Assessing the Potential of Spent Coffee Grounds Valorization as a Renewable Resource for Sustainable Value-Added Products: A Mini Review

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ABSTRACT

Coffee is a popular beverage consumed worldwide, resulting in vast amounts of spent coffee grounds as waste. Coffee waste is amongst the major environmental concerns due to its high organic content and significant carbon emissions. Despite the extensive research on the subject, a comprehensive analysis of the current state of research on coffee waste valorization is still needed. This review paper aims to provide such an analysis, focusing on different valorization approaches such as composting, pyrolysis, and bioconversion. The efficiency and environmental impact of each approach will be evaluated, along with the potential applications of resulting products such as biofuels, bioplastics, and fertilizers. Additionally, the economic feasibility and scalability of coffee waste valorization technologies will be explored, including their potential for implementation in various contexts. By consolidating existing knowledge and identifying research gaps, this review paper aims to contribute to the development of more sustainable and efficient strategies for coffee waste management and valorization.

Introduction

The increase in greenhouse gas emissions is a result of economic development and human behavior. The levels of carbon dioxide have risen by 40% since pre-industrial times, mainly due to the emission from fossil fuels and land use practices, including agriculture. The agricultural industry is among the leading sources of greenhouse gas emissions worldwide, accounting for at least 20% of global emissions, with Asia accounting for over 44% of agricultural sector emissions (Prastiyo & Hardyastuti, 2020). One potential solution to balance the emissions of fossil fuels is the use of biomass, which refers to plant-based sources or biologically generated substances. Coffee is one of the most widely traded and consumed brewed beverages in the world, making it the second-largest biomass commodity after petroleum (Mukherjee et al., 2021). According to the International Coffee Organization, the annual coffee production has increased from 140 to 152 million 60-kilogram bags since 2010. However, the global coffee industry generates substantial amounts of agricultural waste and by-products, with nearly 90% of the coffee berry weight being discarded as waste during the manufacturing process. Spent coffee grounds (SCG) represent a significant portion of this waste stream (Zengin et al., 2020).

SCG Origin and Composition

Spent coffee ground or SCG is a biomass derived from plant matter as a result of photosynthesis, a process in which the sun's energy transforms water and CO_2 into organic matter (Demirbaş & Arin, 2002). In terms of shape and physical properties, biomass is a very flexible feedstock. It can be moist or dry, dense, or fluffy, high, or low in ash, tiny or big in form, homogeneous or inhomogeneous, and so on. SCG is a by-product of solubilized instant coffee production, which involves steaming or heating roasted coffee beans to make a coffee extract for consumption (Janissen & Huynh, 2018). Improper disposal of SCG with high organic content in landfills presents potential toxic problems and environmental concerns due to the release of high levels of nitrogen oxides (NOx) and carbon monoxide (CO). Proper waste management of SCG can recover and utilize 4.40 - 4.65 million tons of SCG waste as usable feedstock for a number of purposes (Lee et al., 2021). The chemical composition of SCG is influenced by several factors, such as the kind of coffee plant, age, location of the plant, and the climate and soil conditions of the region (Matrapazi & Zabaniotou, 2020). The composition of SCG can be represented in several way, by the elements or by its chemical components which is shown in detail in Table 1.

Table1. Chemical components of SCG in different applications

Application	**Location /Coffee type**	**C**	**H**	**N**	**O**	**S**	**Reference**
		%					
Solid biofuel production	Malaysia/ Arabica	47.63	6.57	2.93	45.80	-	(Lee et al., 2021)
hydro char production	UK. 80% Arabica and 20% Robusta	53.94	7.06	2.29	36.72	-	(Afolabi et al., 2020)
Biochar production	Canada	50 ± 0.01	6.7	2.5	39.0	0.9	(Mukherjee et al., 2021)
Bio-oil Production	United Arab Emirates	48.9	6.80	2.88	41.2	0.250	(AlMallahi et al., 2023)
Application	**Location / Coffee type**	**Cellulose**	**Hemicellulose**	**Extractives**	**Lignin**		**Reference**
		% w/w					
Production of antioxidant compounds and biobutanol	Spain	16.3	27.7	12.4	-		(López-Linares et al., 2021a)
Solid biofuel production	Malaysia/ Arabica	16.78	48.22	19.42	34.94		(Lee et al., 2021)
Biobutanol production	Spain	16.3	27.7	12.4	-		(López-Linares et al., 2021b)
Bio-oil and Continuous Hydrothermal Liquefaction Bio-oil production	South Africa	19.26	34.97	-	10.54		(Jansen van Rensburg & Schabort, 2018)

Products and Applications

Residues are no longer seen as trash by businesses, but as raw materials for alternative applications and operations. Every year, approximately 10 million tons of coffee are consumed worldwide, resulting in nearly as many tons of coffee by-products. In reality, 100 kg of powdered coffee can yield approximately 90 kg of SCG (kamgang Nzekoue et al., 2020). As a result, various uses for SCG valorization have been suggested, such as fertilizer, sorbent for metal ion removal, and feedstock for biofuel production. Furthermore, SCG have demonstrated useful ingredient promise in the food, pharmaceutical, and cosmetic sectors. Various research have shown that SCG are an excellent source of beneficial substances such as soluble dietary fiber, protein, polyphenols, and caffeine (kamgang Nzekoue et al., 2020).

Solid Phase: Biochar

In a low presence of oxygen, converted biomass in a controlled pyrolysis process called Biochar. Due to the functional chemical groups that are on its surface, it can interact with organic and inorganic compounds. Additionally, biochar is high in carbon content, porosity, and fine granulation. Carbonaceous Biochar can be prepared from spent coffee grounds (SCGs) using the pyrolysis process. It is used in several applications, includes:

Activated Carbon

It is carbonized material with a high degree of surface area and porosity. Activated carbon contains functional groups such as lactone, carbonyl, phenol, and carboxyl. High carbon and oxygen adsorption, strong abrasion resistance, microscopic pore diameters and high thermal strength result in a higher exposed surface and hence better adsorption capacity of activated carbon. Due to its ability to remove impurities and contaminants from liquids and gases, activated carbon plays an important role in the remittance of the environment. (Heidarinejad et al., 2020). It can be used in:

Liquid Phase: Bio-Oil

It is a dark-colored liquid and chemically complex mixture acids, alcohols, and aldehydes are a few examples of the 300 compounds of their composition (Kazawadi et al., 2021). There are several applications that used the bio-oil, for example:

Gas Phase: Biogas

It is composed mostly of 35% carbon dioxide and 65% methane with tiny quantities of hydrogen sulphide, ammonia, water vapor, nitrogen, and hydrogen (Vanyan et al., 2022). It has several benefits (Rafiee et al., 2021) includes its environmental protection through inorganic fertilizer substitution and reduction of air and water pollution. It has wide applications includes:

Valorization Processes

As previously stated, SCG has a high concentration of organic substances including cellulose, proteins, tannins, fibers, carbohydrates, caffeine, etc. (Atabani et al., 2019). Aside from about 700 volatile chemicals that remain insoluble and unextractable in SCG throughout the thermal water extraction process and may thus be valorized in various ways. These components have been demonstrated to have organic content, excellent physical qualities, energy content, high quality that must be utilized appropriately (Atabani et al., 2019). In general, biological and chemical mechanisms may be utilized to transform biomass into products with high added value.

Table 2. The specifications of various valorization process

Polarization process	Products	Temperature range (°C)	Effective parameter	Reference
Pyrolysis	Biochar, bio-oil	300-700	Reaction temperature	(Sieradzka et al., 2022)
Anaerobic digestion	Biogas	35-60	Carbon-Nitrogen ratio	(Sumantri et al., 2022)
Chemical activation	Activated carbon	400 to 900	Chemical agent	(Anto et al., 2021)
Physical activation	Activated carbon	800-1100	Reaction Temperature	(Abuelnoor et al., 2021)
Hydrothermal carbonization	Biochar	180-250	Reaction temperature	(Ischia & Fiori, 2021)
Gasification	Biochar	above 700	Gasification agent	(Kibret et al., 2021)

Biological Processes

Biological treatment techniques are a potential technology that has various advantages such as employing mild conditions, not requiring any set-up for the reactions, and being a chemical-free procedure. In comparison to thermal, physical, or chemical approaches, biological treatment operations are an economically feasible option for increasing fermentation rates to create native lignin (Singh, 2021). However, Slow reaction rates, a limited range of reaction conditions, and poor recyclability of biological treatment catalysts are the disadvantages of this type of treatment (Singh, 2021).

Anaerobic Digestion

It is one of the most common biological processes. It is an efficient process for recycling diverse organic waste streams into biogas, as well as slurry (digestate) that may be used as a biofertilizer (Mahmoud et al., 2022). There are 2 types: mesophilic and thermophilic. The AD process has various advantages, such as increased generation of inorganic nutrients, humus as fertilizer, and biomethane which can result in significant environmental and economic benefits (Handoyo & Kumoro, 2021). For anaerobic digestion, the carbon-nitrogen ratio is normally between 25 and 30. A lack of nitrogen results in a restricted microbial population, while an excess of nitrogen results in the formation of ammonia and a longer period required for carbon breakdown. Furthermore, because the pH of the system influences the activity of the bacteria groups engaged in each phase of AD, the performance of the AD is strongly dependent on pH. The available carbon provides energy to the microorganisms, while nitrogen limits the amount of germs (Sumantri et al., 2022).

Thermochemical Process (Pyrolysis, Gasification, and Hydrothermal Carbonization)

The chemical pathway with great efficiency is gaining favor as the trend toward unified management and consumption continues (Yu et al., 2022).

Pyrolysis

Pyrolysis is a thermal breakdown of raw materials in a neutral environment in a furnace under N_2 purge to eliminate volatile and non-carbon species such as nitrogen, oxygen, and hydrogen (Fahmy et al., 2020). The pyrolysis process is characterized primarily by solid fuel thermal decomposition, which includes the breakdown of carbon-carbon bonds and the creation of carbon-oxygen bonds. The four primary types of slow (traditional), intermediate, fast, and most recently, flash pyrolysis variate depending on the circumstances surrounding the procedure. The working environment has an impact on their product compositions. Moreover, the temperature, heating rate, nitrogen gas flow rate, and residence duration are the important factors in this process (Reza et al., 2020). The pyrolysis method has several advantages, including lower pollution and the ability to reuse all byproducts (Uddin et al., 2018). The difference between them in term of temperature and other parameters are shown in Table. Several various reactions occur during the pyrolysis process, in which substances initially contained in the raw material, as well as intermediary substances and end products, are involved (Kaczor et al., 2020). Table 3 summarizes some of the research works which have been implemented in pyrolysis area. The table tabulates the data in terms of pyrolysis type and the condition associated with each type. Also, the product yields for solid, liquid and gas production are listed.

Table 3. Details of recent research on the pyrolysis of SCG in terms of process conditions and yields

Pyrolysis Type	Reaction Temperature °C	Heating rate C/s	Vapor residence time (s)	Bio-oil yield %	Biochar yield %	Biogas Yield %	References
Slow	400-500	1.1-1	300-550	20-50	25-35	20-50	(Kazawadi et al., 2021)
	350-550	-	<600	28	40	32	(Gong et al., 2021)
Intermediate	400-650	1-10	0.5-20	35-50	25-40	20-30	(Kazawadi et al., 2021)
	400-500	-	10-30	50	30	20	(Gong et al., 2021)
Fast	850-1250	10-200	0.5-10	60-75	10-25	10-30	(Kazawadi et al., 2021)
	400-550	-	<2	30	20	50	(Gong et al., 2021)
Flash	800-1000	>1000	0.5	60-75	10-25	10-30	(Nanda & Berruti, 2021)
	300-1000	0.2-17	2	60-75	10-25	10-30	(Jouhara et al., 2018)

Gasification

Gasification of biomass is a thermochemical process that converts solid biomass into useful gases such as methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen (H_2), as well as a solid residue known as char. The gases can then be transformed to liquid fuels or heat and energy for power generating units using the F-T process (Mishra & Upadhyay, 2021). A gas such as air, oxygen, or supercritical water might be used as the gasifying medium. Because of its ease of availability and low cost, air is the most utilized gasifying medium for gasification. Nevertheless, if steam is used as a gasifying medium, the resulting gas has a greater H/C ratio (Mishra & Upadhyay, 2021). The steps of gasification are as follows: drying, pyrolysis, oxidation (combustion), reduction (char gasification), and cracking (Safarian et al., 2019). Normally, the moisture content of biomass feed ranges from 5 to 35%, which is lowered to less than 5% throughout the drying process. The biomass is heated from 200 to 700 °C with restricted oxygen or air during the pyrolysis process. The volatile components of the biomass are evaporated under these circumstances. Hydrogen, carbon monoxide, carbon dioxide, methane, tar (heavier hydrocarbon) gases, and water vapor generate the volatile vapor (Safarian et al., 2019). During pyrolysis, tar and char are produced also. The gasifier's oxygen combines with combustible chemicals, creating CO_2 and H_2O. When CO2 and H_2O meet the char formed by pyrolysis, some of it is converted to CO and H_2. Also, the hydrogen in the biomass may be oxidized, producing water. Endothermic reduction processes occur within the gasifier, and the energy necessary for these reactions is provided by the burning of char and volatiles (Safarian et al., 2019). The size and kind of gasifier are determined by numerous factors, including product demand, moisture content, and fuel availability (Mishra & Upadhyay, 2021).

Hydrothermal Carbonization

Hydrothermal processes, which are responsible for the conversion of dead plants and animals into various kinds of fossil fuels such as coal and petroleum, have been occurring in nature for thousands of years. Humans have replicated these geological processes for the creation of biofuels through the transformation of carbohydrates and biomass (Sharma et al., 2020). According to the phase diagram of water and its distinct areas above vapour pressure and critical temperature, hydrothermal conversion is classified into three types: hydrothermal gasification, hydrothermal liquefaction, and hydrothermal carbonization (Sharma et al., 2020). Hydrothermal carbonization or HTC is a thermochemical process that occurs in subcritical water under relatively mild situations, with a reaction pressure between 10 and 50 bar and temperature of roughly 180-250 °C (Ischia & Fiori, 2021). In these conditions, liquid water acts as both a solvent/reaction and reactant media for the biomass, causing it to degrade by heterogeneous chemical processes including such dehydration, hydrolysis, aromatization, and polymerization (Ischia & Fiori, 2021). As a result, a solid phase rich in carbon (known as hydro-char), a liquid by-product, and a gas phase rich in CO_2 are produced. Hydro-char is made up of condensed aromatic compounds and contains a lot of oxygenated functional groups. It is hydrophobic and non-toxic, and it may be utilized as activated carbon, solid fuel, and adsorbent in wastewater treatment (Qin et al., 2020). HTC, which occurs in water, is particularly suitable for the upgrading of biomass with high moisture content, and a wide variety of "wet" biomasses (Ischia & Fiori, 2021). HTC is a promising thermochemical synthesis method for generating useful carbon compounds from SCG. This technique is more energy efficient than classical pyrolysis because it employs mild conditions, does not need drying of the feedstocks, and is exothermic (Qin et al., 2020).

Combined Processes (Pyrolysis and Activation)

To manufacture activated carbon from spent coffee grounds, two crucial methods must be performed. Carbonization (pyrolysis) is the first step which is explained previously, while activation is the second (Reza et al., 2020). The production of AC from biomass is beneficial in two ways: first, it can avoid the production of CO_2 by fixing the carbon, and second, the AC can organically enter the soil (Reza et al., 2020). To create biochar, carbonization is accomplished through pyrolysis at a very high temperature in an inert environment. The carbon composition of the carbonaceous material is produced at this step by eliminating the volatile matter via thermal degradation. Because the obtained biochar has a poor adsorption ability, an activation procedure is required to increase the pore volume, pore width, surface area, physical characteristics, absorption capacity, and pore density (Reza et al., 2020). During the activation process, the disorganized carbon is first removed, followed by the lignin being subjected to activating chemicals and developing the microporous structure. Lastly, by burning the walls between the pores, the current pores are expanded to a large extent. This increases the volume of intermediary pores and macro-porosity while decreasing the volume of micro-pores. Based on the type of activation, it can be a procedure before or after carbonization for the removal of accumulated tarry substances in biochar, which can help to improve porosity and provide large surface areas for the ACs (Reza et al., 2020). Chemical and physical activation are the most common types. The chemical activation is process conducted using a variety of activation chemicals such as potassium hydroxide (Figueroa Campos et al., 2021) whereas physical activation is a two-step process that begins with carbonization (pyrolysis) in a neutral atmosphere and continues with activation in atmospheric oxidizing gases (Heidarinejad et al., 2020).

Chemical Activation

Chemical activation is commonly used in a single or two processes for cellulose-containing raw materials. Prior to thermal treatment at 450-900 °C in an inert atmosphere, the precursor is impregnated with chemical activating agents (Patra, 2021). Activated carbon is eventually created by repeatedly washing the resultant mixture (Heidarinejad et al., 2020). Chemical activation agents are materials important for this process. They are dehydrating agents that influence pyrolytic decomposition by increasing activated carbon content, minimizing bitumen formation, which results changes in the thermal degradation of precursors and development of porous carbon materials (Heidarinejad et al., 2020). These materials penetrate deep into the carbon structure, induce tiny holes to develop in the activated carbon, improving its surface area (Heidarinejad et al., 2020). Distinct compounds have different interactions with precursors, which affects adsorption behavior. Acidic groups and sulphuric acid (H_2SO_4) have been used as potential activators, as have intermediate metal salts, alkaline groups, and other activating agents (Heidarinejad et al., 2020). There are some advantages for this process includes: low cost effective, low activation temperature, shorter processing time, better carbon efficiency, and it may be produced in a single furnace. The downsides are the necessity for a repeated and lengthy washing phase at the conclusion of the activation process to remove the spent activator agent from the final combination, which produces toxic effluent that pollutes the water (Heidarinejad et al., 2020).

Physical Activation

In physical activation there are two stages, pyrolysis, and activation process. Investigation has been conducted by researchers that the physical activation is better than chemical activation. Its cost effective and increase the formation of pores especially mesoporous and microstructure by CO_2 activation. These precursors are high in carbon and pre adsorption material, with slight amount of O_2, H_2, N_2 and S. For the preparation of AC, hybrid willow biomass was used as the feed for the process.

Table 4. Recent research on the activation types including the activation conditions and yield.

Activation type	Agent	Activation Temperature (° C)	Reaction time (h)	Surface area (m^2/g)	Yield (wt.%)	References
Chemical activation	KOH	800	4	1199	-	(Rosson et al., 2020)
	H_3PO_4	350 – 500	1	300-1209	40 ± 3.3	(Ferraz & Yuan, 2020)
	$CaCO_3$	850	1	167	41.0	(Figueroa Campos et al., 2021)
	K_2CO_3	600-800	1 or 5	2337	28.4	(Kim et al., 2020)
	NaOH	80	-	2.3	-	(Meshram et al., 2020)
	$ZnCl_2$	800	2	367	15	(Rosson et al., 2021)
Physical activation	CO_2	700	-	630	-	(Bandosz & Kante, 2015)
	Steam	800	0.83	1,181	9.6	(Kikuchi et al., 2017)
	Steam	700	2	641	13.4	(Tehrani et al., 2015)
	CO_2	700	1	593	-	(Plaza et al., 2012)

Conclusion

As a major source of waste worldwide, coffee waste represents a valuable opportunity for recycling and the creation of value-added products. Various processes such as pyrolysis, anaerobic digestion, chemical or physical activation, hydrothermal carbonization, and gasification can be used to transform coffee waste into products such as biochar, bio-oil, biogas, and activated carbon. However, further experimental studies are needed to explore efficient valorization of coffee waste, as each product has unique properties that can be utilized in various applications. Sustainable waste management practices and investment in the research and development of coffee waste valorization can contribute to the creation of a circular economy and a more sustainable future, as well as reduce waste globally. Oman's 2040 strategy aims to create a diversified and sustainable economy, with a focus on innovation and knowledge-based industries. As part of this strategy, Oman is committed to sustainable development and reducing waste. By investing in the research and development of coffee waste valorization, Oman can contribute to the creation of a circular economy and a more sustainable future, while also creating new economic opportunities and reducing waste management costs. Our findings suggest that spent coffee grounds can be converted into valuable products, with activated carbon being one of the most common and beneficial products that can be extracted from coffee waste. The study identified a slow pyrolysis process followed by physical activation of SCG as an efficient process, particularly considering the limited access to water. Further research can help unlock the full potential of coffee waste valorization and enable Oman to make significant contributions to the creation of a circular economy and a more sustainable future.

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