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REVIEW ARTICLE

Valorization of Coffee Pulp Agricultural, Nutritional, and Biotechnological Opportunities for Waste Utilization

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ABSTRACT

Coffee pulp, the primary by-product of wet coffee processing, has long been regarded as an environmental pollutant due to its bulkiness, high moisture content, and presence of anti-nutritional compounds. However, recent research has shifted this perspective, identifying coffee pulp as a valuable biomass rich in sugars, polyphenols, dietary fiber, and bioactive alkaloids. This review explores the multifaceted opportunities for coffee pulp valorization across agricultural, nutritional, and biotechnological domains. Agriculturally, composted or fermented pulp can enhance soil fertility, act as a green manure, or serve as animal feed after detoxification. In the food sector, coffee pulp is being used in functional beverages, high-fiber products, and as a natural antioxidant or antimicrobial agent. Biotechnologically, it supports fermentation processes to produce ethanol, organic acids, enzymes, pigments, and biodegradable plastics. Sustainability and circular economy perspectives show that valorizing coffee pulp reduces environmental burden, supports rural economies, and contributes to climate resilience. Despite these advances, challenges related to composition variability, detoxification, infrastructure, and policy remain. The article concludes by emphasizing the need for scalable biorefinery models, life cycle assessment, and inclusive value chain integration to fully realize coffee pulp's potential as a sustainable resource.

Key words: Coffee, Pulp, Compost, Bio-refinery, Poly-phenols, Waste valorization;

INTRODUCTION

Coffee is among the most consumed beverages globally, with annual production surpassing 10 million tons. The agro-industrial process of converting coffee cherries into green coffee beans, however, generates massive quantities of by-products—most notably coffee pulp, which constitutes nearly 40–50% of the fresh fruit weight (Esquivel & Jiménez, 2022). For every ton of coffee beans produced, approximately two tons of wet coffee pulp are discarded. This biomass, rich in organic matter and bioactive compounds, is frequently left to rot, dumped into water bodies, or incinerated causing serious environmental and ecological concerns, including water contamination, methane emissions, and phytotoxicity when applied unprocessed.

The traditional disposal of coffee pulp presents a paradox: while it is considered a waste due to its perishability, bulkiness, and phytochemical load (such as caffeine and tannins), it also contains valuable constituents that could be recovered through sustainable valorization processes. These include fermentable sugars, polyphenols, dietary fiber, proteins, pectins, organic acids, and pigments offering significant opportunities for its use in agriculture, food systems, animal feed, bioplastics, and bioenergy (Fan et al., 2023; Avelar et al., 2022). Yet, despite its potential, most coffee pulp remains underutilized, especially in developing countries where infrastructure for waste management and value chain integration is weak.

A growing body of research now positions coffee pulp as a promising resource for biocircular economy models. Its valorization aligns with global trends in sustainable agriculture, clean technology, and food system resilience. In particular, coffee pulp fits within the waste-to-value and zero-waste paradigms, which advocate for converting agricultural by-products into

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inputs for other industries, rather than discarding them. This also resonates with United Nations Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), which call for reduced waste generation through prevention, reduction, recycling, and reuse (FAO, 2023).

The valorization of coffee pulp can be broadly categorized into agricultural, nutritional, and biotechnological domains (Figure 1). Agriculturally, coffee pulp has been trialed as compost, green manure, animal feed, and mulch, offering benefits such as improved soil organic matter, erosion control, and nutrient recycling. However, its direct application is often limited by anti-nutritional factors (e.g., caffeine, phenolics) and high moisture content, which necessitate pre-treatment or microbial processing (Molina et al., 2023). Nutritionally, coffee pulp is being explored for its antioxidant and antimicrobial potential in functional food development, including teas, syrups, and fiber supplements. From a biotechnological standpoint, coffee pulp serves as a low-cost substrate for microbial fermentation to produce ethanol, organic acids, enzymes, pigments, and even bioplastics (Rodríguez-López et al., 2022). These innovations not only add economic value but also create green alternatives to fossil-based products.

Despite its promise, the valorization of coffee pulp faces key challenges, including seasonal availability, inconsistent composition, mycotoxin contamination risk, and the lack of scalable processing technologies. Moreover, regulatory hurdles for its use in food and feed remain significant in many countries, necessitating further research on safety, detoxification, and standardization. Addressing these gaps requires a multi-disciplinary approach involving food technologists, agronomists, microbiologists, and economists, as well as policy support to promote circular waste use.

This review aims to provide a comprehensive synthesis of current knowledge and emerging opportunities for coffee pulp valorization. It covers the chemical and nutritional composition of coffee pulp, highlights its agricultural and nutritional applications, and explores advanced biotechnological routes for conversion into high-value products. In addition, the review discusses sustainability, life cycle, and economic perspectives to contextualize its practical viability. By integrating insights from multiple disciplines, this article seeks to inform researchers, entrepreneurs, and policy-makers of the diverse ways in which coffee pulp, once seen as a nuisance, can be transformed into a valuable resource within sustainable agricultural and industrial ecosystems.

Chemical and Nutritional Composition of Coffee Pulp

Coffee pulp is a rich but complex matrix of bioactive and structural compounds, making it both a promising source of nutrients and a challenge to process. Generated during the wet processing of coffee cherries, the pulp consists of the outer skin and a portion of the mesocarp. Its chemical and nutritional profile is influenced by factors such as coffee variety (*Coffea arabica* or *Coffea canephora*), cultivation altitude, post-harvest handling, and fermentation method. This variability underscores the importance of compositional characterization for tailoring valorization pathways, whether in agriculture, food, or biotechnology.

The major constituents of coffee pulp include carbohydrates (30–45%), proteins (8–11%), lipids (1–2%), fiber (20–30%), and minerals (Ca, K, Mg, P). On a dry weight basis, soluble sugars, such as glucose, fructose, and sucrose, account for a significant portion of total carbohydrates, making the pulp a viable substrate for microbial fermentation (Avelar et al., 2022). The fiber fraction, composed largely of cellulose, hemicellulose, and lignin, contributes to its use as a bulking agent and dietary fiber source in food applications. High potassium content (>2% dry basis) also supports its use in composting and soil amendment (Molina et al., 2023).

Coffee pulp is particularly notable for its content of bioactive compounds:

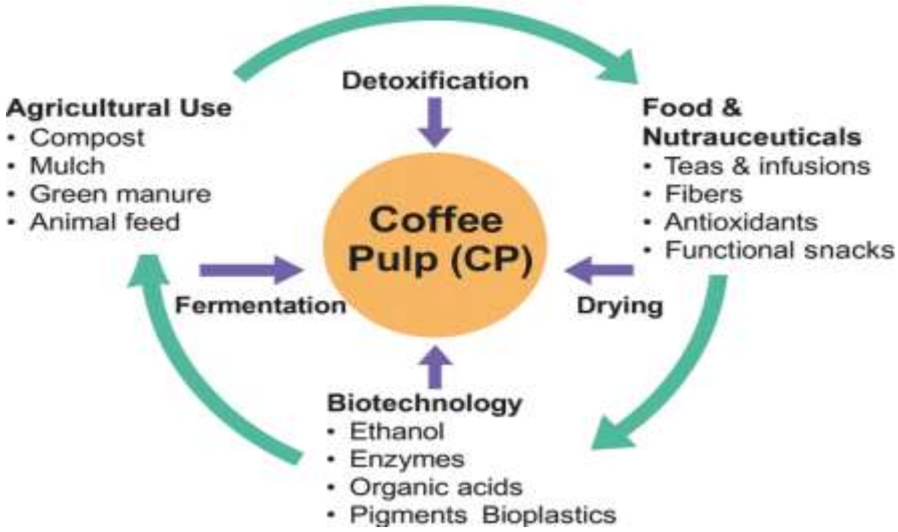

Fig 1: The major valorization routes for coffee pulp (CP) across agricultural, nutritional, and biotechnological domains.

- **Phenolic compounds** (0.5–2.5%): including chlorogenic acids, catechins, and ferulic acid, which provide antioxidant and antimicrobial properties
- **Caffeine** (0.7–1.3% dry basis): a methylxanthine alkaloid with known physiological effects and phytotoxic potential
- **Tannins** and other **polyphenols**: contributing to antioxidant activity but also associated with protein binding and anti-nutritional effects (Esquivel & Jiménez, 2022).

The antioxidant capacity of coffee pulp extracts is well documented and typically correlates with total phenolic content. DPPH, ABTS, and FRAP assays consistently report high scavenging activity, making it a candidate for functional food additives and natural preservatives (Fan et al., 2023). Additionally, several studies have demonstrated moderate antimicrobial activity of coffee pulp extracts against Gram-positive bacteria and some fungi, attributed to synergistic actions of phenolics and alkaloids (Rodríguez-López et al., 2022).

Nutritionally, the protein quality of coffee pulp is modest. While it contains essential amino acids like lysine and leucine, its overall biological value is limited by low digestibility and the presence of anti-nutritional factors. Nonetheless, when combined with enzymatic hydrolysis or microbial fermentation, protein bioavailability improves significantly, opening possibilities for its use in animal feed and protein-enriched foods (Menezes et al., 2023).

From a safety perspective, coffee pulp contains several anti-nutritional compounds that restrict its direct application. These include:

- **Caffeine and tannins**, which can interfere with protein and mineral absorption.
- **Phytates**, which chelate essential micronutrients like iron and zinc.
- **Condensed polyphenols**, which may impart bitterness and reduce palatability.
- Potential **mycotoxins**, especially if stored improperly under humid conditions.

Detoxification through fermentation, washing, or thermal treatment is commonly employed to reduce these compounds to acceptable levels, particularly when the pulp is intended for feed or food applications (Molina et al., 2023). Recent studies also report promising results with fungal solid-state fermentation to degrade caffeine and polyphenols while enhancing protein and flavor profiles (Alemayehu et al., 2022).

Importantly, the nutrient density and functional properties of coffee pulp support its valorization in multiple domains:

- In **food systems**, as a source of natural antioxidants, dietary fiber, and functional ingredients.
- In **agriculture**, as a compost enhancer and potassium-rich soil conditioner.
- In **biotechnology**, as a fermentation feedstock for enzymes, ethanol, and organic acids.

Nevertheless, variability in composition—driven by environmental, genetic, and processing factors—presents a barrier to standardization. Hence, thorough proximate and phytochemical analyses are essential before industrial application. Technologies such as near-infrared spectroscopy (NIRS) and HPLC-MS are increasingly being used for rapid compositional profiling and quality control (Silva et al., 2023).

Coffee pulp is not merely an agricultural residue, but a bioresource with significant nutritional and functional potential. Its valorization must, however, be guided by a clear understanding of its chemical complexity, toxicity risks, and variability, which can be addressed through appropriate treatment and standardization protocols.

Agricultural Applications

The potential of coffee pulp in agriculture lies in its organic richness, bioactive content, and mineral profile. Traditionally viewed as a waste by-product, coffee pulp has increasingly been explored for agricultural applications including composting, soil amendment, mulch, and animal feed. However, its use remains largely localized, experimental, or constrained by its inherent anti-nutritional factors. Optimizing its application requires not only proper treatment but also a clear understanding of its interactions with soil, plant systems, and microbial ecology.

One of the most established uses of coffee pulp in agriculture is in the preparation of compost. Composting coffee pulp transforms a highly biodegradable and phytotoxic waste into a stable organic amendment. Due to its high carbon-to-nitrogen (C/N) ratio, caffeine content, and polyphenols, raw coffee pulp can suppress seed germination and hinder microbial activity if applied directly. However, through aerobic composting, often combined with other agricultural residues such as cow dung, sugarcane bagasse, or poultry litter, these toxic compounds are broken down and microbial populations are stabilized. Compost derived from coffee pulp enhances soil structure, moisture retention, and nutrient availability, particularly potassium, calcium, and organic carbon. It has been shown to increase microbial biomass and stimulate enzymatic activity essential for nutrient cycling in degraded soils (Molina et al., 2023; Lemessa et al., 2022).

In smallholder coffee-growing regions such as Ethiopia, Colombia, and Brazil, farmers apply composted or semi-composted coffee pulp as green manure or mulch. These practices reduce soil erosion, improve aggregate stability, and suppress weed growth. Coffee pulp mulch has also been observed to reduce surface temperature fluctuations and increase water infiltration, thereby supporting plant growth under semi-arid conditions. Nevertheless, the application of non-composted pulp has been reported to cause phytotoxicity, nitrogen immobilization, and acidification, especially in poorly buffered soils (Fan et al., 2023). Therefore, pre-treatment through aerobic fermentation or co-composting is considered essential for field safety and efficacy.

Another promising, yet controversial, use of coffee pulp is as a component of animal feed, particularly for ruminants. Its carbohydrate and fiber content make it suitable as a partial feed supplement, but its inclusion rate is limited by caffeine, tannins, and potential mycotoxins. Feeding trials in cattle and goats have shown that dried, ensiled, or fermented coffee pulp can be used at inclusion levels up to 15–20% of the total diet without adverse effects on growth performance or feed intake. However, higher inclusion rates often lead to reduced palatability, digestive stress, and potential residue accumulation in animal products (Alemayehu et al., 2022). Pre-treatments such as urea-ammoniation, lactic acid fermentation, or fungal detoxification have been explored to improve the safety and digestibility of coffee pulp-based feeds.

Beyond its macronutrient contribution, coffee pulp is rich in secondary metabolites that influence plant-microbe-soil interactions. Its phenolic compounds and organic acids have demonstrated allelopathic properties that, when properly managed, can suppress soil-borne pathogens and weeds. Compost tea derived from coffee pulp has shown antifungal activity against *Fusarium* spp. and *Rhizoctonia solani*, although the variability in bioactive concentration remains a challenge for standardization (Rodríguez-López et al., 2022). In integrated pest and nutrient management systems, coffee pulp may offer dual benefits enhancing soil fertility while contributing to biological disease control.

However, the accumulation of heavy metals or pesticide residues in coffee pulp, depending on cultivation practices, poses an emerging concern. While most studies report metal concentrations within acceptable limits for soil application, long-term and repeated use without monitoring may lead to unwanted buildup, particularly of copper and zinc. Therefore, routine chemical profiling of pulp and proper recordkeeping are recommended for safe reuse in agriculture (Esquivel & Jiménez, 2022).

Economically, the use of coffee pulp as a low-cost soil amendment is attractive in regions with limited access to synthetic fertilizers. However, the logistical challenges of transporting and handling large volumes of wet biomass reduce its appeal unless integrated into localized circular systems. Innovations such as pelletization, co-composting hubs, or mobile fermentation units could improve the feasibility and scalability of agricultural valorization.

Nutritional and Functional Food Potential

Coffee pulp, though traditionally considered an agricultural by-product, is increasingly gaining attention for its potential in the food and nutraceutical sectors. Rich in polyphenols, dietary fiber, and bioactive alkaloids, this material contains functional constituents that align with modern trends in health-conscious consumption, clean-label products, and natural antioxidants. However, unlocking its food potential requires targeted strategies to detoxify, standardize, and incorporate its components into food systems while ensuring consumer safety and regulatory compliance.

One of the most explored food-related avenues of coffee pulp valorization is the extraction of bioactive compounds such as chlorogenic acids, caffeine, flavonoids, and tannins. These compounds exhibit notable antioxidant, anti-inflammatory, and antimicrobial properties that are valuable in both food preservation and health promotion (Fan et al., 2023). Chlorogenic acids, in particular, are known to modulate glucose metabolism and exhibit lipid-lowering effects, making them candidates for functional beverages and dietary supplements (Silva et al., 2023). Several studies have demonstrated that aqueous or ethanol-based extracts of coffee pulp possess antioxidant activity comparable to that of synthetic antioxidants like BHT and ascorbic acid in lipid systems.

In terms of direct incorporation into functional food products, coffee pulp has been formulated into infusions, teas, syrups, jams, bakery products, and high-fiber snacks. Dried and milled coffee pulp has been successfully blended with wheat or maize flour to produce fiber-rich cookies and bread with enhanced shelf life due to its natural antimicrobial compounds. The dietary fiber content, primarily composed of insoluble fibers such as cellulose and lignin, offers gut health benefits and helps improve bowel movement and glycemic control when consumed regularly (Menezes et al., 2023). Soluble fiber fractions also contribute to prebiotic activity, supporting beneficial microbiota in the human gut.

The development of coffee pulp teas has gained commercial traction in several countries, marketed as a source of natural energy and antioxidants. These infusions contain moderate levels of caffeine and polyphenols, resembling a milder version of green tea or yerba mate. However, caffeine content must be standardized to ensure safety, especially for vulnerable populations. Regulatory labeling guidelines require clear disclosure of caffeine levels and any added extracts to comply with food safety standards in Europe, the U.S., and parts of Asia (FAO, 2023).

Despite these promising developments, one of the major challenges is the presence of anti-nutritional factors and toxins, particularly caffeine, tannins, and potential mycotoxins. Caffeine, although a desired component in energy products, must be carefully controlled in food applications to avoid overexposure, especially in products marketed to children or pregnant women. Tannins, while contributing to antioxidant activity, may interfere with iron absorption and cause astringency, affecting taste and palatability. Mycotoxin contamination, such as ochratoxin A, may occur during improper storage and drying of coffee pulp under humid conditions. Therefore, detoxification methods such as washing, fermentation, drying, or enzymatic hydrolysis are essential prior to food application (Alemayehu et al., 2022).

Microbial fermentation is a particularly promising approach to improve safety and enhance nutritional profiles. Fermentation with lactic acid bacteria or fungi not only reduces caffeine and tannin content but also increases the availability of free amino acids and beneficial peptides. Fermented coffee pulp extracts have been shown to enhance antioxidant activity and produce mild, pleasant flavors suitable for food product formulation (Rodríguez-López et al., 2022). Solid-state fermentation has also been applied to produce polyphenol-enriched powders that can be used in capsules or as beverage fortifiers.

Coffee pulp is also being explored as a source of natural preservatives in minimally processed foods. Its antimicrobial activity against pathogens like *E. coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* has been demonstrated in vitro and in model food systems. Extracts used in meat or dairy products have shown effectiveness in reducing microbial spoilage, extending shelf life, and reducing the need for synthetic additives (Molina et al., 2023). These applications fit into the growing demand for "clean-label" functional ingredients, particularly in the organic and natural foods sector.

While laboratory and pilot-scale studies show high promise, the commercial scale-up of coffee pulp for food applications still faces hurdles. Standardization of composition, sensory optimization, toxicity clearance, and regulatory approval are critical bottlenecks. Variability in raw material composition due to geography, coffee species, and post-harvest processing complicates the formulation of uniform food products. Moreover, consumer perceptions about safety and flavor need to be addressed through proper branding, transparency, and education.

Biotechnological Valorization Approaches

The transformation of coffee pulp into value-added products through biotechnological processes has emerged as a promising solution to address its environmental burden and unlock its full potential as a renewable biomass resource. Owing to its high content of fermentable sugars, polyphenols, organic acids, and structural carbohydrates, coffee pulp serves as an excellent substrate for microbial and enzymatic conversion into a variety of bio-based commodities. These include bioethanol, organic acids, enzymes, bioplastics, and microbial pigments (Fig 2). The advancement of bioconversion techniques not only reduces waste but also contributes to a circular bioeconomy, aligning with sustainability goals and industrial decarbonization.

One of the earliest and most extensively studied applications of coffee pulp is its use in ethanol production. Both solid-state fermentation (SSF) and submerged fermentation (SmF) methods have been employed using *Saccharomyces cerevisiae*, *Zymomonasmobilis*, and *Kluyveromycesmarxianus*. Due to the high content of simple sugars such as glucose and fructose, hydrolysis is often not required for initial fermentation. However, pre-treatment such as thermal drying or acid washing improves fermentability and reduces inhibitory compounds like caffeine and phenolics (Molina et al., 2023). Ethanol yields of up to 45 g/L have been reported in optimized SSF setups, suggesting its feasibility for decentralized biofuel production in coffee-producing regions (Rodríguez-López et al., 2022). Besides ethanol, coffee pulp is a viable feedstock for the microbial production of organic acids including citric acid, lactic acid, and acetic acid. Fermentation with *Aspergillus niger* or *Lacto-bacillus spp.* enables the production of citric and lactic acids, respectively, both of which are widely used in food preservation and pharmaceutical industries. Citric acid yields from coffee pulp hydrolysates have reached up to 60 g/L under controlled fermentation conditions (Alemayehu et al., 2022). Similarly, the production of polyhydroxy alkanoates (PHAs), a class

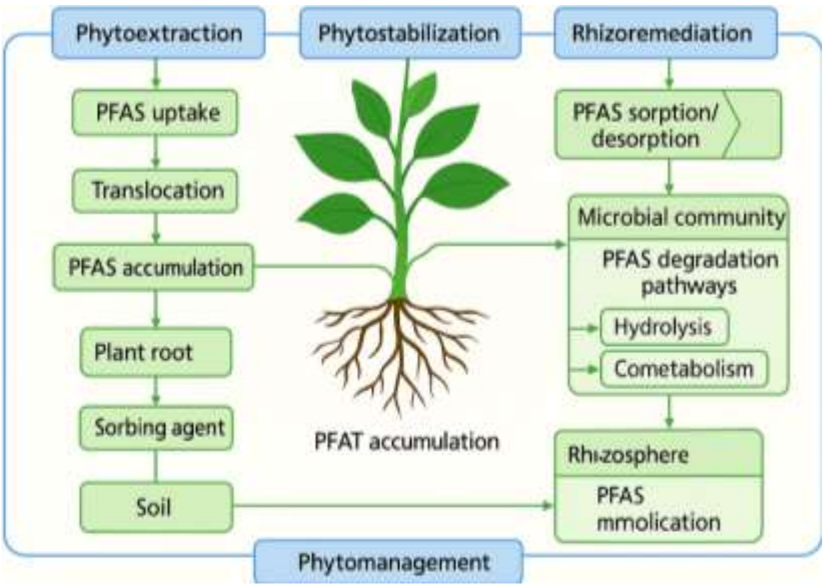

Fig 2: A schematic representation of key biotechnological processes for the conversion of coffee pulp into bio-based commodities. Pre-treated coffee pulp serves as a substrate for microbial fermentation leading to ethanol production (via *Saccharomyces cerevisiae*, *Zymomonas-mobilis*), enzyme synthesis (via *Aspergillus* spp., *Trichoderma* spp.), and organic acid production (e.g., citric and lactic acids). Additional pathways include the generation of biodegradable polyhydroxyalkanoates (PHAs) using *Cupriavidusnecator* and natural pigments using *Monascus* and *Talaromyces* species. These processes form the basis of integrated biorefinery models, supporting sustainable waste valorization and industrial decarbonization.

of biodegradable bioplastics, has been demonstrated using *Cupriavidusnecator* grown on coffee pulp extract, offering a sustainable alternative to petroleum-derived plastics (Gouvea et al., 2023).

Another high-potential area is the use of coffee pulp in enzyme production. Several fungi, including *Trichoderma reesei*, *Penicillium spp.*, and *Aspergillus spp.*, have been cultivated on coffee pulp to produce cellulases, xylanases, and pectinases. These enzymes are essential in food processing, textile, and biofuel industries. Coffee pulp provides both the carbon and nitrogen sources necessary for fungal growth, and SSF methods have proven particularly efficient in enzyme yields and cost-effectiveness (Menezes et al., 2023). Additionally, co-fermentation with other agro-industrial residues such as wheat bran or sugarcane bagasse further enhances enzymatic output.

Microbial pigment production is a relatively recent but exciting frontier in coffee pulp valorization. *Monascus purpureus*, *Talaromyces spp.*, and *Serratia marcescens* have been used to convert coffee pulp sugars into natural colorants with antioxidant and antimicrobial properties. These pigments are increasingly sought after in cosmetics and natural food coloring, offering non-toxic, biodegradable alternatives to synthetic dyes (Fan et al., 2023).

The pretreatment of coffee pulp is a crucial step in most biotechnological processes. Alkaline or dilute acid pretreatments are employed to break down lignocellulosic structures and improve enzymatic access. However, these methods must balance efficiency with environmental safety, as excessive use of chemicals can lead to effluent toxicity. More sustainable approaches, such as biological pretreatment using lignin-degrading fungi, are under investigation for preserving the bioactive properties of coffee pulp while improving fermentability (Silva et al., 2023).

Recent advancements in genetic and metabolic engineering have expanded the toolkit for bioconversion. Engineered microbial strains now possess enhanced tolerance to caffeine, improved substrate uptake, and optimized metabolic pathways for producing target compounds. For instance, modified strains of *Escherichia coli* and *Corynebacterium glutamicum* have been tailored to ferment coffee pulp hydrolysates into high-value amino acids and biosurfactants. These technologies open new possibilities for integrating coffee pulp into biorefinery platforms that can co-produce multiple products from a single feedstock (Gatica & Cytryn, 2022).

The integration of coffee pulp into biorefinery concepts which emphasize total biomass utilization represents the pinnacle of valorization. A typical model might involve initial extraction of phenolics and caffeine, followed by microbial fermentation of sugars into ethanol or acids, and finally anaerobic digestion of residual biomass into biogas or compost. Such cascaded use not only maximizes economic return but also minimizes waste generation. Pilot-scale bio-refineries in Colombia and Brazil have demonstrated the viability of these models, although scalability, regulatory hurdles, and consistent feedstock supply remain significant challenges (FAO, 2023).

Sustainability and Economic Perspectives

The valorization of coffee pulp offers not only technological and nutritional potential but also profound implications for sustainability, waste management, and rural development. As coffee remains one of the most globally traded commodities, its associated waste streams particularly coffee pulp have grown to represent a significant environmental challenge and an untapped bioresource. From a sustainability perspective, coffee pulp valorization supports the principles of circular economy, zero-waste agriculture, and climate-resilient rural livelihoods. However, the economic feasibility of such processes hinges on scalability, infrastructure, and the integration of local value chains.

One of the key sustainability drivers of coffee pulp valorization is its contribution to waste reduction and resource efficiency. In many coffee-producing countries, especially in Latin America, Africa, and Southeast Asia, wet processing of coffee generates substantial organic waste that, when unmanaged, leads to leachate pollution, methane emissions, and eutrophication of nearby water bodies (FAO, 2023). Converting this waste into inputs for agriculture, food, or bioindustry can significantly reduce the environmental footprint of coffee production while also mitigating the greenhouse gas emissions associated with uncontrolled pulp decomposition.

Coffee pulp also contributes to soil restoration and climate-smart agriculture when composted or used as biofertilizer. It helps build soil organic matter, enhance microbial diversity, and improve water retention features that are critical under climate stress scenarios such as prolonged droughts or nutrient depletion. These practices align with regenerative agriculture principles and reduce dependency on synthetic fertilizers, whose production and transport are carbon-intensive (Molina et al., 2023). Furthermore, by promoting on-farm recycling of waste, coffee pulp reduces input costs and supports the long-term productivity of smallholder farming systems.

From an economic perspective, coffee pulp valorization presents multiple pathways for value creation. The extraction of bioactives, such as chlorogenic acid or polyphenols, commands premium markets in the nutraceutical and functional food sectors. The production of microbial enzymes or fermentation-derived ethanol has shown favorable profit margins under decentralized, small-scale models, especially when integrated with local supply chains. Cost–benefit analyses conducted in pilot-scale operations in Colombia and Ethiopia indicate that fermented coffee pulp products such as silage, ethanol, or compost can yield positive net returns when logistics, labor, and pre-treatment costs are optimized (Alemayehu et al., 2022).

The economic sustainability of coffee pulp valorization improves significantly when designed as part of an integrated biorefinery model. In such systems, different components of coffee pulp sugars, polyphenols, fiber are fractionated and used to generate multiple products. For instance, initial polyphenol extraction can be followed by fermentation of residual sugars into ethanol, while the fibrous residue can be composted or used for animal bedding. Such cascade utilization maximizes resource use and minimizes waste generation, improving both the ecological and financial performance of the system (Rodríguez-López et al., 2022).

Techno-economic assessments (TEAs) and life cycle assessments (LCAs) are increasingly used to evaluate the environmental and economic trade-offs of various valorization routes. TEAs consider capital investment, operational costs, revenue generation, and payback periods under different scenarios (manual vs. automated processing, centralized vs. decentralized). LCAs, on the other hand, quantify the overall carbon footprint, water usage, and pollutant emissions across the product lifecycle. Studies comparing composting, ethanol production, and enzyme fermentation from coffee pulp consistently show that, while initial investment may be high, the long-term environmental benefits and potential revenues outweigh the costs under optimized conditions (Fan et al., 2023; Gouvea et al., 2023).

Nevertheless, several barriers to economic scalability remain. These include the seasonal availability of coffee pulp, variability in its composition, the bulkiness of wet biomass, and the high transportation costs in rural or mountainous regions. Innovations in drying, densification, and preservation are necessary to overcome logistical hurdles and stabilize raw material quality. Moreover, the lack of established markets for coffee pulp-based products and insufficient policy support continue to constrain investment. Market development strategies, including certification schemes (e.g., organic, zero-waste), branding, and consumer education, are essential to stimulate demand and confidence in these products.

An often-overlooked benefit of coffee pulp valorization lies in its potential for rural entrepreneurship and job creation. Small-scale enterprises focused on compost production, functional beverage development, or artisanal bio-cosmetics using coffee pulp extracts have begun to emerge in coffee-growing regions. These businesses create new income streams for producers, particularly women and youth, and support inclusive development by adding value locally rather than exporting raw material alone (FAO, 2023). The establishment of cooperative processing units, facilitated by NGOs or rural extension services, can further empower farmers to collectively invest in and benefit from coffee pulp-based enterprises.

Conclusion and Future Directions

The global expansion of the coffee industry has brought with it the challenge of managing vast amounts of agro-industrial waste, particularly coffee pulp. Long considered an environmental liability, coffee pulp is now increasingly recognized as a versatile bio-resource with the potential to support sustainable agriculture, nutrition, and industrial biotechnology. Its rich composition featuring fermentable sugars, poly-phenols, fiber, and bioactive compounds makes it well-suited for a variety of valorization pathways that align with circular economy and zero-waste principles.

This review has highlighted the chemical and nutritional attributes of coffee pulp, underscoring its role as a source of antioxidants, dietary fiber, and functional metabolites. In agriculture, composted or treated pulp enhances soil fertility, microbial activity, and crop performance, while detoxified pulp shows potential as a supplementary feed for ruminants. In the food sector, functional products such as teas, high-fiber snacks, and natural preservatives derived from coffee pulp can meet the rising demand for clean-label, health-oriented goods. Biotechnologically, coffee pulp has demonstrated value as a substrate for fermentation-based production of bioethanol, organic acids, enzymes, pigments, and biodegradable plastics. These opportunities not only reduce environmental burden but also contribute to value chain diversification, rural development, and industrial sustainability.

However, several critical gaps and challenges must be addressed to fully integrate coffee pulp into commercial and sustainable use. These include:

- **Toxicity mitigation**, particularly the standardization of detoxification methods to ensure safety in food and feed applications.
- **Variability in composition**, which limits consistency in processing and product formulation.
- **Infrastructure and logistics**, especially in rural areas where pulp is abundant but processing facilities are lacking.
- **Regulatory frameworks**, which are still evolving and often lack specific guidelines for novel products derived from agricultural waste.

Future research should focus on scalable detoxification and stabilization techniques, strain engineering for high-yield fermentation, and biorefinery models that optimize the cascade utilization of pulp components. Integrating life cycle analysis (LCA) and techno-economic assessment (TEA) into development plans will help identify the most sustainable and profitable valorization routes. Importantly, participatory models involving farmers, processors, and local entrepreneurs will be essential to ensure that coffee pulp valorization contributes not only to environmental goals but also to inclusive economic development.

In conclusion, coffee pulp is not waste it is a latent resource whose full potential lies in multidisciplinary innovation and coordinated action. With thoughtful investment in research, infrastructure, and policy, this abundant biomass can be transformed from an environmental concern into a cornerstone of green growth in coffee-producing regions worldwide.

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