

Original Research Paper

## Coffee Processing Technology: From Waste to Value

Rucitra Widyasari<sup>1\*</sup>, Satrijo Saloko<sup>1</sup>, Murad<sup>2</sup>, Sukmawaty<sup>2</sup>, Rahmat Sabani<sup>2</sup>, Joko Sumarsono<sup>2</sup>, I Wayan Sweca Yasa<sup>1</sup>, Ansar<sup>2</sup>, Wiharyani Werdiningsih<sup>1</sup>, Made Gendis Putri Pertiwi<sup>1</sup>, Reza Kusuma Nurrohman<sup>2</sup>, Yuhendra AP<sup>2</sup>, Endang Purnama Dewi<sup>2</sup>, Yesica Marcelina Romauli Sinaga<sup>1</sup>, Diah Ajeng Setiawati<sup>2</sup>, Isnaini Puspitasari<sup>2</sup>, Wenny Amaliah<sup>2</sup>, Tri Isti Rahayu<sup>1</sup>, Lingga Gita Dwikasari<sup>1</sup>, Firman Fajar Perdana<sup>1</sup>, Ince Siti Wardatulatifah S<sup>2</sup>, Fuad Sauqi<sup>1</sup>, Mi'raj Fuadi<sup>2</sup>, Fakhrol Irfan Khalil<sup>2</sup>, Rini Nofrida<sup>1</sup>, Yeni Sulastri<sup>1</sup>, Ida Ayu Widhiantari<sup>2</sup>, Hary Kurniawan<sup>2</sup>, Qabul Dinanta Utama<sup>1</sup>, Agriananta Fahmi Hidayat<sup>2</sup>, Gagasage Nanaluh De Side<sup>2</sup>, Setyaning Pawestri<sup>1</sup>, Rosnah Shamsudin<sup>3</sup>, Zanariah Mohd Dom<sup>3</sup>, Nur Hamizah Abdul Ghani<sup>3</sup>, Revata Anwar<sup>1</sup>, Attar Riza Maulana<sup>1</sup>, Surya Ananda Firmansyah<sup>2</sup>, I Kadek Widiastawan<sup>2</sup>, Ingka Wira Yuda<sup>2</sup>.

<sup>1</sup> Food Science and Technology Department, University of Mataram, Mataram, Indonesia;

<sup>2</sup> Agricultural Engineering Department, University of Mataram, Mataram, indoneisa;

<sup>3</sup> Departement of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, Malaysia.

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\*Corresponding Author:

Rucitra Widyasari, University of Mataram, Mataram, Indonesia;

Email:

[rucitrawidyasari@unram.ac.id](mailto:rucitrawidyasari@unram.ac.id)

**Abstract:** Coffee is one of the most widely traded agricultural commodities globally, generating substantial volumes of by-products and waste streams throughout its processing chain. These by-products including coffee pulp, cascara, mucilage, parchment, silverskin, and spent coffee grounds represent a significant environmental burden when improperly managed, yet simultaneously constitute a rich reservoir of bioactive compounds and valorizable biomass. This manuscript presents a community engagement initiative focused on disseminating and implementing coffee processing technologies that transform waste streams into value-added products, aligned with circular bioeconomy principles. The activity was conducted on 22 April 2026 with participants are small and medium enterprises (SMEs) KWT Kaki Rinjani in Karang Sidemen Village, Central Lombok with the . The session was delivered directly by Prof. Rosnah Shamsudin that introduced *aerospace* 3.0 the latest small-scale coffee press from UPM. accompanied with theoretical presentation technique drying of coffee, waste treatment and sensory demonstration of functional coffee conducted from Fatepa-Unram. The expected outcomes include enhanced technical and entrepreneurial capacities among SME actors, improved ability to design functional coffee product, and waste treatment of coffee into valuable product. The long-term impact is the creation of a more resilient SMEs ecosystem in Karang Sidemen Village, with a portfolio of functional, high-value coffee products. Furthermore, optimizing the management of production waste is projected to significantly reduce environmental burdens while opening up new income diversification opportunities for the community. Ultimately, the sustainability of this program will strengthen local coffee's position as a leading commodity managed innovatively, efficiently, and environmentally friendly.

**Keywords:** Coffee; community engagement; central lombok; drying coffee; functional food; waste treatment.

## Introduction

Coffee stands as one of the most widely consumed beverages on the planet, representing the second largest traded commodity in the world after petroleum (Atabani et al., 2022). Its global popularity has driven an unprecedented surge in production and consumption, with coffee grown in approximately 80 countries, with Brazil, Vietnam, and Colombia serving as the primary producers and exporters (Atabani et al., 2022). However, this extraordinary level of consumption comes with a profound and often underappreciated environmental cost: the generation of massive quantities of waste at virtually every stage of the coffee supply chain, from farm to cup (Durán-Aranguren et al., 2021; Hamedani et al., 2025).

The scale of coffee waste generation is staggering. Global coffee production delivers over 23 million tons of waste annually (Durán-Aranguren et al., 2021; Rebollo-Hernanz et al., 2023), while the worldwide production of coffee waste from the coffee industry alone is estimated at around 10 million tons per year (Pandey et al., 2025). Only 50–55% of the harvested coffee fruit ultimately becomes the final consumable product, leaving approximately 8 million tons of residual waste generated each year (Nutrizio et al., 2024). These figures underscore a critical and urgent challenge: the coffee industry, as currently structured along a predominantly linear economic model, is deeply inefficient and environmentally burdensome (Hamedani et al., 2025; Sisti et al., 2021).

The process of obtaining coffee involves several sequential steps, including de-pulping, fermenting, washing, drying, roasting, and brewing, all of which generate significant residues at each stage (Hamedani et al., 2025). These residues include coffee pulp, coffee husk, mucilage, parchment, silver skin, and spent coffee grounds (SCG), collectively representing more than 50% of the coffee fruit by weight (Hamedani et al., 2025; Pandey et al., 2025). For every ton of green coffee produced, the byproducts of the process account for approximately 500 kg of coffee pulp, 180 kg of coffee husk, and 650 kg of spent coffee grounds, along with other minor byproducts such as coffee silver skin, coffee parchment, and mucilage (Stufano et al., 2022). A significant quantity of waste, ranging from 40 to 45% of total coffee cherry mass, is generated during the coffee production process

(Hamedani et al., 2025), and these materials are frequently discarded without further valorization, posing serious environmental hazards (Rebollo-Hernanz et al., 2023).

When coffee waste is improperly disposed of in landfills, it generates methane a potent greenhouse gas thereby accelerating global warming (Hutabarat & Mangindaan, 2024). Furthermore, the high concentrations of caffeine, tannins, and polyphenols present in coffee by-products can be toxic to plants and aquatic life, making their uncontrolled disposal a significant ecological threat (Mak et al., 2023; Meduri et al., 2025). Coffee processing wastewater also represents a major pollution vector, particularly in coffee-producing regions where wet processing methods are prevalent (Plaza-Dorado et al., 2023). These environmental realities make the valorization of coffee waste not merely an academic exercise but an urgent practical necessity.

In response to these challenges, the principles of the circular economy have gained increasing traction as a framework for transforming the coffee industry's relationship with its waste streams (Hamedani et al., 2025; Sisti et al., 2021). Rather than following the traditional linear model of "take-make-dispose," the circular economy envisions a system in which waste materials are continuously cycled back into productive use, generating economic value while minimizing environmental impact (Ahmed et al., 2024; Song et al., 2026). Implementing circular economy practices can drive sustainability in the coffee sector, creating new economic opportunities while simultaneously reducing the industry's environmental footprint (Hamedani et al., 2025).

Research has demonstrated that upcycling coffee waste has significant environmental benefits, including waste reduction to landfills and substantial carbon savings (Hamedani et al., 2025). For instance, one documented case study found that the valorization of 8 metric tons of used coffee grounds from landfill sites resulted in CO<sub>2</sub> equivalent savings of 1,506.47 kg (Hamedani et al., 2025). By transforming waste coffee into biofuels, bio-based products, and fertilizers, the environmental footprint of coffee production can be substantially minimized, particularly by preventing methane emissions from decomposing organic waste in landfills (Hamedani et al., 2025; Saldaña-Mendoza et al., 2022).

The concept of a biorefinery in which integrated processes are used to produce a broad range of goods and energy from a single biomass source has emerged as a particularly promising approach to coffee waste valorization (Ahmed et al., 2024). Coffee by-products are rich in a diverse array of bioactive compounds, including polyphenols, carotenoids, organic acids, cellulose, hemicellulose, lignin, lipids, and proteins, all of which represent valuable raw materials for industries ranging from food and pharmaceuticals to materials science and energy (Bairwan et al., 2024; Sisti et al., 2021). The valorization of these compounds through biorefinery strategies represents a clear example of waste-to-value transformation that aligns with both environmental sustainability goals and economic development imperatives (Sisti et al., 2021; Rebollo-Hernanz et al., 2023).

Understanding the specific waste streams generated by different coffee processing methods is essential for designing effective valorization strategies. Two primary post-harvest processing methods are employed globally: the dry (natural) method and the wet (washed) method (Rebollo-Hernanz et al., 2023; Ruță & Fărcășanu, 2021). Following these primary processing steps, the green coffee beans undergo roasting, during which the thin tegument covering the bean known as the silver skin or coffee silverskin (CS) is detached and represents the only by-product of the coffee roasting industry (Iriundo-DeHond et al., 2020). Finally, roasted beans are ground and brewed, generating spent coffee grounds (SCG) as the last and most voluminous coffee by-product (Iriundo-DeHond et al., 2020). SCG represents the most abundant residue generated during processing, with approximately 0.6 tons produced per ton of coffee, while coffee pulp and husks account for 0.50 and 0.18 tons per ton of fresh coffee, respectively (Mak et al., 2023). Globally, spent coffee grounds are produced in quantities of up to 6,000,000 tonnes per year, primarily as a result of instant coffee production (Meduri et al., 2025).

The chemical richness of coffee by-products makes them exceptionally promising candidates for valorization across multiple sectors. Coffee pulp, husks, and spent grounds are repurposed as manure, compost, or biochar in agriculture, which can increase soil fertility, enhance water retention capacity, and reduce the use of synthetic fertilizers (Hamedani et al., 2025). Coffee husks and pulp are

considered rich sources of minerals, especially potassium, making this residual waste suitable as organic fertilizer, primarily in potassium-deficient soils (Pandey et al., 2025). Coffee waste is also used as a substrate for mushroom cultivation, demonstrating the breadth of its agricultural applications (Hamedani et al., 2025).

Beyond agriculture, coffee by-products have demonstrated significant potential for the production of biofuels, including biodiesel, bioethanol, bio-oil, biochar, and biogas (Sisti et al., 2021; Saldaña-Mendoza et al., 2022). The high oil content of SCG ranging from 10% to 30% of dry weight depending on the brewing technique, variety, and extraction method makes biodiesel production a particularly attractive valorization pathway (Durán-Aranguren et al., 2021). Coffee-derived biodiesel has been shown to contribute to an 80.5% reduction in CO<sub>2</sub> emissions compared to conventional diesel during its life cycle (Saldaña-Mendoza et al., 2022). Additionally, SCG can be converted into fuel pellets with a best lower calorific value of 21.08 MJ/kg, representing a viable alternative fuel source (Atabani et al., 2022).

In the realm of materials science, coffee waste has been explored as a filler in polymer matrices to create eco-friendly composites with improved mechanical, antioxidant, and antibacterial properties (Bairwan et al., 2024). Coffee husk fibers, known for their long and fibrous nature, exhibit high aspect ratios and rough surface textures that facilitate strong interfacial bonding with matrix materials in biocomposites (Bairwan et al., 2024). Furthermore, nano-structured porous carbon materials obtained from coffee waste are emerging as active materials for electrochemical energy storage devices like supercapacitors and batteries (Stufano et al., 2022), representing a high-value exploitation strategy that exemplifies the transformative potential of coffee waste valorization.

From a food science perspective, coffee by-products are rich in bioactive compounds suitable for producing functional food ingredients and nutraceuticals (Rebollo-Hernanz et al., 2023); Coffee silver skin and spent coffee grounds have been found to be excellent sources of antioxidants, fibers, and proteins (Nutrizio et al., 2024). These by-products hold antidiabetic, antioxidant, and anti-inflammatory properties, in addition to being sources of minerals such as potassium, calcium, and magnesium, and vitamin C (Ospina-Maldonado et

al., 2024). The valorization of these compounds into functional food ingredients represents a promising avenue for waste reduction while simultaneously creating value-added products with potential health benefits (Rebollo-Hernanz et al., 2023).

Despite the enormous valorization potential of coffee by-products, the large-scale implementation of recycling and upcycling methods remains limited, particularly in developing coffee-producing regions (Mak et al., 2023). Efforts to scale up such practices are frequently hampered by feedstock consistency issues, logistical inefficiencies, and regulatory barriers (Hamedani et al., 2025). Moreover, awareness among coffee farmers, processors, and local communities regarding the economic and environmental value of coffee waste remains insufficient, creating a significant knowledge gap that community service programs are uniquely positioned to address.



Figure 1. Presentation session with resources

This community service program, conducted by a team from Universiti Putra Malaysia (UPM), was designed to bridge this gap through a series of practical demonstrations and educational sessions focused on coffee processing technology and waste valorization. The program encompassed four core thematic areas: (1) demonstration of the AeroPress 3.0 manual coffee brewing device as a model for understanding coffee extraction and the generation of spent coffee grounds; (2) explanation of coffee drying methods and their implications for by-product quality and quantity; (3) comprehensive discussion of coffee waste processing and valorization strategies aligned with circular economy principles; and (4) introduction to

functional coffee formulations incorporating local spices and herbs as value-added ingredients.

By engaging directly with local communities, farmers, and small-scale processors, this program aimed to translate cutting-edge research on coffee waste valorization (Sisti et al., 2021; Rebollo-Hernanz et al., 2023; Lee et al., 2023) into practical, accessible knowledge that can be implemented at the community level. The ultimate goal is to empower local stakeholders to transform coffee waste from an environmental liability into a source of economic opportunity and community resilience, consistent with the broader global movement toward sustainable and circular food systems (Song et al., 2026; Ahmed et al., 2024). The following sections describe in detail the content, methodology, and outcomes of each component of this community service program, situating each within the broader scientific literature on coffee processing technology and waste valorization.

## Method

The program implementation methodology is executed in a one-day, intensive, and structured format thru a series of integrated activities. The program began with a presentation of comprehensive research results on the potential use of coffee waste and the optimization of coffee drying techniques to enhance the economic value of local commodities, followed by an interactive discussion session with the participants. The activity was then developed thru a live demonstration of the use of the AeroPress 3.0, utilizing coffee beans harvested by the local community as the main raw material, to provide practical experience in modern brewing techniques. As the highlight of the event, a presentation and demonstration of functional coffee formulations integrating local spice richness were conducted, designed to showcase health-based product innovations for business practitioners. The entire series of activities is systematically organized to ensure that the transfer of knowledge and technical skills can be effectively implemented within a limited time, aiming to strengthen the innovation capacity and creative economy competitiveness of the local coffee farmer community.



Figure 2. Participants demonstrate the Aeropress 3.0 tools.



Figure 3. Participants taste functional coffee with a blend of local spices.

## Results and discussion

### **Implementation of Biomass Rocket Stove Heating Systems for Enhanced Grain Quality**

The community service program successfully implemented an integrated drying system combining a mechanical dryer with a biomass-powered rocket stove to improve the quality of grain and agricultural seeds in Karang Sidemen. By utilizing a rocket stove, which is a highly efficient biomass combustion technology, the system achieves stable drying temperatures between 600–800°C. This setup creates a self-sufficient and environmentally friendly operation that does not rely on expensive external energy sources like electricity or solar fuel, making it particularly suitable for local farmer groups and cooperatives.

The application of this technology has demonstrated significant economic and practical benefits for the local farming community. The system utilizes locally available agricultural waste such as rice husks, corn cobs, and wood chips effectively turning waste into energy and reducing operational costs by up to 60% compared to LPG or diesel-powered heaters. Furthermore, the drying process successfully reduces moisture content to a

balanced level, inhibiting the growth of mold and microorganisms. This not only extends the shelf life and maintains the nutritional quality of the produce but also reduces the product's volume, thereby increasing efficiency in storage and transportation.

### **Utilization of Coffee Waste for Sustainable Energy and Product Quality Enhancement**

Coffee pulp, the mesocarp of the coffee cherry, represents approximately 41% to 45% of the total weight of coffee fruit. Traditionally regarded as industrial waste with the potential to cause environmental pollution, this byproduct contains significant nutritional and bioactive compounds, including proteins, fiber, and various phenolic components such as chlorogenic and gallic acids. Through appropriate extraction processes, coffee pulp can be transformed into high-value products, ranging from organic fertilizers and animal feed to renewable fuel briquettes.

The community service findings highlight the remarkable efficacy of coffee pulp extracts as natural antibacterial and preservative agents. Laboratory analysis demonstrates that different extraction fractions—specifically chloroform, ethyl acetate, and water—exhibit varying degrees of inhibition against a wide spectrum of foodborne pathogens and spoilage bacteria. Notably, the water-soluble fraction showed a significant inhibition diameter of up to 24.0 mm against *P. fluorescens*, while the chloroform extract was highly effective against *L. monocytogenes*. By utilizing these antimicrobial properties, coffee pulp serves as a sustainable alternative for food preservation and helps mitigate health risks associated with pathogens like *E. coli* and *Salmonella*.

### **Development and Implementation of Low-Caffeine Functional Coffee Integrated with Local Spices**

The community service initiative successfully demonstrated the development of a functional beverage that combines low-caffeine (decaf) coffee with indigenous local spices to address health concerns associated with excessive caffeine consumption, such as insomnia and increased gastric acid. By integrating bioactive compounds from local spices, the resulting product offers enhanced health benefits, including antioxidant and anti-inflammatory properties, while simultaneously boosting the body's immune system. This innovation provides a healthier alternative to

conventional coffee without compromising the authentic taste and aroma preferred by the community.

Furthermore, the implementation of this program in Karang Sidemen Village has empowered the local community by introducing a standardized production process for both coffee and spice preparation. The strategic combination of these ingredients not only adds functional value to the beverage but also enhances the economic potential of the village's local resources. As a result, this low-caffeine spiced coffee is positioned as a viable product for local Micro, Small, and Medium Enterprises (MSMEs), fostering sustainable economic growth and improving the overall welfare of the village residents.

### ***Optimizing Coffee Extraction Through the Implementation of AeroPress Brewing Science and Technique***

The community service program focused on the masterclass module "The Art of Coffee Brewing Using AeroPress," which effectively introduced participants to the science of immersion and pressure to achieve cafe-quality results at home. By implementing the AeroPress method, which was originally designed to solve issues of inconsistent extraction and bitterness, participants learned how to produce a highly concentrated, balanced, and intensely aromatic cup of coffee. The program successfully demonstrated that premium-quality coffee does not require complex machinery, but rather an understanding of precise variables such as optimal water temperature (90–96°C), a consistent medium-ground size, and the application of the "Golden Ratio".

Furthermore, the training specialized in the "Inverted Method" to ensure full control over the extraction process and prevent premature leakage during the steeping phase. Participants were also trained in developing signature café-style recipes, such as the Hot Coconut Latte and Iced Spanish Latte, utilizing the "Espresso-like" intensity produced by the AeroPress. This initiative has empowered the community with the skills to experiment with flavor profiles by adjusting variables like the coffee-to-water ratio, thereby fostering a culture of innovation and creativity in home-based brewing.

### **Conclusion**

The community service program in Karang Sidemen successfully implemented a multifaceted approach to agricultural innovation, centered on the adoption of biomass rocket stove heating systems. This technology has proven to be a sustainable and cost-effective alternative to traditional energy sources, reducing operational costs by up to 60% while ensuring stable drying temperatures. By utilizing local agricultural waste, the system not only enhances the quality and shelf life of grain and seeds by inhibiting microbial growth but also fosters environmental stewardship within the farming community.

Furthermore, the initiative demonstrated the high strategic value of repurposing coffee industry byproducts. The transformation of coffee pulp from environmental waste into high-value antimicrobial agents and organic materials marks a significant shift toward a circular economy. Laboratory findings confirming the efficacy of coffee pulp extracts against foodborne pathogens highlight its potential as a natural preservative, offering a dual benefit of mitigating health risks and increasing the economic utility of previously discarded materials.

The program also successfully bridged the gap between traditional agricultural production and modern consumer health trends through the development of low-caffeine functional coffee and advanced brewing techniques. By integrating local spices into decaffeinated coffee, the initiative created a health-oriented product that supports the local MSME ecosystem. This was further complemented by the introduction of AeroPress brewing science, which empowered residents with professional-grade skills to optimize flavor extraction. Collectively, these interventions have strengthened the local economy, improved product value chains, and established a foundation for sustainable community welfare.

### **Recommendations**

#### **1. Scaling Biomass Energy for Wider Agricultural Use**

The success of the biomass rocket stove should be expanded beyond grain drying. It is recommended to adapt this technology for other local post-harvest processes, such as coffee bean roasting or spice drying. This would further reduce dependency on fossil fuels and maximize the utility

of agricultural waste across different commodity sectors.

## 2. Standardization and Certification of Functional Products

To transition the low-caffeine spiced coffee and coffee pulp extracts into formal markets, the community should seek official food safety and health certifications (such as BPOM or Halal certification). Standardizing the production process will ensure consistent quality, which is essential for building consumer trust and expanding the reach of local MSMEs.

## 3. Development of Coffee Pulp-Based Commercial Products

Given the proven antimicrobial properties of coffee pulp extracts, further research and development should be directed toward creating commercial natural preservatives or organic fertilizers. Establishing a small-scale processing facility could turn "waste management" into a primary revenue stream for the village.

## 4. Establishing a Community-Led Maintenance Program

To ensure the longevity of the rocket stove and AeroPress equipment, a specialized technical team within the local farmer groups or cooperatives should be formed. Regular maintenance training will prevent equipment downtime and ensure that the technological shift remains a permanent fixture in the community's operations.

## 5. Integration with Agrotourism and Educational Initiatives

Karang Sidemen Village has the potential to become an "eco-friendly coffee village." The combination of sustainable drying technology, functional beverage innovation, and AeroPress brewing techniques can be packaged into an educational tourism experience. This would attract visitors, create additional income, and serve as a model for other agricultural regions.

## 6. Strengthening Market Links and Digital Branding

While the technical production is now established, the next step should focus on digital marketing and branding. Training the local MSMEs to utilize social media and e-commerce platforms will allow them to market their "scientific and sustainable" coffee products directly to urban consumers and specialty cafes, capturing a higher profit margin.

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