Journal of Mines, Metals and Fuels, *71(12D): 97-104; 2023. DOI: 10.18311/jmmf/2023/47999*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

Sustainable Management of Coffee Bean Processing Waste for Bioethanol Production

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Abstract

Coffee being one of the most consumed beverages in the world, is also an extremely valuable agricultural commodity. However, its processing generates millions of tons of solid waste annually. These wastes are usually dumped in landfills, added to animal feed, or incinerated, Due to the high caffeine and tannin content, it tends to affect soil quality and can be toxic and carcinogenic to the animals that consume it. Coffee processing wastes have been used in biofuel production for a few years now. The ever-increasing demand for energy, sharp inflations in fuel prices and the non-renewability of conventional energy sources have heightened the necessity for alternative energy sources. Biofuels, due to their renewable nature and clean emissions on combustion are rapidly gaining popularity as an alternative energy source. Conventional production of bioethanol includes pretreatment, saccharification and fermentation of sugar-containing feedstocks. Coffee bean processing waste being rich in fermentable sugars, can be channelised for bioethanol production. Therefore, the production of bioethanol from an agricultural waste substrate will not only help in the production of a valuable, eco-friendly biofuel but also will help in the effective utilisation of coffee processing waste, reducing environmental pollution. Sustainable management of coffee bean processing waste for bioethanol production indirectly benefits the mining industry by reducing environmental impact, fostering community development, and influencing market trends. Bioethanol contributes to local energy independence, potentially decreasing reliance on non-renewable resources. Innovations in waste management and sustainability practices create a ripple effect, positively impacting various industries, including mining. This review aims to discuss the prospects of sustainably managing coffee bean processing waste for the production of bioethanol and its promising future.

Keywords: *Agricultural Waste, Alternative Energy Source, Bioethanol, Biofuel, Coffee Processing Waste, Sustainable Management of Waste*

1.0 Introduction

Coffee production and manufacturing refers to the process of turning a coffee plant's unripe fruit into finished coffee. Coffee plants are typically grown in huge commercial enterprises. The two main species of coffee plants are tropical evergreen shrubs or small trees with African ancestry, (*Coffea arabica* and *Coffee canephora*). They are cultivated for the beans or seeds, which are then roasted, ground and sold to coffee brewers. While the Robusta form (*C. canephora*) predominates in Africa, the Arabica species of coffee (*C. arabica*) is mostly grown in Latin America. Robusta, as its name suggests, is a sturdier plant, so it costs less to grow. It is also the bean of choice for low-cost commercial coffee brands and has twice the caffeine concentration of Arabica, which is thought to be a milder, more flavourful and aromatic drink. Both types of coffee are cultivated in India, Indonesia and other Asian nations, and they come in a wide range of variations, forms and sorts. This diversity is further increased

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by the influences of the environment and cultivation styles[1].

India ranks seventh in global coffee production as per 2021 reports, after Brazil, Vietnam, Colombia, Indonesia, Ethiopia and Honduras, producing a total of around 5.7 million bags (each bag being 60 kgs). Around 70% of this is exported, and the exported beans are distributed roughly as 30% Arabica and 70% Robusta[2].

India has been producing coffee since 1600 A.D. The father of Indian coffee, Baba Budan, was a Sufi saint from India who travelled to Mecca. Baba Budan set off for his native India from the Yemeni city of Mocha, where he encountered coffee along the route in the form of a dark, delicious beverage known as Qahwa. Due to the Arab's safeguarding of their coffee production, he took seven coffee beans from Mocha secretly. Which he sowed in his hermitage's enclosure in Chikmagalur, Karnataka, India. As a result, this location is where Indian coffee originated. The coffee had spread in his backyard before eventually reaching the now Baba Budan Hills. The coffee industry expanded both under and after British rule. In the Malabar region, the Dutch started coffee production. The British established Arabica coffee plantations throughout the Southern Indian hills. In the southern region of India, the climatic conditions were favourable for the production of coffee, and thus its cultivation thrived[3].

In 2019–20, there were estimated to be 169.34 million bags (each weighing 60 kg) of coffee produced worldwide, of which 60–75% were Arabica and the remaining less than 40% were Robusta[4].

Brazil leads all other countries in terms of production, with a market share of 37.4%, followed by Vietnam (17.1%), Columbia (8.4%), Indonesia (7.1%), Ethiopia (4.3%), Honduras (3.6%), and India (3.4%) [5].

Ever since the five-thousand-year-old Indus civilisation, tea has been a popular beverage in China and India. But tea was subject to a levy throughout the British rule of India. Due to this, India's population became more and more dependent on coffee, which remains the country's most enjoyed beverage[3].

In India, Arabica production was very common, earlier but severe infestations causing rust of coffee leaves forced many fields to convert to Arabica/Liberica hybrids or Robusta. The southern states of Karnataka, Kerala and Tamil Nadu, known traditionally as the main coffee-growing region of the nation, produce approximately 90% of the total crop. The remaining crops are farmed in the northeast states of Assam, Meghalaya, Manipur, Mizoram, Arunachal Pradesh, Nagaland and Tripura, as well as in the more recently industrialised regions of Andhra Pradesh and Orissa in the Eastern Ghats. Indian coffee is typically produced beneath a two-tiered mixed-shade canopy of leguminous evergreen trees, which is frequently punctuated by spice and fruit crops including banana, orange, cardamom, pepper and vanilla trees[2].

Coffee is among the most important agricultural commodities produced worldwide. Acidity, fragrance and taste are three of coffee's key distinguishing characteristics. It is made up of more than 1500 chemicals, including 700 soluble and 850 volatile ones. Most of the hydrophobic components of coffee, including lipids, fatty acids, triglycerides and oils, as well as carbohydrates that are incapable of dissolution like cellulose and several other indigestible sugars, are left behind during the extraction of coffee in water. Additionally, coffee includes phenolics that protect, exquisite and fragrant essential oils and structural lignin[7].

The operations involved in coffee production produce large amounts of wastewater and solid by-products. The primary solid by-products of coffee production and preparation are by-products of coffee fruit i.e., the coffee cherry, by-products of coffee bean processing, like coffee husks, peel and pulp, and spent coffee grounds. Significant

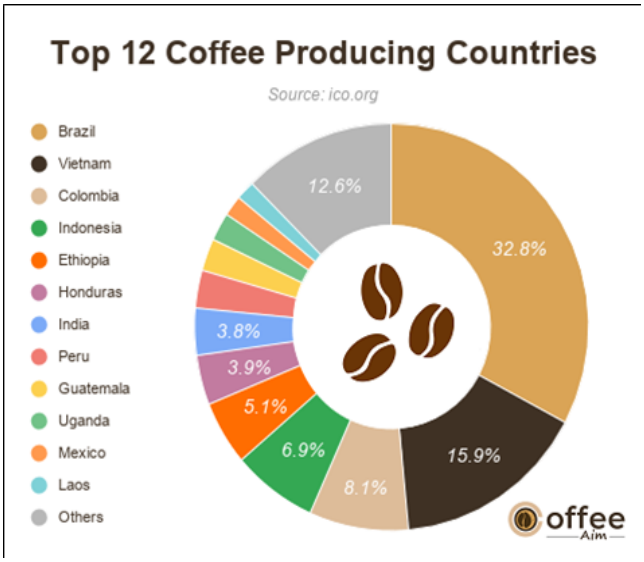


Figure 1. Global coffee production[6].

amounts of water that is contaminated are also left behind after numerous washing processes, having a carbon load that is quite high, and correspondingly causing significant environmental impact. Flawed green coffee beans and tree leaves after harvest are examples of other minor wastes[7].

There are claims from sustainability reports that, the whole process, right from extracting the pulp of fresh coffee cherries, to the packaging and transport of the roasted beans to your favourite local barista, generates more than 23 million tons of waste annually. The most glaring example of this wastage at the consumption end of the supply chain is the used coffee grounds, which we discard after each freshly brewed cup[8].

The following by-products may be created during the processing of coffee, depending on the method used:

- By-products of coffee pre-roasting.
- Coffee husks, from dry processing.
- Coffee pulp, from wet and semi-dry processing.
- Coffee silverskin from coffee beans that are roasted and spent coffee grounds.
- Coffee waste water.

Large volumes of solid waste are produced by the coffee industry. Presently, there is a lot of legal and social pressure to reduce pollution brought on by industrial activities. By altering industrial operations so that their residues may be recycled, nearly all developed and developing nations are attempting to adjust to this fact. As a result, the majority of large businesses consider residues less as waste and more as a source of raw materials for other subsequent activities. There are numerous methods of utilising coffee waste, depending on the type of by-product. For instance, effective utilisation of these coffee wastes can be the fabrication of briquettes and fuel pellets, removal of dyes and heavy metals from aqueous solutions by using the waste as a sorbent, making spirit beverages, growing edible mushrooms, for the preparation of ion exchange material, to provide natural phenolic antioxidants, manufacturing of reusable cups, producing biofuels, alcohol and compost using the waste as a substrate, and in the pharmaceutical industry as a biomaterial. Due to the hazardous and toxic nature of these leftovers, which can be damaging if disposed of into the environment, finding alternatives for their use is of utmost importance[7].

Large amounts of Spent Espresso Grounds (SEGs), which are abundant in lignocellulose and important bioactives, are produced by traditional coffee brewing methods. The coffee pulp contains several bioactive substances, including phenolic compounds (5-caffeoylquinic acid, 3,5-dicaffeoylquinic acid, 5-feruloyl quinic acid, epicatechin, catechin, rutin, and ferulic acid), flavonols, and anthocyanins (cyanidin-3-rutinoside, cyanidin-3-glucoside). While lignocellulose breaks down into metabolisable sugars that can be utilised to produce a variety of high-value goods including biofuels, amino acids, and enzymes, these bioactive chemicals can be employed as a nutraceutical or utilised in a variety of food products. The phenolic chemicals and bioenergy found in used coffee grounds can be quite valuable[9].

The objective of this article is to discuss the prospects of sustainably managing coffee bean processing waste for the production of biofuel and bioethanol.

2.0 Bioethanol

Climate change and energy security are two issues that concern nations all over the world. Additionally, the overuse of traditional fuels like coal and crude oil exacerbates the problems of air pollution and the depletion of non-renewable resources. The best liquid transportation fuel for minimising our reliance on fossil fuels is bio-ethanol, an alternative energy source[10]. Additionally, bio-ethanol can either be used in combination with existing gasoline to reduce the depletion of contaminants or in its original, pure form. However, due to concerns about food security and dwindling arable land areas, the public has criticised the preponderance of terrestrial crops used to produce bioethanol, such as maize and sugarcane[11]. In this perspective, waste from the processing of coffee beans is among the most promising alternative renewable feedstock for the development of biofuels[12].

In addition to being more environmentally friendly than fossil fuels like petroleum, bioethanol is also becoming more and more popular as an alternative fuel. Its fuel efficiency is comparable to that of petroleum. It has been noted that the manufacture of bioethanol from lignocellulosic-based agro-wastes is sustainable, environmentally friendly and economical. Coffee husks,

coffee pulp and spent coffee grounds are coffee leftovers utilised in the manufacturing of bioethanol. The primary factor contributing to their aptitude for bioethanol production is their lignocellulosic composition. The part of the residual coffee that is lignocellulosic is hydrolysed (saccharified) and the resulting hydrolysates are then fermented to generate bioethanol. It must first undergo several pre-treatments before it can be hydrolysed. Yeasts are then used to ferment the hydrolysates[13].

Coffee by-products, having high carbohydrate and nutritive content have a wide variety of uses. In some regions of the world, the pulp portion of the residue is employed as a fertiliser and a direct fuel source for burning. Spent Coffee Grounds (SCGs), left over after the oil has been extracted, can also be utilised as a feedstock to manufacture biofuels like biogas and bioethanol, bio-oil and fuel pellets. SCGs are an excellent media substrate for industrial boiler use, due to their high calorific value of roughly 24.9 MJ/kg (dry weight). Additionally, a certain amount of coffee husk is combined with animal feed as food for cattle and other domestic animals, but its direct use is impossible because of the chemicals that are toxic and detrimental (such as tannins and caffeine) to animal health. Due to the absence of extensive uses, a sizeable amount of the waste generated during the manufacturing of coffee is currently being underutilised, which has had a substantial negative impact on the environment, health, and the release of hazardous phenolic chemicals into wetlands. One of the most crucial methods for reducing waste, risks to human health and environmental pollution from coffee by-products is by vapourising it and channelling it towards biofuel production. Before making biofuels, delignification of coffee by-products is necessary, especially for the manufacture of bioethanol and biogas because the yield of the biofuel would be quite low otherwise[14].

Coffee wastes/ by-products that can be used for bioethanol production through the fermentation process are given in below Table 1.

2.1 Microbes Producing Bioethanol

Identifying a microbe that can digest these sugars and turn them into ethanol is crucial given the different types of sugars found in these wastes. The microbe most frequently utilised to produce ethanol is *Saccharomyces cerevisiae* because of its high ethanol yield and capacity to grow in medium with high sugar concentrations. However, this yeast can only ferment hexoses; it cannot convert pentoses like xylose to ethanol. The process of hydrolysing the hemicellulose in agro-waste typically yields xylose and the bioconversion of xylose is a crucial step in its recycling. There have been reports of ethanol production from pentoses using yeast strains from the *Pichia*, *Candida*, *Schizosaccharomyces* and *Pachysolen* genera, as well as filamentous fungi *Paecilomyces*, *Mucor*, *Monilia* and *Fusarium*, and bacteria *Clostridium*, *Bacillus*, *Bacteroides*, *Thermoanaerobacter* and *Erwinia*. *Pichia stipitis* (NRRL-Y-7124), *S. cerevisiae* (RL-11), and *Kluyveromyces fragilis* (Kf1) were shown to yield a fair amount of ethanol from various sugar sources[22].

Table 1. Coffee bean processing wastes that can be used for bioethanol production

Coffee Wastes/ By-Products	Fermentative Bioethanol Yield	References
Coffee Husk	8.49 g/100 g dry basis or 13.6 g/L	[15]
Coffee Pulp	8 wt.% (bioethanol/substrate)	[16]
Coffee Pulp	18.3 g/L	[17]
Coffee Pulp	77%	[18]
Spent Coffee Grounds	0.5 g/g or 19 g/L	[19]
Spent Coffee Grounds	0.43 g/g	[20]
Spent Coffee Grounds	22 g/L	[21]

2.2 Coffee Bean Producing Waste for Bioethanol Production

For successful hydrolysis and to increase the sugar content in the biomass for the synthesis of bioethanol, it is necessary to first break down the hemicellulose and cellulose polymer in the coffee wastes.

The following four steps are necessary to produce bio-ethanol from lignocellulosic biomass:

- Pre-treatment of lignocellulosic biomass
- Saccharifying enzymatically the pre-treated biomass to produce sugar monomers
- Fermenting the hydrolysed sugars using suitable organisms to bioethanol
- Distillation

When saccharification takes place, Separate Hydrolysis and Fermentation (SHF) are the terms used to describe the process[14].

After pre-treatment, concurrent fermentation and saccharification processes, using thermotolerant yeast strains and fermenting the sugar monomer of xylose, the bio-ethanol production from coffee by-products was greatly increased. The output of bio-ethanol from coffee husk was also increased using cellulolytic hydrolysis and genetically altered lignocellulosic yeast strains for pervaporation and fermentation at ideal temperatures not exceeding 50°C[15].

Producing bioethanol with the aid of *Saccharomyces cerevisiae*, and with the batch fermentation of coffee husks, was found to be a viable option. Aqueous extract from ground coffee husks was used in batch fermentation tests. It was shown that as yeast concentration increased, fermentation yield decreased. The amount of ethanol produced by coffee husks was an acceptable result when compared to the literature review for other agro-waste residues such as barley straw, maize stalks, and hydrolysed wheat stillage. These findings indicate that coffee husks have great potential in producing bioethanol from waste residues[15].

By creating biofilms that are polymicrobial from new strains (one strain can devour lignin while the other performs fermentation), there can be a significant increase in the conversion of biomass to bio-ethanol[14].

Different waste residues that can be used for bioethanol production are shown in below Table 2.

2.3 Fermentative Routes

Saccharomyces cerevisiae was found to be the strain that yields the highest amount of bioethanol. First, by using the oven drying procedure, the residues' moisture content has to be identified. The residues had to be weighed and dried repeatedly until a constant weight was reached and the moisture content was eliminated. Following hydrolysis, the flasks containing the hydrolysate residues have to be autoclaved and cooled to room temperature. Then fermentation can be carried out at optimal temperatures

Table 2. Comparison of bioethanol yield from coffee wastes/by-products with other agro-waste residues[14]

Residues	Yield of bioethanol using SHF method with *S. cerevisiae* (g/l)	References
Wheat Straw	12	[23]
Corn Cob	24	[24]
Barley Straw	12.6	[25]
Spent Coffee	7	[26]
Coffee Pulp	7.4	[16]
Sweet Sorghum Bagasse	22.3	[27]
Sugarcane Bagasse	13.1	[28]
Poultry Manure	5	[29]
Coffee Husk	13.6 +/- 0.5	[15]

with yeast (*S. cerevisiae*). Gas chromatography is used to measure bioethanol concentration at various fermentation times to establish the fermentation duration that will result in the highest bioethanol yield.

As the fermentation time increased, the concentration of bioethanol fell and then increased again. According to an optimisation experiment conducted, the peak bioethanol concentration was reached after fermentation for 24 hours and then began to decrease. The production of bioethanol had lessened as the time required for fermentation exceeded 24 hours; this could be because the microorganisms that produce the bioethanol consume sugar, or it could be because the hydrolysate contains high concentrations of accumulated metabolic inhibitors that can prevent fermentation. The goal is to choose the best technique for efficiently using the waste to make bioethanol. The potential is established to provide long-term sustainable environmental protection by turning garbage into useful fuel[18].

Converting coffee bean processing waste to bioethanol mainly benefits the mining and fuel industries by offering a sustainable alternative to fossil fuels, reducing environmental impact, and promoting waste utilisation. This process contributes to energy independence, creates economic opportunities, and addresses waste management challenges, ultimately supporting carbon emission reduction and fostering technological innovation in bioenergy.

3.0 Current Limitations and Future Prospects

The greatest barrier to the efficient use of wet waste is typically its low dry matter content, which makes it difficult to transport, store and preserve this residue and encourages the growth of microorganisms like filamentous fungus and yeasts, which further degrade the waste. Most health-related chemicals' concentration and biological activity must undergo several heat treatments, which significantly diminish both. As a result, a variety of substitute technologies for low-temperature processing have been developed, including microwave, vacuum drying, freezing, irradiation, and Pulsed Electric Field (PEF) treatment. These processes should be able to inactivate bacteria and enzymes without causing heat-labile components to degrade, hence maintaining the waste's nutritional value. The availability of raw materials is a significant issue with bioethanol production because it is dependent on the starch and sugar content of the biomass used, which together account for 60% of the bioethanol produced. As a result, the cost of producing bioethanol will depend on the cost of the raw materials, which will vary depending on the area and the season[30].

Due to the need for acid and alkali during coffee pulp hydrolysis, which calls for costly high-tech equipment, certain techniques of manufacturing ethanol from coffee pulp are still restricted and environmentally unfriendly[31].

The extent of the benefits to the mining and fuel industries also depends on factors such as efficiency, competition with other biofuels and regulatory support.

Just like all other wastes, the production of bioethanol from coffee bean production wastes has its limitations, therefore minimising such limiting factors will help in the optimisation of the final output.

Due to its particular effects on environmental social and economic progress, sustainable development is turning into a major aim for both the existing and the coming generations and sustainability is becoming a guiding strategy for society. Suitable strategies to manage waste, sustainable use of natural resources and suggestions for a more affordable and eco-friendly waste disposal process, to combat the massive amounts of waste generated, should be the key focus of the farmers, commercial manufacturers, policy framers and end users[32].

Coffee production is quite significant to the economy of the nation. Since one kg of coffee husks is generated for every kg of beans produced, they are the main solid residues from handling and processing coffee. Coffee husks have several other uses, including adding them to animal feed, using them as fuel directly, fermenting them to make a variety of goods (including enzymes, citric acid, and flavourings), growing mushrooms on them and using them as adsorbents[15]. Therefore, finding other unconventional uses for this solid waste is necessary, given the enormous amounts generated. Given that this residue is primarily made up of coffee fruit pulp and hull, it has a high carbohydrate concentration and can be considered a viable substrate for the manufacturing of bioethanol. Furthering the application of sustainable development in the entire production process, the produced ethanol might be used to produce biodiesel based on coffee oil

acquired from faulty coffee beans[15]. Given that there are no expenses associated with the growth of raw materials, recent studies have shown that the usage of residues for the production of bioethanol has excellent potential. Additionally, it is predicted that the amount of ethanol produced from agricultural waste might increase significantly compared to what it is now[15].

4.0 Conclusion

Sustainable coffee waste management for bioethanol production promotes environmental responsibility in coffee-producing regions. This practice indirectly benefits the mining industry by reducing environmental impact, fostering community development, and influencing market trends. Renewable energy generation from bioethanol contributes to local energy independence, potentially decreasing reliance on non-renewable resources. Government incentives and global supply chain dynamics further encourage sustainability, while technological innovations in waste management may transfer to mining operations. Collectively, these effects create a ripple of positive environmental and socio-economic impacts, indirectly influencing sustainable practices in various industries, including mining.

We have only one Earth and it is our responsibility to recycle and efficiently utilise what we have instead of causing pollution and damage through wastage. Only a small bit of the materials used and produced by the coffee industry make it to our coffee mugs. The ability to channel the remaining huge waste residue output into the generation of a renewable, clean and sustainable energy source, like bioethanol, allows us to solve two considerable issues at once.

Furthermore, in this aspect, the rapid advancements in technology can only aid the whole process, potentially promising us a bright and sustainable future.

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