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Opportunities and Constraints of Coffee Byproducts in Ethiopia: Review

Daba Etana and Dawit Merga
Ethiopian Institute of Agricultural Research, Jimma Agricultural Research Center, Jimma, Ethiopia

ABSTRACT
Arabica coffee is the backbone of the Ethiopian economy, contributing 30-35% to the country's foreign exchange income. The byproducts generated during both dry and wet processing methods have both positive and negative environmental impacts. Most negative impacts result from poor byproduct management and usage. The extent of coffee byproducts ranges from pulping red cherries to the leftover remnants after brewing coffee. These byproducts present enormous opportunities and challenges for eco-friendly use in coffee-producing countries like Ethiopia. The major objective of this study was to review and compile different findings and information related to the opportunities and constraints of coffee byproducts that contribute to a sustainable coffee production system. The major opportunities for coffee byproducts include both classical and modern approaches, such as sustainable agriculture, value-added products, renewable energy, and environmental benefits. However, if not managed appropriately, coffee byproducts can cause chronic environmental pollution that directly affects humans, animals, other organisms, and aquatic biodiversity. The constraints of coffee byproducts in Ethiopia encompass limitations in infrastructure, market access, education and training, and technologies. Generally, there is a research gap on the effective eco-friendly use and management of coffee byproducts. Investing in research on how to eliminate coffee byproduct waste through sustainable agriculture and value-added products can contribute to the sustainable development of Ethiopia's coffee industry. Lastly, it fosters the development of a circular and green economy in coffee-producing countries like Ethiopia.

KEYWORDS
Coffee, coffee byproducts, constraints, environment, management, opportunity

INTRODUCTION

Ethiopia is renowned as the birthplace of Arabica coffee, boasts a rich history and cultural heritage deeply intertwined with the cultivation and production of this beloved beverage. More than 124 coffee species with distinctive characteristics are identified, but only a few species dominate the world market[1]. Arabica and Robusta coffee are the species that cover more than 99% of the world's coffee production and markets. However, Arabica coffee is the only species with high quality, and covers more than 60% of the world coffee market[2], produced in more than 80 countries around the world,and endowed to world from the Ethiopian rainforest montane region.

Arabica coffee plays an enormous role in the Ethiopian economy, contributing 30-35% of the country's total export earnings. Over 15 mL small-scale farmers directly or indirectly depend on coffee production

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for their livelihoods[3]. The coffee industry contributes 5-20% of Ethiopia's GDP, with nearly a quarter of the population relying on it for survival. From over five decades of research efforts, 49 improved coffee varieties have been developed to suit different agro-ecological zones across the country[4]. Ethiopia produced around 559 thousand metric tons of Arabica coffee in the 2023/2024. The country also has a strong domestic consumption culture, with nearly half of its coffee production consumed locally. With its diverse coffee varieties, unique growing conditions, and centuries-old traditions, Ethiopia stands as a global leader in the coffee industry. However, beyond the prized coffee beans lies a wealth of untapped potential in the form of coffee byproducts. These byproducts, including coffee pulp, husks, parchment, and more[5], hold significant opportunities for economic development, agricultural sustainability, and environmental stewardship.

Yet, alongside these promising prospects, a set of formidable constraints poses challenges to effectively utilizing coffee byproducts. In this comprehensive exploration, the opportunities and challenges associated with coffee byproducts in Ethiopia were investigated, shedding light on pathways to harness their full potential while navigating the obstacles ahead. Against this backdrop, the utilization of coffee byproducts presents both opportunities and constraints for Ethiopia's economy and agricultural sector.

The byproducts generated from wet and dry coffee processing methods offer enormous economic and environmental benefits. Husks and pulp together account for over half of the byproducts produced by coffee processing industries. From 2 tons of coffee cherries, 1 ton of coffee pulp is generated, while 0.18 tons of husks are produced from 1 ton of dried coffee fruit[6,7]. Among the most promising opportunities lies the economic potential of coffee byproducts. Coffee pulp, husks, parchment, and other residues can serve as valuable resources beyond the primary coffee beans[8]. These byproducts can be repurposed into various products, including organic fertilizers, animal feed, biomass fuel, and value-added goods such as cosmetics and pharmaceuticals.

Among the most promising opportunities lies in the economic potential of coffee byproducts, which include coffee pulp, husks, parchment, and other byproducts can serve as valuable resources beyond the primary coffee beans[8]. These byproducts can be repurposed into various products, including organic fertilizers, animal feed, biomass fuel, and value-added goods such as cosmetics and pharmaceuticals[9-11]. Effectively leveraging these byproducts can create new revenue streams for coffee farmers and processors. Thus, the efficient utilization of coffee byproducts has a tremendous impact on poverty alleviation, rural economic development, and environmental sustainability.

Furthermore, the agricultural benefits of coffee byproducts, ranging from soil health to crop productivity, are not yet fully elucidated. Coffee pulp and husks, when used as organic fertilizers or soil conditioners, can enhance soil fertility and promote sustainable agriculture[12]. By returning organic matter to the soil, these byproducts improve soil structure, water retention, and nutrient availability, leading to higher crop yields and greater resilience to climate change[10,12,13]. Additionally, utilizing coffee byproducts in agriculture reduces reliance on chemical fertilizers, helping to mitigate environmental pollution and promote eco-friendly farming practices. Another promising opportunity is energy generation from coffee byproducts[14]. Through processes such as anaerobic digestion or combustion, coffee pulp, husks, and parchment can be converted into biomass fuel, providing a renewable energy source for rural communities. This decentralized energy production not only reduces reliance on traditional fuels like firewood and diesel but also helps mitigate deforestation and lower greenhouse gas emissions. Moreover, the surplus energy generated from coffee byproducts can be harnessed to power agricultural processing facilities, further enhancing the sustainability of the coffee value chain[15].

In addition to economic and environmental benefits, the utilization of coffee byproducts provides huge opportunities for innovation and value addition[13]. Having better investment in research and development, coffee byproducts can be transformed into a wide range of high-value products, providing to diverse

to premium skincare products, and the possibilities are endless. By capitalizing on Ethiopia's reputation as a premium coffee origin, these value-added products can command premium prices in global markets, thus boosting export earnings and foreign exchange reserves.

Despite abundant opportunities, the effective utilization of coffee byproducts in Ethiopia faces several constraints that must be addressed to fully explore their potential for various applications. One of the primary constraints involves logistical challenges associated with collecting, transporting, storing, and processing these byproducts. In rural areas where coffee farming predominates, inadequate infrastructure and transportation networks hinder their efficient collection and distribution to processing facilities. Poor road conditions, limited access to storage facilities, and a lack of proper handling equipment contribute to post-harvest losses and drive up operational costs for coffee producers and processors. Moreover, technological limitations pose a significant barrier to the efficient utilization of coffee byproducts. Although various methods exist for converting coffee byproducts into value-added products or energy[17], the necessary advanced technologies and specialized equipment are neither readily available nor affordable for small-scale producers. The lack of access to appropriate technologies hampers innovation and limits the scalability of byproduct utilization initiatives, especially in remote rural areas where coffee byproducts are plentiful.

The market demand for products derived from coffee byproducts remains relatively limited, both domestically and internationally. In many cases, consumer awareness of their potential benefits is low, resulting in weak demand and market penetration. Developing strong marketing strategies, increasing awareness about the value of coffee byproducts, and fostering consumer demand are key steps to stimulate market growth and drive adoption of byproduct utilization initiatives. Regulatory hurdles also hinder the effective utilization of coffee byproducts in Ethiopia. Current regulations on waste management, agriculture, and energy production may be outdated or insufficient to address their unique characteristics. Meeting regulatory requirements, securing permits, and navigating bureaucratic processes can be both time-consuming and costly, especially for small-scale entrepreneurs and startups entering the byproduct utilization market. Although, the circular economy for coffee byproducts remains limited in Ethiopia, promising scientific findings and their potential applications are drawing interest from experts and coffee-producing nations. Therefore, this review aims to present comprehensive scientific findings and insights on the opportunities and challenges of coffee byproducts in Ethiopia.

COFFEE BYPRODUCTS IN ETHIOPIA

The management and utilization of coffee byproducts in coffee-producing countries are not as efficient as expected. Especially in Ethiopia, coffee byproducts are commonly found around coffee machines. However, less attention is given to how coffee byproducts can be reutilized and incorporated into a circular economy. Regardless of whether coffee is processed using wet or dry methods for export or local markets, more than 60% of the coffee cherry becomes a byproduct. Only the bean is used in coffee production, while all other components, known as byproducts, are discarded, potentially harming the environment[18,19]. Thus, instead of contributing positively to environmental improvement and supporting the livelihoods of small-scale farmers, coffee byproducts become a source of pollution and health risks.

Coffee byproducts make up a significant portion of the coffee fruit, accounting for more than 60%, including husks and green beans[5]. However, in impoverished countries like Ethiopia, only the dry skin of coffee beans and the wet-process output are considered valuable. Meanwhile, developed countries also utilize spent coffee grounds for food, food fibers, alternative energy sources, and organic fertilizers[20]. Valorization of coffee byproducts across various industries could provide a solution to the growing environmental concerns caused by excessive coffee solid waste production. Based on processing techniques, major coffee byproducts fall into three categories: Coffee pulp, coffee husk, and spent coffee grounds (SCG)[21].

COFFEE PULP AND HUSK

Husk and pulp are external layer byproducts from dry and wet processing, respectively. Both contain phytochemical compounds such as tannins, chlorogenic acid, and alkaloid compounds such as caffeine, in addition to being rich in minerals, proteins, and carbohydrates[22]. Coffee husk, which is composed of parchments, pulp, and dry skin left over from processed red cherries, is properly dried after harvesting using recommended methods. The dried coffee processing results in husks making up about 45% of the whole berry[23]. Coffee husk is rich in organic matter, including proteins (8-11%), carbohydrates (58-85%), lipids (0.5-3%), minerals (3-7%), hemicellulose (7%), lignin (9%), and small amounts of bioactive substances like caffeine (~1%) and chlorogenic acid (~2.5%), as well as phytochemical compounds like tannins (5-9%) and cyanidins (20%)[23,24].

Natural antioxidants like polyphenols, anthocyanins, and vitamin C are found in cascara, which is derived from coffee husk or pulp, along with other bioactive substances such as tannins, alkaloids, and caffeine[25]. It also has potential value for human consumption due to its gluten-free nature, which does not trigger allergic reactions[16]. These coffee byproducts have versatile applications, including composting, vermicomposting, detoxification, solid biofuel production, ethanol and biogas generation, adsorbents, organic fertilizer for mushroom cultivation, energy drinks, energy bars, and fermentation studies[22].

Pulp is a byproduct of wet coffee processing that constitutes up to 29% of the dry weight and contains 6-8% mucilage. If mucilage is released into the environment and not properly controlled, it can have a significant negative impact on both biotic and abiotic factors[26]. Pulp contains a significant amount of tannins (3%), chlorogenic acids (2.4%), caffeic acid (1.6%), caffeine (1.5%), proteins (5-15%), minerals (9%), fats (2-7%), total pectic substances (6.5%), reducing sugars (12.4%), non-reducing sugars (2%), and carbohydrates (2-32%)[23,24]. These findings highlight the crucial biochemical compositions found in coffee husks and pulp, which can be utilized in various beverages, foods, and cosmetic products[9].

COFFEE SILVER SKIN

The internal integument of the coffee bean, known as the coffee silver skin, constitutes about 1 to 2% of the coffee fruit and is typically formed during roasting[27]. Coffee silver skin is rich in dietary fibers and phenolic compounds[22]. This thin coating remains in direct contact with the coffee bean and clings tightly to it, but separates at high roasting temperatures. As the primary byproduct of the coffee roasting industry, extensive research has been conducted to determine its chemical composition and potential applications. Despite its high nutritional value, silver skin is not widely recognized as a valuable byproduct in industrialized nations, where it is mainly used as fertilizer, in bakeries, and various industries.

SPENT COFFEE GROUND

This type of coffee byproduct is the final product that is produced in the coffee industry during brewing instant coffee and the leftover of the coffee crude brew. More than six million tons of spent coffee grounds (SCG) are produced annually on average around the world[28]. Martin *et al.*[29] estimated that throughout the coffee processing, 650 kg of wasted coffee are produced for every ton of green coffee, and 2 kg of wet spent coffee are produced for every kilogram of powder coffee. On the other hand, it generates large amounts of dark colored waste (550 to 670 g/kg coffee beans) depending on coffee varieties[29]. The roasted coffee beans are then used to produce coffee via extraction and are the final step for the manufacturing of a finished product. Nowadays, given sustainability issues and environmental concerns that urge to use of waste products coming from food processing in novel and smart ways.

Current understanding of coffee by-products for alternative uses needs to be advanced and enriched with a diverse nutritional composition. The chemical composition of SCG consists of neutral detergent fiber (86.60%), acid detergent fiber (78.50%), moisture (74.72%), crude fiber (36.87%), nitrogen-free extract

(23.30%), protein (10.32%), lipids (15.2-17.3%), and ash (0.47%), which form its typical dry matter composition[30]. SCG contains high concentrations of organic substances such as minerals, polyphenols, fatty acids, amino acids, and polysaccharides, supporting its valorization.

In Ethiopia, information regarding spent coffee grounds (SCG) is limited, and their utilization has not yet begun. Instead, SCG is often deposited in flood canals, polluting urban areas and appearing as mere waste without any evident benefits. Therefore, an urgent investigation is needed to develop practical and innovative strategies for utilizing this low-cost coffee byproduct and unlocking its full potential, thereby enhancing the overall sustainability of the coffee agro-industry.

Environmental risks of coffee byproducts: The three main coffee byproducts, husk, pulp, and spent coffee grounds, are considered major sources of environmental problems if not properly managed within the production system. Husk dust generated during the dry process can accumulate over time, be transported by air over long distances, and when burned, produce an unpleasant odor, especially during the rainy season[31]. Dust released during hulling pollutes the air, leading to negative impacts on plant growth, physiology, stomatal conductance, and the health of workers and surrounding communities. According to Sakwari *et al.*[32], allergenic compounds, primarily chlorogenic acid present in dust and endotoxins released during processing, may induce asthma, rhinitis, or dermatitis in workers and nearby communities. Health risks and discomfort are often heightened in communities surrounding the coffee dry-processing industry due to air pollution[33]. However, the severity of its health impact across different ages, sexes, and other demographic factors has not been thoroughly studied.

The second environmental risk associated with coffee byproducts arises from wet processing effluents and influents. Conventional demucilaging methods in wet processing require more than 16 L of water per kilogram of red cherries. However, eco-friendly machines have reduced water usage and enabled their reutilization[26]. Despite these advancements, such sophisticated machines have yet to be widely adopted in developing countries like Ethiopia and other African nations. As a result, severe environmental pollution posing a threat to both aquatic and terrestrial organisms is observed in water contaminated by effluents.

Effluents in coffee wet processing consist of dissolved mucilage, which is discharged into safety tanks or water bodies, primarily through man-made canals. This mucilage decomposes very slowly, and when the wastewater oxygen supply is exceeded, it creates abnormally high Biological Oxygen Demand (BOD) levels, leading to anaerobic conditions[34]. Elevated BOD levels indicate the amount of oxygen required to break down organic matter in coffee wastewater. Additionally, the oxygen needed to degrade organic chemicals is known as Chemical Oxygen Demand (COD). Due to the large discharge of coffee mucilage and solid particles, wastewater requires a very high COD to break down its chemical contents. This increased demand exacerbates pollution and prolongs degradation time. Consistent with this, Endris *et al.*[35] reported a COD level of 1600 mg/L, depleted oxygen levels of 2 mg/L, and inhibited nitrification. As a result, oxygen scarcity triggers anaerobic reactions, or "rotting", leading to high COD and BOD values in water contaminated by effluent discharge, foul odors, and the death of aquatic life. The proliferation of anaerobic bacteria in such environments often causes health risks through contaminated drinking water.

Another environmental concern arises from residues produced during coffee wet processing, as the pulp pathway generates tannins, caffeine, and polyphenols, which are considered antinutritional factors[23]. Additionally, the high content of sugars, proteins, and minerals contributes to environmental issues by providing an ideal medium for the proliferation of microorganisms[24]. Therefore, these residues may have harmful effects and require sustainable management to minimize risks and maximize benefits. The final byproduct, spent coffee grounds (SCG), is discharged into the environment, contributing to pollution. The SCG has a similar chemical composition to coffee beans and contains potentially beneficial

resources. It is generated at coffee shops, households, and various industries that utilize coffee for different purposes. In Ethiopia, particularly in municipalities ranging from small to large, SCG is often discarded in canals and waste disposal areas, causing environmental pollution. Its potential benefits have not yet been extensively studied. However, in rare cases, farmers in rural areas may use SCG as animal feed.

Coffee byproducts

Potential impacts in the country: The total volume of annual agricultural waste is estimated to constitute 80% of overall agricultural production, with approximately two billion tons generated by the coffee industry. If not properly managed, this represents a major environmental pollution risk[36]. There is clear evidence that coffee byproducts have both positive and negative impacts, particularly on the livelihoods of producing countries rather than consumers. Despite its valuable roles in environmental improvement, circular economy integration, and serving as an input for beverages, animal feed, and other essential products, coffee byproducts remain largely overlooked in Ethiopia. It is estimated that 50% of coffee production results in byproducts. For example, in 2022, Ethiopia produced around 800,000 60 kg bags of coffee. This means that approximately half of this amount consists of byproducts, which are often discarded at coffee processing sites and in households. When left unmanaged, these discarded byproducts can become breeding grounds for harmful insects and wild animals, as well as contribute to chronic health issues in nearby communities.

In Ethiopia, aside from a few informal uses such as organic composting or direct disposal into fields, the broader utilization of coffee byproducts remains very limited. In contrast, developed countries with advanced technologies repurpose coffee byproducts for multiple applications, including antioxidants, fibrous materials, vermicompost, compost, and caffeine extraction[37]. However, in developing countries like Ethiopia, coffee byproducts are often left in specific areas for years or burned, and only a small number of farmers, many of whom lack access to proper information, use them as fertilizers. Some farmers utilize coffee husks for beverages and income generation, but their use as animal feed has not yet been widely reported. Therefore, Ethiopia should adopt existing technologies from abroad and allocate significant resources to research these valuable byproducts for enhanced utilization and sustainability.

Opportunities and challenges of byproducts

Opportunities: Coffee byproducts, such as coffee pulp, husks, and spent coffee grounds, can be utilized for various purposes, including animal feed, compost, biofuels, and even as raw materials for pharmaceuticals and cosmetics[15,17]. These byproducts offer versatile opportunities, benefiting both environmental sustainability and economic gains for producers by generating additional income streams for coffee farmers and processors, as well as improving soil quality[5,16]. Recycling coffee byproducts also enhances resource use efficiency within the coffee value chain. Instead of discarding these materials as waste, their utilization can reduce environmental pollution, promote a circular economy approach[38], and minimize waste generation[10]. Additionally, coffee pulp and husks contribute to soil improvement by being composted and used as organic fertilizers, enriching soil fertility[12] and enhancing crop productivity. This is particularly beneficial for smallholder coffee farmers who may have limited access to chemical fertilizers.

Energy production is another significant application of coffee byproducts[10,13]. Coffee husks and parchment are often overlooked byproducts of coffee production, but it serve as biomass fuels for heating and electricity generation. Their use helps reduce reliance on non-renewable energy sources and mitigate greenhouse gas emissions associated with traditional energy generation methods. Beyond their role in energy production, coffee byproducts can be transformed into high-value products such as coffee flour, extracts, and cosmetics[9]. By leveraging these opportunities, Ethiopian businesses can explore niche markets, diversify their offerings, and enhance their competitiveness in the global marketplace.

Constraints: In Ethiopia, the main constraints hindering the efficient utilization of coffee byproducts and the adoption of a circular economy include technological limitations, logistical challenges, and market access[13-39]. The collection, transportation, and storage of coffee byproducts can be particularly challenging, especially in remote coffee-growing regions with limited infrastructure. Addressing these logistical constraints may require investments in transportation networks and storage facilities.

The limitation of advanced technology is one of the key bottlenecks in commercializing coffee byproducts[31]. Some processing technologies for converting coffee byproducts into value-added products are costly or require specialized equipment and expertise. Limited access to appropriate technologies and technical know-how presents a significant challenge for small-scale producers and processors. Additionally, developing markets for coffee byproduct-derived products requires concerted marketing efforts to raise consumer awareness and generate demand. Furthermore, meeting regulatory requirements for food, pharmaceutical, or cosmetic products can create additional barriers to market access.

While coffee byproducts offer significant environmental benefits when properly managed, improper disposal or utilization practices can contribute to pollution and ecological degradation[31,40]. Addressing these concerns may require regulatory frameworks and enforcement mechanisms to ensure sustainable waste management practices. Additionally, in regions where coffee production is expanding, competition for land and water resources between coffee cultivation and other agricultural activities or natural ecosystems may limit the availability of coffee byproducts for alternative applications. Unlocking the full potential of coffee byproducts in Ethiopia requires targeted interventions, including investments in infrastructure, technology transfer, market development, and sustainable management practices. By implementing these strategies, Ethiopia can maximize the economic, social, and environmental benefits derived from its thriving coffee industry.

CONCLUSION

In Ethiopia, a significant amount of coffee byproducts are generated during both wet and dry processing methods. It is a huge resource with opportunities that can be utilized by producers and at the country level. However, due to mismanagement, the byproducts are causing environmental pollution and health risks to humans and animals. Still, there are gaps in technologies, regulations, and policies related to coffee byproducts that need to be addressed. Thus, investing in research, infrastructure, and market development initiatives could unlock their full potential and contribute to the sustainable development of the coffee industry.

SIGNIFICANCE STATEMENT

The mismanagement of coffee byproducts leads to environmental pollution and health problems for humans and animals, especially in developing countries. However, findings validated their versatile application opportunities in soil fertility improvement, energy production, animal feed, beverages, human nutrition, cosmetics, and pharmaceuticals. Their roles in the circular economy and repurposing for environmental benefit and value-added products chain have been identified as key factors for climate change mitigation and enhancing sustainable coffee production. Despite these opportunities, developing countries face constraints in fully exploiting their economic importance due to a lack of advanced tools and technology and logistical problems. The findings suggest that adopting the available technologies and investing in research and logistics could help developing countries. This information can also be used for academic purposes.

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