et al. 2021).

In addition to energy conversion efficiencies, understanding the environmental impacts of SCGs bioenergy production is essential for sustainable development. Utilising SCGs as a bioenergy feedstock offers several environmental benefits. Firstly, it helps reduce waste generation by diverting SCGs from landfills and preventing their decomposition, which could contribute to methane emissions. Secondly, by replacing fossil fuels, SCGs bioenergy production reduces greenhouse gas emissions, mitigating climate change. Moreover, using SCGs as a renewable energy source can potentially reduce reliance on non-renewable resources and support the transition towards a more sustainable and circular economy (Leder et al. 2020).

Like any bioenergy production process, there are potential environmental challenges associated with SCGs bioenergy. These include issues such as land use, water consumption, and potential ecosystem impacts from cultivating coffee crops. Therefore, it is essential to consider a comprehensive approach when evaluating the sustainability of SCGs bioenergy production, considering factors such as feedstock sourcing, production practices, and waste management strategies.

4.4.3. The Economic Feasibility and Market Potential of SCGs-based Bioenergy Systems

Analysing the economic feasibility and market potential of spent coffee grounds (SCGs)-based bioenergy systems is crucial to understanding the viability and attractiveness of such ventures.

The economic feasibility of SCGs-based bioenergy systems relies on several key factors. The availability and accessibility of SCGs as feedstock play a vital role. Coffee consumption is widespread globally, resulting in significant volumes of SCGs being generated (Forcina et al. 2023). Establishing a reliable supply chain and securing enough SCGs at a reasonable cost can be a challenge, particularly in regions where coffee production and consumption are lower (Johnson et al. 2022).

Another aspect of economic feasibility lies in the efficiency of energy conversion technologies employed for SCGs bioenergy production (Czekała et al. 2023). Investing in efficient and cost-effective conversion processes is essential to ensure adequate energy yields and maximize economic returns. Technologies such as anaerobic digestion, pyrolysis, and combustion should be evaluated based on their capital costs, operating expenses, and maintenance requirements.

The revenue potentials of SCGs-based bioenergy systems must be considered. This includes exploring potential markets for the energy products generated, such as electricity, heat, or biofuels (Yeoh & Ng 2022). Identifying suitable end-users or establishing partnerships with existing energy providers can facilitate the commercialisation and sale of the energy produced. Additionally, by-products like biochar or other value-added materials derived from SCGs can create revenue streams in sectors such as agriculture or cosmetics, further enhancing the economic viability of the system.

Government policies and incentives can significantly impact the economic feasibility of SCGs-based bioenergy projects. Supportive regulations, subsidies, tax incentives, or renewable energy targets can encourage investments and create a favourable market environment (Johnson et al. 2022). Understanding the local policy landscape and engaging with relevant stakeholders can help determine the financial viability of such ventures.

When assessing market potential, it is important to consider the growing global interest in renewable energy sources and sustainable practices. The increasing focus on reducing greenhouse gas emissions and transitioning towards a low-carbon economy creates opportunities for SCGs-based bioenergy systems (Banu et al. 2021). Coffee-producing countries, where SCGs availability is abundant, may offer favourable markets for such ventures due to their inherent connection to the coffee industry.

The rising demand for renewable energy in various sectors, including residential, commercial, and industrial, presents a market opportunity for SCGs-based bioenergy. By positioning SCGs bioenergy as a sustainable and cost-effective alternative to conventional energy sources, market penetration can be achieved.

It is essential to assess market saturation and competition from other bioenergy feedstocks, such as agricultural residues or dedicated energy crops. Understanding the market dynamics, pricing structures, and consumer preferences will enable businesses to tailor their offerings effectively and seize potential market niches.

4.4.4. Challenges and Future Prospects

Scaling up the valorisation of SCGs (spent coffee grounds) valorisation for bioenergy purposes comes with several significant challenges that need to be addressed. These challenges revolve around three key areas: feedstock availability, collection logistics, and technology optimisation (Yeoh & Ng 2022).

Firstly, feedstock availability poses a challenge when scaling up SCGs valorisation. While there is an abundant supply of spent coffee grounds generated daily from households, coffee shops, and industries, ensuring a consistent and reliable feedstock supply becomes crucial. A diverse range of stakeholders, including coffee shops, waste management companies, and local governments, must be involved in establishing establish efficient collection and delivery mechanisms. Furthermore, developing strategic partnerships with coffee manufacturers or cooperatives can help secure a steady supply of high-quality SCGs.

Secondly, collection logistics play a vital role in scaling up SCGs valorisation. Efficient collection systems must be established to ensure the timely and cost-effective transportation of SCGs from the point of generation to the processing facilities. It involves designing collection routes, optimising collection schedules, and selecting the appropriate vehicles to handle the volume and characteristics of SCGs. Collaboration with waste management companies or the establishment of dedicated collection centres can streamline the logistics process and ensure the smooth flow of SCGs to valorisation plants (Yeoh & Ng 2022).

Lastly, technology optimization is crucial to effectively scale up SCGs valorisation for bioenergy purposes. Existing technologies, such as anaerobic digestion, pyrolysis, or composting, need to be evaluated and improved to maximise the energy recovery potential of SCGs. This includes optimising process parameters, improving conversion efficiencies, and exploring innovative techniques such as hydrothermal carbonisation or enzymatic treatments (Sugebo 2022). Investing in research and development initiatives, collaborating with academic institutions, and taking advantage of advancements in biotechnology can aid in the development of efficient and sustainable methods for the valorisation of SCGs.

4.4.5. The Potential Integration of SCGs Valorisation with Other Waste-to-Energy Systems

The integration of spent coffee grounds (SCGs) valorisation with other waste-to-energy systems has significant potential in terms of both environmental and economic benefits. This approach not only helps to reduce waste disposal but also utilises the energy content of SCGs for further use.

One of the potential integration options is co-digestion with other organic waste in anaerobic digesters. Anaerobic digestion is a process in which organic materials are broken down by microorganisms in the absence of oxygen, resulting in the production of biogas. SCGs can be added to the feedstock mix in anaerobic digesters, enhancing the production of biogas and the overall energy output (Orfanoudaki et al. 2020; Kim et al. 2024). This integration reduces the dependence on fossil fuels and provides a sustainable solution by utilising SCGs as a renewable resource.

Another option for integration is co-firing SCGs with biomass or coal in thermal power plants. SCGs have a high calorific value and can be used as a supplementary fuel. Co-firing SCGs reduces the greenhouse gas emissions associated with traditional fossil fuel combustion and can contribute to more sustainable and cleaner energy generation (Lachman et al. 2022).

SCGs can also be used in the production of biofuels. Through various biochemical and thermochemical processes, SCGs can be converted into biodiesel, bioethanol, or other biofuels. Integrating SCGs valorisation into existing biofuel production facilities can increase their feedstock availability and diversify the range of resources used, making biofuels more sustainable and environmentally friendly (Kafková et al. 2023; Czekała et al. 2023).

In terms of economic benefits, integrating SCGs valuation with other waste-to-energy systems can create new revenue streams and business opportunities.

SCGs, which are regarded as waste, can become a valuable resource that generates income through the production of energy or bio-based products. Additionally, this integration can also contribute to job creation and stimulate local economies (Banu et al. 2021).

It is important to consider the potential challenges associated with the integration of SCGs valuation with other waste-to-energy systems. These challenges include ensuring the consistent supply of SCGs, developing efficient collection and transportation methods, and addressing any technological or operational constraints in the existing waste-to-energy systems.

4.4.6. Emerging Trends and Advancements in SCGs Valorisation Technologies

SCGs can be used as feedstock for biofuel production. Researchers are investigating different methods, such as pyrolysis, hydrothermal liquefaction, and anaerobic digestion, to convert SCGs into biofuels like biodiesel and bioethanol. These processes help reduce waste and generate renewable energy.

SCGs contain bioactive compounds like antioxidants and polyphenols, which have potential health benefits. Researchers are developing efficient extraction techniques to obtain these compounds from SCGs (Bouhzam et al. 2023). These extracts can be used in various industries, including pharmaceuticals, cosmetics, and food additives.

SCGs can be processed and used as an ingredient in animal feed due to their rich nutritional content. It is being explored as a potential alternative to conventional feed sources, reducing the environmental impact of livestock farming (Martin et al. 2023). Additionally, SCGs can also be converted into organic fertilisers, enriching soil quality and promoting sustainability (Bomfim et al. 2022).

SCGs provide an ideal substrate for mushroom cultivation. Oyster mushrooms, for example, can be grown using SCGs as a nutrient source. This not only helps in utilising SCGs but also produces a valuable food resource with high nutritional value (Chai et al. 2021).

SCGs can be incorporated into composite materials, such as bioplastics and construction materials, to enhance their properties and reduce their environmental impact. Researchers are investigating the potential of blending SCGs with polymers to create eco-friendly materials with improved strength and durability (Masssijaya et al. 2023).

Recently, scientists have explored using SCGs-derived activated carbon as an electrode material in energy storage devices such as supercapacitors and batteries. This research aims to develop sustainable and cost-effective energy storage solutions by repurposing waste SCGs (Pagett et al. 2022).

These emerging trends in SCGs valuation technology highlight the potential of transforming this waste product into valuable resources. By implementing these advancements, we can reduce waste generation, promote sustainability, and find innovative solutions for a more environmentally friendly future.

5. Recommendations

5.1. Techno-Economic Analysis

A comprehensive techno-economic analysis is crucial to assess the commercial viability of spent coffee grounds (SCGs) valorisation as a bioenergy production strategy. This analysis involves evaluating various aspects that influence the feasibility and sustainability of the valorisation process.

One key aspect of the techno-economic analysis is evaluating the cost-effectiveness of the SCGs valorisation process. This includes assessing the capital costs involved in setting up the valorisation facilities, operational costs, maintenance expenses, and the overall cost per unit of bioenergy produced. Understanding the cost structure is essential for determining the economic viability of the process.

Another critical component of the analysis is estimating the revenue generation potential of SCGs valorisation. This involves identifying potential revenue streams from selling bioenergy products, such as biofuels or electricity, as well as any valuable by-products obtained during the valorisation process. Calculating the potential revenue helps determine the profitability of the valorisation project.

In addition to economic considerations, the techno-economic analysis should also include an assessment of the environmental impact of SCGs valorisation. Conducting a lifecycle assessment helps in quantifying the environmental footprint of the valorisation process, including greenhouse gas emissions, energy consumption, and waste generation. Understanding the environmental implications is essential for ensuring the sustainability of bioenergy production from SCGs.

Evaluating the risks associated with SCGs valorisation is also important in the techno-economic analysis. This involves identifying potential risks that could impact the project's financial performance or environmental sustainability. Assessing risks allows for the development of mitigation strategies to ensure the success of the valorisation project.

It is important to perform sensitivity analysis as part of the techno-economic evaluation. This analysis helps in understanding how changes in key parameters, such as feedstock availability, energy prices, or regulatory policies, can impact the financial viability of the SCGs valorisation process. By conducting sensitivity analysis, stakeholders can make informed decisions and plan for potential uncertainties.

5.2. Sustainability and Environmental Impact Assessment

Future studies in the field of spent coffee grounds (SCGs) valorisation should concentrate on a thorough evaluation of sustainability aspects, carbon footprint, potential emissions, and the overall environmental impact of the valorisation process. Researchers can gain valuable insights into the environmental implications of utilising SCGs for bioenergy production by conducting in-depth research in these areas.

One crucial aspect that future studies should focus on is conducting a comprehensive sustainability assessment of SCGs valorisation. This involves analysing the environmental, social, and economic sustainability of the valorisation process. Researchers can determine the overall sustainability of bioenergy production from SCGs by evaluating factors such as resource efficiency, waste reduction, and societal benefits.

Understanding the carbon footprint of SCGs valorisation is essential for assessing its environmental impact. Future studies should aim to quantify the greenhouse gas emissions associated with the valorisation process, including carbon dioxide, methane, and nitrous oxide emissions. Researchers can identify opportunities to reduce emissions and enhance the environmental performance of bioenergy production from SCGs by measuring and analysing the carbon footprint.

Assessing the potential emissions from SCGs valorisation is another critical area for future studies. This includes studying air pollutants, such as particulate matter, volatile organic compounds, and nitrogen oxides, that may be generated during the valorisation process. Researchers can develop strategies to mitigate potential environmental impacts and ensure compliance with regulations by characterising emissions.

Conducting a comprehensive life cycle assessment (LCA) of SCGs valorisation is essential for understanding the overall environmental impact of the bioenergy production process. Researchers can identify hotspots and implement measures to minimise environmental impacts by evaluating the environmental burdens associated with each stage of the valorisation process, from feedstock collection to energy generation.

5.3. Utilisation of by-products

Further research is essential to delve deeper into the potential applications of the by-products derived from the valorisation process of spent coffee grounds. By-products such as char, tar, and gas offer promising opportunities for energy generation and serve as valuable industrial feedstocks, presenting a sustainable approach towards maximising the utility of SCGs.

One area that warrants exploration is the potential applications of char obtained during the valorisation process. Char, a carbon-rich material produced from the pyrolysis or gasification of SCGs, can be utilised as a renewable fuel source for energy generation. Further studies could investigate the energy content, combustion properties, and suitability of char for use in various energy conversion technologies, such as boilers, gasifiers, or even as a precursor for activated carbon production.

Another aspect that requires attention is the valorisation of tar, a liquid by-product produced during the pyrolysis of SCGs. Tars contain valuable organic compounds that can be upgraded and converted into higher-value products, such as biofuels or chemicals. Future research could focus on developing efficient tar upgrading processes, exploring catalytic conversion technologies, and assessing the economic feasibility of utilizing tar as a renewable feedstock for the production of value-added products.

The gas generated during the valorisation of SCGs represents a valuable resource that can be harnessed for energy production or as a feedstock for industrial applications. Studies could investigate the composition of the gas stream, optimise gas cleaning and conditioning processes, and explore its potential use in combined heat and power (CHP) systems, syngas production, or as a chemical feedstock for hydrogen or methane production.

5.4. Optimisation of Process Parameters

Examining the influence of temperature on the valorisation process is crucial. Research efforts can be directed towards determining the temperature range that facilitates the efficient conversion of SCGs into bioenergy products, such as syngas, bio-oil, or biogas. Understanding the kinetics of thermal decomposition and identifying the temperature thresholds for desirable product formation will aid in optimising bioenergy production.

Investigating the residence time during the valorisation process is essential for achieving optimal bioenergy yields. Researchers can explore the correlation between residence time and product distribution to identify the duration required for complete decomposition of SCGs and the maximisation of bioenergy output.

Assessing the impact of pressure on the valorisation process is another critical aspect. Studies can delve into the effects of varying pressure conditions on the composition and quality of the bioenergy products obtained from SCGs. Understanding the role of pressure in enhancing reaction rates and product selectivity will contribute to optimising bioenergy production efficiency.

Exploring suitable catalysts for the valorisation of SCGs is paramount. Research endeavours should aim to identify catalyst materials, composition, and active sites that promote the conversion of SCGs into high-value bioenergy products. Investigating catalyst stability, reusability, and catalytic mechanisms will enable the development of efficient valorisation systems.

5.5. Integration with Existing Bioenergy Systems

Researching the integration of spent coffee grounds (SCGs) valorisation with current bioenergy systems is crucial for elucidating the feasibility and benefits of incorporating SCGs-derived bioenergy into the existing energy infrastructure.

Investigating how SCGs valorisation can complement and enhance current bioenergy systems is a key research focus. By analysing the compatibility between SCGs-derived bioenergy production processes and existing energy infrastructure, researchers can identify opportunities for synergy and resource optimisation. Understanding how SCGs can be effectively integrated to diversify feedstock sources and improve overall energy output efficiency is essential.

Research efforts can delve into conducting techno-economic assessments to evaluate the cost-effectiveness and commercial viability of integrating SCGs valorisation with current bioenergy systems. By quantifying the economic benefits, assessing the environmental impact, and analysing the scalability of the integrated system, researchers can provide valuable insights for policymakers, investors, and stakeholders.

Exploring the technical compatibility of SCGs valorisation with existing bioenergy infrastructure is essential for seamless integration. Research can focus on analysing the infrastructure requirements, processing capabilities, and logistical considerations involved in incorporating SCGs-derived bioenergy production units within the current energy landscape. Identifying any necessary modifications or adaptations to infrastructure components can facilitate the smooth integration of SCGs valorisation technologies.

Research can also investigate optimisation strategies for maximising the benefits of integrating SCGs valorisation with current bioenergy systems. This may involve developing hybrid energy systems that leverage the strengths of both SCGs-derived bioenergy and traditional bioenergy sources, as well as implementing smart grid technologies to enhance energy distribution and utilisation efficiency.

6. Conclusions

This review highlights the potential for the valorisation of spent coffee grounds (SCGs) as a renewable biomass resource for the production of bioenergy. The study provides a comprehensive understanding of the valorisation processes, technologies, and economic and environmental considerations associated with SCGs utilisation. It has been demonstrated that SCGs possess favourable physicochemical properties, making them suitable for various valorisation pathways such as thermal conversion, biochemical conversion, and chemical extraction.

The review also showcases successful case studies and examples of SCGs valorisation projects, which further validate the feasibility and practicality of utilising SCGs for bioenergy generation. The different bioenergy products derived from SCGs, including biogas and solid fuels, offer diverse options for energy conversion with varying efficiencies and environmental impacts.

However, several challenges hinder the scaling up of SCGs valorisation. These challenges include feedstock availability, collection logistics, and the optimisation of technologies. Overcoming these challenges will require strategic collaborations, innovative approaches, and continued research and development efforts.

Looking towards the future, the integration of SCGs valorisation with other waste-to-energy systems holds immense potential. This would not only enhance the overall efficiency of waste management but also contribute to the circular economy concept. Advancements in SCGs valorisation technology, coupled with emerging trends and market opportunities, further strengthen the prospects of SCGs as a valuable biomass resource for sustainable bioenergy production.

This review underscores the promising potential of spent coffee grounds as a renewable and abundant source of biomass for bioenergy purposes. Encouraging further research, collaborations, and implementation of SCGs valorisation strategies will pave the way for a more sustainable and greener energy future.

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