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Valorization of Kintamani Arabica Coffee Pulp as a Functional Food Ingredient: Integrating Environmental Risk Reduction and Antioxidant Potential

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Abstract: The increasing production of Arabica coffee in the Kintamani region, Bali, has led to a proportional rise in coffee pulp waste, which remains inadequately managed. This study aims to evaluate the potential of Kintamani Arabica coffee pulp as a functional food raw material while simultaneously assessing its role in environmental risk mitigation through a zero-waste approach. Laboratory experiments were conducted to determine total phenolic content and antioxidant activity using the DPPH method, while a semi-quantitative Environmental Risk Assessment (ERA) was applied to evaluate pollution risks associated with coffee pulp disposal. The results demonstrated that coffee pulp contains phenolic bioactive compounds with very strong antioxidant activity (IC_{50} = 13.96 ppm), comparable to established antioxidant-rich agricultural by-products. From an environmental perspective, converting coffee pulp into cascara (coffee pulp tea) reduced odor-related gas emission and groundwater contamination risks from high to low categories, achieving an overall risk reduction exceeding 75%. This study uniquely integrates functional food characterization with environmental risk assessment, providing scientific evidence that coffee pulp valorization supports circular economy strategies and sustainable coffee production systems.

Keywords: Coffee Pulp; Circular Economy; Environmental Risk Assessment; Functional Food; Kintamani Arabica Coffee.

Introduction

Kintamani Arabica coffee is internationally recognized for its distinctive sensory profile and its status as a Geographical Indication (GI) product originating from Bali, Indonesia. Alongside its growing global demand, wet coffee processing systems generate substantial quantities of solid by-products, particularly coffee pulp, which accounts for approximately 40–45% of the total coffee cherry biomass. In smallholder-based coffee production systems, this biomass is commonly disposed of through open dumping, leading to environmental challenges related to odor emissions, water pollution, and greenhouse gas formation [1], [3].

Previous studies on horticultural and agricultural by-products have demonstrated that processing residues often contain higher concentrations of bioactive compounds than the edible portions of fruits. Citrus peel, for example, has been widely reported as a rich source of phenolic antioxidants and has been successfully developed into functional food ingredients [1]. Coffee pulp exhibits a comparable phytochemical profile, dominated by polyphenolic compounds such as chlorogenic acids, and is accompanied by bioactive alkaloids, including caffeine. These characteristics suggest strong potential for coffee pulp valorization as a functional food ingredient rather than being treated solely as waste [4], [5], [7].

From an environmental perspective, unmanaged disposal of coffee pulp presents significant ecological risks. High moisture content and fermentable organic matter promote anaerobic decomposition, resulting in methane generation, offensive odors, and acidic leachate capable of contaminating soil and groundwater systems. Similar environmental risks have been reported in other agro-industrial waste streams, emphasizing the need for integrated waste management approaches that combine pollution control with resource recovery [2], [8], [9].

Globally, the coffee industry produces millions of tons of by-products annually, with coffee pulp representing the largest fraction of solid waste generated during wet processing. In many coffee-producing countries, limited infrastructure and weak regulatory enforcement exacerbate uncontrolled disposal practices, intensifying environmental externalities [14], [19]. As sustainability, traceability, and environmental responsibility become increasingly important attributes in speciality coffee markets, waste valorization strategies are no longer optional but essential components of quality assurance and sustainable production systems [14], [15].

Recent advances in food science have highlighted agri-food by-products as promising sources of bioactive compounds with antioxidant, anti-inflammatory, and metabolic health benefits. Coffee pulp and cascara have attracted attention for their phenolic richness and functional potential; however, most existing studies focus primarily on compositional analysis or extraction methods without evaluating their broader environmental implications [4], [9], [16], [24]. Consequently, translating laboratory-scale findings into holistic, sustainable production frameworks

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remains limited, particularly in smallholder-dominated regions such as Kintamani.

Therefore, this study aims to bridge this gap by integrating functional food characterization with environmental risk assessment. Specifically, the antioxidant potential of Kintamani Arabica coffee pulp is evaluated alongside a semi-quantitative Environmental Risk Assessment (ERA) to quantify pollution risk reduction achieved through zero-waste processing into cascara. This integrated approach provides scientific evidence supporting coffee pulp valorization as both a functional food resource and an effective environmental management strategy aligned with circular economy principles [12], [14].

Recent advances in food science have highlighted the potential of agri-food by-products as sources of bioactive compounds with antioxidant, anti-inflammatory, and metabolic health benefits. Coffee pulp, in particular, has attracted attention for its high phenolic content and unique composition, distinct from that of coffee beans. However, translating these laboratory findings into sustainable production systems remains limited, especially in smallholder-dominated regions such as Kintamani [15], [25].

Integrating functional food development with environmental risk management offers a holistic framework to address both economic and ecological challenges in coffee-producing areas. By embedding zero-waste principles into post-harvest handling, coffee by-products can be repositioned from environmental liabilities into value-added resources, thereby enhancing farm resilience, supporting circular economy objectives, and aligning local practices with global sustainability standards.

Research Methods

Material and Sample Preparation

Arabica coffee (Coffea arabica L.) pulp samples were collected from smallholder plantations in the Kintamani region, Bali, during the peak harvest season. Fresh pulp was washed to remove impurities and dried using a cabinet dryer at 50°C until the moisture content reached below 12% (wet basis). The dried material was milled and stored in airtight containers prior to analysis, representing cascara powder [6].

Phytochemical and Antioxidant Analysis

Moisture content was determined by gravimetric analysis. Total phenolic content was analyzed using the Folin–Ciocalteu method and expressed as mg gallic acid equivalents (GAE) per gram of dry sample. Antioxidant activity was measured using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, with IC_{50} values calculated from inhibition curves [7].

Environmental Risk Assessment

Environmental risk analysis was conducted using a semi-quantitative Environmental Risk Assessment (ERA) approach adapted from industrial organic waste management studies. Risk was calculated using the equation:

$$\text{Risk} = \text{Likelihood} \times \text{Severity}$$

Likelihood and severity were scored on a 4-point scale (1 = negligible, 4 = very high) based on field observations, the waste's physicochemical characteristics, and literature benchmarks. Risk levels were classified as low (1–4), moderate (5–9), or high (10–16). Two scenarios were evaluated: (1) open dumping of fresh coffee pulp and (2) zero-waste processing into cascara [8], [9].

Data Analysis

All analyses were conducted in triplicate, and results are presented as mean ± standard deviation. Total phenolic content data were expressed as mg gallic acid equivalent per gram of dry sample (mg GAE/g). Antioxidant activity was evaluated based on the percentage inhibition of DPPH radicals at various extract concentrations. The IC_{50} value was calculated by linear regression of extract concentration versus percentage inhibition, representing the concentration required to scavenge 50% of DPPH radicals [10].

Environmental risk scores were calculated by multiplying the likelihood and severity values for each risk parameter. Risk reduction percentages were determined by comparing risk scores between open dumping and zero-waste processing scenarios [14].

Results and Discussion

Physicochemical Properties and Antioxidant Potential

The physicochemical characteristics and antioxidant activity of Kintamani Arabica coffee pulp are presented in Table 1. The dried cascara exhibited a moisture content of 11.2%, indicating adequate drying efficiency and reduced susceptibility to microbial spoilage. The brewing pH value of 5.17 suggests mild acidity, consistent with previous reports on cascara-based beverages and suitable for functional drink formulations [17], [20].

Antioxidant activity was determined by measuring the percentage inhibition of DPPH radicals at different extract concentrations (10–50 ppm). The inhibition values increased proportionally with extract concentration, indicating a dose-dependent antioxidant response. Linear regression analysis of inhibition percentage versus concentration yielded an IC_{50} value of 13.96 ppm, confirming the very strong antioxidant capacity of coffee pulp extract [18].

Table 1. Physicochemical characteristics of Kintamani Arabica coffee pulp

Parameter	Average value	Unit
Moisture content (dry)	11.20 ± 0.35	%
Brewing pH	5.17 ± 0.08	−
Total phenols	12.50 ± 0.62	mg GAE/g
Antioxidant activity (IC_{50})	13.96 ± 0.41	ppm

The total phenolic content of coffee pulp reached 12.5 mg GAE/g, reflecting a high concentration of antioxidant compounds. Correspondingly, the DPPH assay showed very strong antioxidant activity, with an IC_{50} of 13.96 ppm. According to commonly accepted classifications, IC_{50} values below 50 ppm indicate very strong antioxidant capacity, positioning cascara as a competitive plant-based antioxidant source [10], [24].

The strong antioxidant performance observed in this study is consistent with previous findings attributing the antioxidant capacity of coffee by-products primarily to chlorogenic acids and related phenolic compounds [4], [8], [21]. Compared with other agricultural residues such as citrus peel and coffee silverskin, the IC_{50} value obtained in this study indicates that Kintamani coffee pulp has substantial functional potential, suitable for incorporation into functional beverages or nutraceutical formulations [5], [18], [24].

Environmental Risk Reduction through Zero-Waste Processing

The comparative environmental risk assessment between open dumping and zero-waste scenarios is summarized in Table 2.

Table 2. Comparison Risk Reduction through Zero Waste Processing

Risk parameter	Open dumping	Zero-waste processing	Risk reduction
Gas emissions (odor/methan)	16 (High)	4 (Low)	75%
Water pollution (leachate)	12 (Moderate)	2 (Negligible)	83%
Disease vectors (flies)	12 (Moderate)	3 (Low)	75%

Open dumping of coffee pulp with high moisture content promotes rapid microbial degradation, generating offensive odors and acidic leachate that threatens soil and groundwater quality. Drying and processing the pulp into cascara significantly reduced these risks by lowering water activity and eliminating uncontrolled decomposition pathways. This approach is particularly relevant for smallholder coffee systems with limited waste management infrastructure [11].

Environmental risk assessment results clearly demonstrate the effectiveness of zero-waste processing in mitigating pollution risks associated with coffee pulp disposal. In the open dumping scenario, high moisture content and readily degradable organic matter resulted in elevated risk scores for gas emissions, leachate formation, and disease vector proliferation. These findings align with previous studies reporting significant environmental impacts arising from unmanaged agro-industrial waste streams [2], [8], [11].

Conversion of fresh coffee pulp into cascara significantly reduced environmental risks across all assessed parameters. Gas emission risks related to odor and methane generation decreased from high to low categories, while groundwater contamination risks associated with acidic leachate were reduced to negligible levels. This risk reduction is primarily attributed to moisture removal during drying, which lowers water activity and inhibits uncontrolled microbial decomposition [9], [20].

The observed risk reduction exceeding 75% highlights the effectiveness of zero-waste processing as a practical environmental management strategy, particularly for smallholder coffee systems with limited access to centralized waste treatment facilities. Similar outcomes have been reported in studies emphasizing on-site valorization of agricultural residues as an environmentally sustainable alternative to conventional disposal practices [14], [22].

Implications for Sustainability Environment, Circural Economy, and Food Safety

The valorization of coffee pulp into cascara demonstrates a practical application of circular economy principles within the coffee industry. By transforming waste streams into value-added functional food products, material loops are closed at the production site, reducing transportation requirements, disposal costs, and environmental emissions. This approach strengthens sustainability at both the farm and community levels, especially in geographically indicated coffee regions, where environmental stewardship directly contributes to product reputation and market value [14], [19].

From a functional food perspective, the strong antioxidant activity observed in Kintamani coffee pulp supports its potential role in mitigating oxidative stress, a key factor associated with chronic non-communicable diseases. Phenolic compounds derived from coffee by-products have been reported to exhibit anti-inflammatory and metabolic regulatory effects, further enhancing their functional relevance [21], [24].

Nevertheless, commercialization of coffee pulp-derived food products requires careful consideration of food safety and regulatory compliance. Coffee pulp naturally contains caffeine, and improper post-harvest handling may increase the risk of mycotoxin contamination. Therefore, standardized drying protocols, quality control measures, and compliance with novel food regulations are essential to ensure consumer safety and product acceptance [10], [12], [13]. Future studies should focus on caffeine profiling, toxicological assessment, and sensory evaluation to support large-scale application and regulatory approval.

Conclusion

Kintamani Arabica coffee pulp exhibits dual benefits as a functional food ingredient with very strong antioxidant activity (IC_{50} = 13.96 ppm) and as an effective environmental risk mitigation strategy. Zero-waste processing of cascara reduced pollution-related risks by more than 75%, supporting sustainable coffee production and the implementation of the circular economy. This study provides a scientific basis for integrating coffee waste valorization into agri-food and environmental management systems in coffee-producing regions. Future studies should focus on caffeine profiling, toxicological assessment, and sensory evaluation to support large-scale application and regulatory approval.

Author's Contribution

I.G.A.Y. Rabani RS: conceptualization, methodology, investigation, manuscript writing, and revision. A. Antares and I.A.A. Prawitasari: supervision, validation, and manuscript review. I.N.A.M. Putra: data analysis and revision.

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