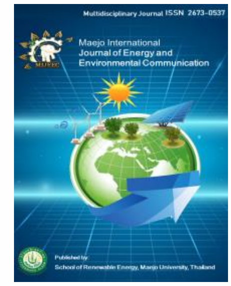
Maejo International Journal of Energy and Environmental Communication 7-2 (2025) 19-26

Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Circular bioeconomy valorization of coffee bark residues: Soil chemical transformation and yield enhancement in highland arabica coffee systems

Nakhalin Phounsavath[1], Vannasinh Souvannasouk[2]*, Khamphisay Khammingsavath[1], Phoutsavath Phanthavong[1], Chantiem Silalai[3], Bualaphanh Mingkhuan[3], Odeth Sihavong[3], Salongxay Fongsamouth[4]

[1]Faculty of Agriculture and Forestry, Champasack University, Champasack 16000, Lao PDR
[2]Scientific Academic Research Office Champasack University 16000, Lao PDR
[3]Faculty of Natural Science, Champasack University, Champasack 16000, Lao PDR
[4]Faculty of Economics and Management, Champasack University, 16000, Lao PDR

A R T I C L E I N F O

Article history:
Received 11 May 2025
Received in revised form
13 June 2025
Accepted 14 June 2025

Keywords:
Compost
Arabica Coffee
Coffee Bark
Yield
Organic Fertilizer
Soil Nutrients

A B S T R A C T

Comparative research on the effect of coffee bark composting on the yield of Arabica coffee in Phu Oi Village, Pak Chan District, Champasak Province was conducted. The objectives of the study were as follows: 1) to evaluate the quality of coffee bark compost and 2) the impact of the application of this compost on coffee yield. The research was conducted on a farmer's coffee farm in Phu Oi Village, Paksong District, with the comparative model on a 1-hectare plantation of Arabica coffee. The trees were planted with a spacing of 1.5 m x 1 m, totaling 6,600 trees. The coffee grounds compost was analyzed and determined to have 1.42% total nitrogen (% Total N), 6.32 ppm of useful phosphorus, 0.04 ppm of useful potassium, 28.35% organic matter and pH= 7.27. When comparing with the standards of the organic fertilizer of the Ministry of Agriculture and Forestry of Lao PDR (2000), the nitrogen, organic matter, and pH values were close to the standards. Compost changed the chemical characteristics of the soil, including P, N, and organic matter content, etc. Nitrogen content increased from 0.17% to 0.95% and phosphorus from 15.45 ppm to 19.50 ppm of soil. Organic matter content was increased from 3.33% to 15.75%. The pH of the soil was changed from 4.67 to 6.25 by the compost. The employment of coffee bark compost resulted in an increase in the Arabica coffee yield as compared to unfertilized farms. In 2022, the yield was 12 T/ha, this yield increased to 15 T/ha in 2023 with the application of compost, whereas in unfertilized farms, the yield was 11.5 T/ha. Thus, the use of compost in coffee cultivation contributes to the enhancement of nutrients and soil fertility, and consequently to improvement in coffee production, with the content of nutrients being equivalent to organic fertilizers.

1. Introduction

The sustainability of agricultural systems around the world is increasingly threatened by soil degradation, reduction of organic matter content in the soil, imbalances in nutrients, and climate variability (Ramaraj & Dussadee, 2015; Li and Bhuyar, 2024).

Over the past decades, intensive dependence upon synthetic fertilizers has drastically increased crop productivity but has been associated with adverse environmental consequences such as soil acidification, nutrient runoff, greenhouse gas emissions, and disturbance of microbial soil communities (Pandi et al., 2024). In many developing countries, agricultural production is further

* Corresponding author
E-mail address: vannasinhnoummin@gmail.com ; vannasinh@cu.edu.la (Souvannasouk.V)

constrained by high dependence on imported agrochemical inputs, which exposes farmers to volatility in global markets, the supply chain, and rapidly rising costs of production. These interrelated environmental and economic pressures have strengthened the search at a global scale for regenerative soils management strategies based on circular bioeconomy principles and localized nutrient recycling management systems.

Within this framework, the valorization of agricultural residues by means of composting has made a growing number of efforts within sustainable nutrient management approaches (Reansuwan et al., 2024; Gammatantrawet et al., 2023). Composting is a process that converts organic waste into a stabilized and humified material, which can contribute to the improvement of soil structure, water retention, cation exchange capacity, and the activities of beneficial microbes (Gupta et al., 2023). Apart from the agronomic benefits, composting limits pollution by reducing the amount of waste sent to landfills and emissions in the form of methane emissions) and uncontrolled decomposition. Agro-industrial by-products, especially those that are produced in high volumes in localized production systems, are strategic geographical feedstocks for circular nutrient recovery programs (Mejica et al., 2022; Nong et al., 2022; Sophanodorn et al., 2022).

One such underutilized organic resource is coffee bark (coffee husk), which is a lignocellulosic byproduct produced during coffee processing. In coffee-producing regions, high quantities of coffee bark are seasonally produced, and often this is disposed of through open dumps or uncontrolled decomposition (Chali Terfassa, 2020). This practice, along with the odor generation, the growth of pests, the formation of leachate, and the local contamination of soil and waters, may result. However, when properly composted, coffee bark can be a nutrient-rich organic amendment. Mature coffee bark compost is in the form of stabilized organic carbon with essential macronutrients, and the slow nutrient-release characteristics are beneficial for sustained plant growth with minimal losses to leaching (Chali et al., 2021). Moreover, its addition and incorporation into soil systems can improve soil carbon sequestration and contribute to climate-resilient agricultural practices (Gebisa & Regasa, 2024).

In Champasak Province, especially in the Paksong highlands, coffee plantation is a key economic activity and one of the major income earners in rural society. Despite the good agroecological conditions, coffee is strongly reliant on imported chemical fertilizers. National trade data show that there has been a strong growth in fertiliser imports between 2016 and 2019, from USD 42.34 million to USD 86.16 million, with major suppliers being in the countries of China, Thailand, and Vietnam. This increasing dependence on the importation of fertilizers creates both economic vulnerability and higher costs of production for smallholder farmers and reduces resilience in local agricultural systems. Furthermore, the prolonged application of chemical fertilizers, without any sufficient organic matter inputs, may speed the decline in soil fertility of tropical highland soils.

Against this backdrop, the development of coffee bark as locally available compost is an opportunity for trees as a strategic element in synchronizing waste management elements with sustainable soil fertility enhancement elements (Hoseini et al., 2025). By reducing dependence on outside inputs, closing nutrient loops in the coffee production system can result in improved soil health and increased agroecological sustainability by using coffee bark compost. In addition to the environmental benefits, local compost production may help to increase the autonomy of farmers, reduce the cost of production, and contribute to long-term agricultural resilience. This study, therefore, aimed at evaluating the physicochemical properties and maturity indices of coffee bark compost produced at local conditions, and evaluating its effect on coffee yield under field conditions. The research was conducted in a farmer-managed coffee plantation in Phu Oi village in Paksong district in Champasak province in Lao PDR, which can represent a typical coffee production system in Laos highlands.

2. Materials and Methods

2.1 Study Area

The study was carried out in Phu Oi Village, Paksong District, Champasak Province, which is a major highland coffee-producing zone with elevations ranging between 1,000 and 1,300 m above sea level. The region has a tropical monsoon climate with two well-defined wet and dry seasons and a total average annual rainfall of over 2,000 mm, and a moderate average temperature favorable for the cultivation of Arabica coffee. Soils in this region are mostly of volcanic origin and generally acidic in nature and of medium fertility, but prone to nutrient depletion due to continuous monocropping and the use of synthetic fertilizers. The experimental site comprised farmer-managed Arabica coffee plantations to ensure the research is realistic concerning agronomic and socioeconomic conditions prevailing in the production systems of small holders in the region.

2.2 Experimental Design and Framework of Comparison

The methods used for the research were a field-based comparative design to assess the agronomic performance of coffee bark compost in comparison to existing practices of farmer fertilization. Three management conditions were evaluated to allow for meaningful comparisons to be made under practical production environments. The first treatment was plots of Arabica coffee amended with coffee bark compost in the production year. The second treatment was the conventional farming practice that was based on the use of synthetic or mixed fertilizers that are traditionally used by farmers, and the yield data were collected from the 2022 production year. The third condition acted as a control, which were Arabica coffee plots without the application of compost during the production year 2023. Yield data were collected from similar plantation sections of similar plant age, spacing, and management history to reduce the confounding variability in the data. The comparison was based on the annual yield performance (kg/ha) and visible indicators of plant vigour. This design allowed for assessment of the effectiveness of the composts in actual field conditions as opposed to controlled greenhouse conditions, allowing for improved ecological validity and practicality of the assessment.

2.3 Coffee Bark Compost Production

Coffee bark compost was produced with a static aerated pile method without mechanical turning. Because of the ease of use, it was recommended to represent low cost, amenable to farmers. The composting materials were mainly composed of the coffee bark residues, amounting to 1,000 kg for each pile, with 200 kg of cow dung to improve nitrogen content and the benefits of microbial inoculation. Molasses (1 L) and Effective Microorganisms (EM, 1 L) were mixed into 100 L of water to stimulate the activity of microorganisms and to enhance the rate of decomposition.

An aeration system was built out of a 3 m long perforated PVC pipe that was installed at the bottom of the compost pile. Holes were drilled at 1 cm intervals along the pipe to help with passive airflow, and the pipe was covered with protective cloth to prevent clogging by organic particles. The compost pile was constructed by alternating about 40cm of coffee bark and 10cm of cow dung in order. The diluted molasses-EM solution was evenly distributed across three composting layers to ensure even activation of the microbes. Upon completion, the pile was covered with plastic sheeting, which was to conserve moisture and to maintain optimum decomposition conditions.

Moisture content of the material was kept between about 60-70% by light watering when needed and checked by the physical appearance of the seed. Every seven days, the forced aeration was made available through a blower for 30-40 minutes to increase the oxygen availability and support the aerobic microbial process. An additional set of vertical perforations was also produced by hand at 40 cm intervals to enhance internal aeration and moisture distribution. Compost maturity was measured using reduction in pile height, limiting the internal temperature to near ambient temperature, dark brown to black coloring, friable texture, and lack of identifiable feedstock materials. The composting process took about 60-100 days, depending on the ambient environmental conditions.

2.4 Data Collection and Analysis Procedures

Data collection included both evaluation of the quality of the compost and agronomic evaluation in the field. During composting, the key parameters that were recorded were the duration of decomposition, moisture status, temperature trends, and physical transformation of the materials. Upon maturity, composite samples of coffee bark compost were collected for physicochemical analysis; pH, content of organic matter, total nitrogen (N), available phosphorus (P) and exchangeable potassium (K) were determined. These parameters were chosen to test the nutrient availability and compost stability parameters.

Soil samples were taken before compost application and after harvest in order to determine changes in nutrient status due to compost amendment. Standard soil analytical procedures were used to establish the levels of macronutrients and selected indicators of fertility. Coffee yield data were gathered at harvest as total weight of cherry per plot and extrapolated to hectare level productivity where applicable. Comparisons of yields were made in the three management conditions to test the agronomic efficiency of coffee bark compost as compared to that of the conventional use of fertilizers and to non-amended controls. Observations about plant vigor, canopy development, and general appearance of crops were also recorded to aid in quantitative yield results.

2.5 Statistical Analysis

Statistical analysis was performed to test the impact of coffee bark compost on soil properties and coffee yield. Data were presented as mean ± standard deviation (SD). Normality and homogeneity of variance were tested before analysis. Differences between treatments were analyzed by one-way ANOVA at the significance level $p < 0.05$ and separation of means was conducted by the Least Significant Difference (LSD) test if there were significant effects. Percentage changes were measured to evaluate agronomic improvements. Statistical analyses were done with a standard statistical program, and results were presented using SD error bars.

3. Results and Discussion

3.1 Composting Performance and Organic Matter Transformation

The time taken for the composting of coffee bark under the static aerated pile system was about 140 days for its maturity. This relatively longer time for composting indicates the biochemical recalcitrance of coffee bark, which showed a high initial carbon to nitrogen (C/N) ratio of 90:1-115:1. Lignocellulosic residues that have high C/N ratios are generally subject to slower microbial mineralization by the limited availability of nitrogen during the initial thermophilic phase (Taechawatchananont et al., 2024). The nitrogen deficiency limits the expansion of the microbial biomass and postpones the breakdown of the fast decomposition (Vu et al., 2022). Although cow dung was incorporated to optimize the nitrogen balance and Effective Microorganisms (EM) were added to promote the microorganism colonization, probably the structural rigidity and high lignin content of coffee husk fibers limited the rapid humification.

Through the course of the composting time, physical progressive transformation of the material was noted. The compost went from coarse, fine fibrous husks and fiber, broken down to a fine friable, thick substrate that is dark brown to black in coloration, indicative of the advanced humification and stabilization of organic matter. Reduction in pile height and stabilization of internal temperature near ambient temperature were indicative of the completion of the active thermophilic stage and transition to the curing phase. While in a few cases some partially degraded husk fragments were still visible, such residual lignocellulosic structures may have a beneficial contribution to the aggregation and aeration after their incorporation into the field soils.

3.2 Compost Characteristics of Physicochemical Properties of Coffee Bark Compost

The total nitrogen concentration of the matured compost was 1.42%, which was close to the national compost standard threshold of 1.5% (Table 1). Although a little below the regulatory benchmark, this nitrogen level is nevertheless of agronomic significance because of the slow-release nature of organic nitrogen. Unlike synthetic fertilizers, which offer quick nutrient availability and risk of leaching losses, compost-based nitrogen undergoes gradual mineralization processes such as ammonium and nitrate forms, which provide for a sustained supply of the nutrient for a longer period of the cropping system. This slow-release means improved efficiency of use of nitrogen and reduced risks to the environment from volatilization and groundwater contamination (Jiang et al., 2023; Khoirunnisak et al., 2025).

Phosphorus and potassium concentrations were determined as 0.0632% phosphorus pentoxide and 0.0004% potassium oxide, respectively, which are less than the national fertilizer standards. These rather low levels of macronutrients are probably due to the inherent nutrient composition of coffee bark feedstock as well as possible leaching of nutrients during compost maturation (Jibril et al., 2022; Jiang et al., 2024; Kiup et al., 2025). However, compost must not be viewed as a concentrated source of nutrients only. Its main agronomic role, however, is to enhance the biological activity of the soil, nutrient cycle processes, and physical structure rather than replacing high-analysis mineral fertilizers.

Organic matter content was 28.35%, which is somewhat below the reference value 30% but still on an acceptable agronomic range. Increased levels of organic matter help increase cation exchange capacity, water retention, aggregate stability, and proliferation of microbial biomass. The compost pH of 7.27 was in the range of optimal maturity (6.5-8.0), thus representing adequate stabilization and reduction of phytotoxic organic acids. Neutral pH conditions are especially favorable for the enhancement of nutrient exchange processes and the reduction of the risk of plant stress.

Table 1. Comparison of Nutrient Content in Coffee Bean Compost with Manure Management Standards of the Ministry of Agriculture and Forestry

No	Chemical and nutritional properties	Compost coffee bark	Organic fertilizer standards as determined by the Ministry of Agriculture and Forestry
1	% Total N	1.42 %	1.5%
2	% Total P	0.0632 %	3%
3	% Total K	0.0004 %	0.5%
4	OM	28.35 %	≥ 30%
5	pH	7.27	6.5 - 8

3.3 Soil Fertility Dynamics

3.3.1 Baseline Soil Conditions

Initial soil analysis showed the presence of strongly acidic conditions with a mean pH of 4.99, which is not ideal for Arabica coffee production. Acidic soils favor greater solubility of aluminum and other potentially toxic metal ions, which may adversely affect root development and reduce the efficiency of nutrient uptake. In spite of a relatively high organic matter content average of 9.81%, the nutrient availability was restricted. Total nitrogen was found to be 0.44%, and available phosphorus and potassium were found to be 13.66 ppm and 83.33 ppm, respectively. These values show that even though organic residues had accumulated in the soil, chemical limitations associated with the low pH probably restricted the bioavailability of nutrients and overall soil productivity. The baseline findings underline that it is not only the quantity of organic matter in soil that determines soil fertility, but also the balance of chemicals and accessibility of nutrients. Under acidic conditions, the fixation of phosphorus and toxicity of aluminum may constrain crop performance to considerable levels, even though the level of organic matter may be apparently sufficient.

3.3.2 Chemical Transformation of Soil after Compost Application

Following the incorporation of composts, significant improvements in soil chemical properties were recorded. Soil pH rose from 4.99 to 6.41 and was found to be statistically significantly changed to slightly acidic soil pH conditions that would favor coffee cultivation ($F = 287.15$, $p < 0.001$). This pH correction is especially relevant in soils of the tropical highlands, where the long-term use of synthetic fertilizers will tend to accelerate the acidification process (Figure 1). Compost-derived humic substances and organic anions have buffering action against soil acidity, decrease the toxicity of exchangeable aluminum, and increase retention of base cations, thereby increasing nutrient exchange efficiency.

Total soil nitrogen increased from 0.44% to 0.95%, indicating an improved nitrogen enrichment after compost application (Table 2). Although the level of statistical significance was limited by the size of the replication, the amount of increase is indicative of meaningful agronomic improvement. Compost makes a contribution to organic nitrogen pools, which undergo progressive mineralization processes that favor an extended plant growth with less mutual dependence on artificial nitrogen inputs. Available phosphorus was increased from 13.66 ppm to 16.16 ppm. The improved soil pH probably decreased phosphorus fixation by aluminum and iron complexes, which increased plant-available phosphorus. Organic acids during decomposition of compost can also chelate metal ions further increasing phosphorus mobility and uptake

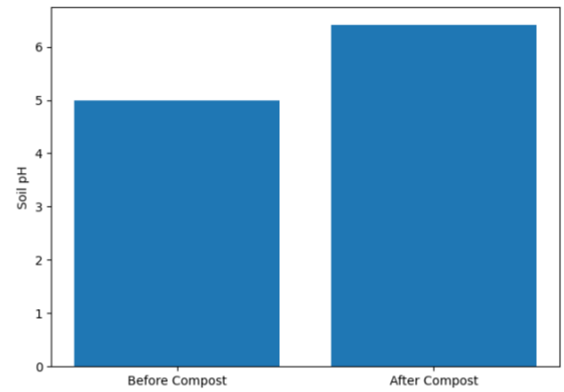


Figure 1. Effect of Coffee Bark Compost on Soil pH

In contrast, the available potassium was reduced from 83.33 ppm to 48.21 ppm. This decrease is most likely attributable to the enhanced uptake by plants at fruit development or by depletion of soils, rather than by soil depletion. Potassium functions in the transport of carbohydrates and the accumulation of sugar in coffee cherries; the increased yield may be associated with increased removal of nutrients from the soil. Collectively, the results confirm that compost application has improved the soil chemical balance significantly, especially in regulating the pH and improving N, thus providing a better environment for crop productivity.

3.4 Coffee Yield Enhancement

Coffee yield under compost treatment achieved the yield of 15 t ha-1 as compared to 12 t ha-1 yield under traditional fertilization and 11.5 t ha-1 without the use of compost. This represents a 25-30% increase in yield in an approximate way due to the incorporation of compost. The yield response is a result of synergistic effects on soil physical, chemical, and biological properties (Table 3). The enhancement can be explained by a number of interrelated mechanisms. First of all, pH correction increased nutrient solubility and root nutrient uptake efficiency. Second, more available nitrogen favored the growth of vegetation and the development of canopies. Third, better soil structure provided for better aeration and root penetration. Fourth, enhanced microbial activity was associated with increased nutrient cycling and organic matter stabilization. Finally, enhanced water-holding capacity minimized moisture stress at the critical time of growth. It is important to note that fresh coffee bark contains caffeine, tannins and phenolic compounds, which may have phytotoxic effects if used directly into soil. Composting is able to significantly reduce these compounds via microbial decomposition to make them safe for agricultural use. It, therefore, requires adequate maturation time to avoid phytotoxicity and to ensure the best possible response in plants.

3.5 Implications of Environmental and Circular Bioeconomy

From the point of view of environmental sustainability, the treatment of coffee bark residues for their transformation into compost is an important contribution to the principles of circular bioeconomy (Table 4). Coffee processing residues are often discarded in open environments and are responsible for methane emissions, as well as localised environmental pollution (Pham et al., 2020). Composting is a process through which this waste is transformed into a value-added soil amendment, which reduces environmental burdens while helping improve soil fertility.

The inclusion of composting in coffee production systems helps to promote waste reduction, greenhouse gas reduction, nutrient recycling, and reduction in the use of imported chemical fertilizers (Martinez et al., 2024; Maro et al., 2024). In addition, the higher organic matter in the soil brings carbon sequestration and long-term soil health immunity. In relation to highland tropical systems that are susceptible to degradation and acidification, such regenerative soil management practices are the keys to sustainable intensification (Netsere & Takala, 2021). The results show that the function of the coffee bark compost is more as a soil system regulator and less as a nutrient supplier. Its best agronomic value is the stabilization of the acidity of soils, biological activity, physical structure, and the gradual cycling of nutrients (Reetsch et al., 2020; Takala & Chali, 2025). While concentrations of macronutrients were moderate, systemic improvements in soil health made huge yield improvements. Overall, nutrient management with compost is a feasible and environmentally sustainable approach to lethal and the expansion of Arabica coffee productivity and circular bioeconomy provision and climate-smart agriculture provisions in highland agroecosystems.

Table 2. Soil Chemical Properties Before and After Compost Application

Description	OM (%)	Total N (%)	Available P_2O_5 (ppm)	Available K_2O (ppm)	pH
Soil before planting					
Soil in Arabica coffee farm (1)	10.28	0.12	15	83	5.01
Soil in Arabica coffee farm (2)	9.90	1.10	12	83	4.98
Soil in Arabica coffee farm (3)	9.25	0.11	14	84	5.00
Average	9.81	0.44	13.66	83.33	4.99
Soil after planting					
Soil in Arabica coffee farm (1)	13.45	0.95	19.50	40.65	6.25
Soil in Arabica coffee farm (2)	14.75	1.05	20	55	6.5
Soil in Arabica coffee farm (3)	13.75	0.85	19	49	6.5
Average	13.98	0.95	16.16	48.21	6.41

Table 3. Arabica Coffee Yield Under Different Fertilization Practices

No	Coffee farm	Production (T/ha)	Remark
1	Coffee bark compost utilization	15	Coffee in 2023
2	Traditional fertilizer	12	Coffee in 2023
3	Date in 2022	11.5	Coffee in 2022

From the study of the use of compost on the production of Arabica coffee at Phu Oi Village, Paksong District, Champasak Province, it can be concluded that: the amount of nutrients in the compost of coffee bark is the amount of essential nutrients for the growth of the plant. There is useful potassium (Available K) equal to 0.04 ppm. There is organic matter (OM) equal to 28.35% and the value of acidity-alkalinity is equal to 7.27. By comparing the standards of organic fertilizers as determined by the Ministry of Agriculture and Forestry in 2000, it is seen that only nitrogen (N), organic matter (OM) and acidity-alkalinity (pH) have values close to the standards. Also, it was found that the production of coffee bark compost has the longest fermentation period of 140 days. Coffee bark compost has the effect of changing the chemical properties of the soil by increasing the amount of main nutrients in the soil, such as N, which increased from 0.44% to 0.95%, and P, which increased from 13.66 ppm to 16.16 ppm. Also, increasing the amount of organic matter (OM) increased from 9.81% to 13.98% and can adjust the soil acidity (pH) from 4.99 to 6.41. Composting coffee bark has the effect of increasing the yield of Arabica coffee, with the production of Arabica coffee in 2022 being equal to 11.5 T/ha. In 2023, composting coffee bark has seen an increase to 15 T/ha. Therefore, it can be concluded that the use of compost in coffee cultivation can increase the amount of nutrients in the soil, making the soil more fertile, and increasing the yield of coffee.

3.6 Sustainability Implications within the SDG Framework

The results of this study show that coffee bark composting goes beyond the scope of agronomic improvement and has significant contributions to several Sustainable Development Goals (SDGs) with integrated environmental, economic, and social benefits (Trujillo-González et al., 2024; Wijaya et al., 2025). Figure 2 illustrates how coffee bark composting contributes to multiple United Nations Sustainable Development Goals (SDGs) through integrated agronomic, environmental, and socio-economic impacts. By giving coffee processing residues a new life as a stabilized organic amendment, sustainable agricultural intensification, even in the Third World, can be brought closer, with circular bioeconomy principles in mind. The great improvement achieved in soil fertility parameters, such as the correction of soil acidity (pH increase from 4.99 to 6.41), the improvement of organic matter (9.81% to 13.98%), and the higher availability of nitrogen (0.44% to 0.95%), directly refers to SDG 2 (Zero Hunger), especially Target 2.4, which calls for resilient and sustainable agricultural food production systems. The effect of nutrient management in composts as sources of up to 30% more yield of Arabica coffee underscores the potential of compost-based nutrient management to improve productivity while lessening environmental degradation.

Table 4. Environmental, Agronomic, and Circular Bioeconomy Implications of Coffee Bark Composting

Category	Indicator / Parameter	Before Compost	After Compost	Implication
Waste Management	Coffee bark disposal	Open dumping / uncontrolled decomposition	Compost valorization	Reduced methane emissions and environmental pollution
Compost Quality	Total Nitrogen (%)	—	1.42%	Close to national standard (≥1.5%); supports gradual nutrient release
	Organic Matter (%)	—	28.35%	Near standard (≥30%); improves soil carbon and structure
	pH	—	7.27	Within optimal maturity range (6.5–8.0)
	Available Potassium	—	0.0004%	Moderate nutrient content; functions mainly as soil conditioner
	Composting Duration	—	140 days	Adequate stabilization and phytotoxicity reduction
Soil Fertility	Soil pH	4.99	6.41	Significant correction of soil acidity
	Total Nitrogen (%)	0.44%	0.95%	Improved nitrogen enrichment
	Available P_2O_5 (ppm)	13.66	16.16	Enhanced phosphorus availability
	Organic Matter (%)	9.81%	13.98%	Increased soil carbon and fertility
Crop Productivity	Arabica Coffee Yield (t ha^{-1})	11.5	15.0	25–30% yield increase
Climate Action	Methane Emissions	High (from waste decomposition)	Reduced (controlled composting)	Lower greenhouse gas emissions
Circular Bioeconomy	Fertilizer Dependency	High reliance on imports	Reduced chemical fertilizer use	Strengthened local nutrient cycling
Sustainability Outcome	Soil System Function	Acidic, nutrient-limited	Improved biological and chemical balance	Supports regenerative and climate-smart agriculture

At the center of the framework is “Sustainability Impacts of Coffee Bark Composting,” representing the core intervention—transforming coffee processing residues into stabilized organic compost (Kumar et al., 2025). Surrounding this central concept are five SDGs directly supported by the study findings: From a sustainable development goal (SDG), the valorization of coffee bark residues is used to contribute to SDG 12 (Responsible Consumption and Production) to promote waste reduction (Target 12.5) and the sustainable management of resources. Instead of displacing methane in the open frame and contributing to local pollution, coffee bark is recycled to a value-added soil amendment, and nutrient flows in the production process are thus closed. Composting also plays a role in achieving SDG 13 (Climate Action) by reducing greenhouse gas emissions to the atmosphere related to uncontrolled decomposition of organic waste by microorganisms and indirect emissions related to the production of synthetic fertilizer. The boost in soil organic matter helps to increase the storage of soil organic carbon, making highland agroecology more climate resilient. Furthermore, the enhancement of soil structure, biological activity, and nutrient cycle advances SDG 15 (Life on Land) by promoting sustainable land management and avoiding soil degradation. The restoration of acidic tropical soils improves the functioning of the ecosystem and long-term productivity. Finally, the decrease in the dependence on imported chemical fertilizers contributes to achieving SDG 8 (Decent Work and Economic Growth) by decreasing the cost of production and enhancing the autonomy of farmers, as well as increasing the economic resilience of rural communities. Overall, coffee bark composting is a multifaceted sustainability intervention and can simultaneously promote agricultural productivity, environmental protection, climate mitigation, and rural development in the framework of the SDGs.

Figure 2. Alignment of Coffee Bark Composting with the United Nations Sustainable Development Goals (SDGs)

4. Conclusion

The research validates composting coffee bark as a possible approach to increase the soil fertility and productivity of Arabica coffee in highland agroecosystems. The composting process was performed in 140 days with a static aeration procedure to stabilize a high C/N ratio lignocellulosic residue. This prolonged fermentation guaranteed humification, the decrease of phytotoxic compounds, and the production of a mature organic amendment. The compost contained essential plant elements: Total nitrogen was 1.42%, organic matter was 28.35%, and pH was 7.27, which were at the level of the Ministry standards. Despite the reduced amounts of phosphorus and potassium, the compost showed sufficient maturity. Improving soil conditions and biological activity - Primarily, its function is to work as a soil conditioner; the compost improves soil stability. Soil properties improved after compost application, where pH rose from 4.99 to 6.41, leading to increased nutrient availability. An increase in total nitrogen (0.44 to 0.95%) and available phosphorus (13.66 to 16.16 ppm) was observed. Soil organic matter went from 9.81% to 13.98%. The decrease in available potassium (83.33 to 48.21 ppm) was caused by plant uptake during fruit growth. Coffee yield was improved from 11.5 t ha-1 to 15 t ha-1 after the application of the compost, which was a 25-30% improvement. This response is based on changes in soil conditions for the better and indicates that compost-based management contributes to the sustainable production of coffee under farm conditions. Converting coffee bark into compost is part of a circular bioeconomy strategy, as it cuts out waste and improves the recycling of nutrients. In the tropical highlands, where degradation is a major problem, these practices are essential to the resilience of agriculture. Coffee bark compost stabilizes the soil acidity and enhances the biological properties. Despite moderate nutrients, improvements in the soil boost productivity. Thus, composting of coffee bark improves the highland coffee production sustainability.

References

Chali Terfassa, G. (2020). Effect of integrated use of coffee husk compost and NPS fertilizer on soil physicochemical properties, growth and yield of coffee (Coffea arabica L.) at Haru Research Center, Western Ethiopia (Doctoral dissertation, Ambo University).

Chali, G., Abera, T., & Wakgari, T. (2021). Effect of coffee husk compost and NPS fertilizer rates on growth and yield of coffee (Coffea arabica L.) at Haru Research Sub-center, Western Ethiopia. American Journal of Bioscience and Bioengineering, 9(3), 81-87. https://doi.org/10.11648/j.bio.20210903.14

Gammatantrawet, N., Susawaengsup, C., Tongkoom, K., Chatsungnoen, T., Leelapattana, W., Sitthikun, S., Dangtungee, R. and Bhuyar, P. (2023). Organic farming management: An approach towards sustainable agriculture development towards green environment. Maejo International Journal of Energy and Environmental Communication, 5(3), 6-15. https://doi.org/10.54279/mijeec.v5i3.251199

Gebisa, L., & Regasa, M. (2024). Biochar's role in enhancing soil fertility and current trends of utilization for sustainable coffee (Coffea arabica L.) production: A review. Journal of Energy, Environmental & Chemical Engineering, 9(4), 100-108. https://doi.org/10.11648/j.jeece.20240904.12

Gupta, S., Sharma, S., Aich, A., Verma, A.K., Bhuyar, P., Nadda, A.K., Mulla, S.I. and Kalia, S.(2023). Chicken feather waste hydrolysate as a potential biofertilizer for environmental sustainability in organic agriculture management. Waste and Biomass Valorization, 14(9), 2783-2799. https://doi.org/10.1007/s12649-023-02123-6

Hoseini, M., Cocco, S., Casucci, C., Cardelli, V., Ruello, M. L., Serrani, D., & Corti, G. (2025). Producing agri-food derived composts from coffee husk as primary feedstock at different temperature conditions. Journal of Environmental Management, 373, Article 123485. https://doi.org/10.1016/j.jenvman.2024.123485

Jiang, Z., Liu, X., Sun, W., Cui, N., Guo, J., Chen, H., & Huang, W. (2024). Fertilizer optimization combined with coffee husk returning to improve soil environmental quality and young coffee tree growth. Journal of Soil Science and Plant Nutrition, 24(1), 650-665. https://doi.org/10.1007/s42729-023-01572-1

Jiang, Z., Lou, Y., Liu, X., Sun, W., Wang, H., Liang, J., ... & Yang, Q. (2023). Combined application of coffee husk compost and inorganic fertilizer to improve the soil ecological environment and photosynthetic characteristics of Arabica coffee. Agronomy, 13(5), Article 1212. https://doi.org/10.3390/agronomy13051212

Jibril, T., & Bekele, G. (2022). Effect of coffee husk compost and NPSB fertilizers on selected soil chemical properties of potato field in Chora District, south west Ethiopia. Applied and Environmental Soil Science, 2022, Article 7397872. https://doi.org/10.1155/2022/7397872

Khoirunnisak, A., Prijono, S., Nopriani, L. S., Prasetya, B., & Hanuf, A. A. (2025). Improving coffee soil health using compost made from sugarcane leaves, coffee pulp, and Gliricidia sp. SAINS TANAH-Journal of Soil Science and Agroclimatology, 22(2), 271-281. https://doi.org/10.20961/stjssa.v22i2.103549

Kiup, E., Swan, T., & Field, D. (2025). Soil management practices in coffee farming systems in the Asia-Pacific region and their relevance to Papua New Guinea: A systematic review. Soil Use and Management, 41(2), Article e70068. https://doi.org/10.1111/sum.70068

Kumar, A., Thakur, M. K., Hart, P., & Thakur, V. K. (2025). Sustainable valorization of spent coffee grounds: A green chemistry approach to soil amendment and environmental monitoring. ACS Sustainable Resource Management, 2(9), 1630-1642. https://doi.org/10.1021/acssusresmgt.5c00083

Li, Y., & Bhuyar, P. (2024). Brassinosteroid-enhanced phytoremediation for a sustainable strategy for mitigating vanadium contamination in agricultural soils. Maejo International Journal of Energy and Environmental Communication, 6(3), 9-19. https://doi.org/10.54279/mijeec.v6i3.258340

Maro, G., Kilambo, D., Kiwelu, L., & Mbwambo, S. (2024). Integrated soil fertility management practices for coffee in Tanzania: A review. World Journal of Agricultural Research, 12(1), 8-17.

Martinez, H. E. P., Andrade, S. A. L. D., Santos, R. H. S., Baptistella, J. L. C., & Mazzafera, P. (2024). Agronomic practices toward coffee sustainability: A review. Scientia Agricola, 81, Article e20220277. https://doi.org/10.1590/S0103-9016.2024.81.e20220277

Mejica, G. F. C., Unpaprom, Y., Whangchai, K., & Ramaraj, R. (2022). Cellulosic-derived bioethanol from Limnocharis flava utilizing alkaline pretreatment. Biomass Conversion and Biorefinery, 12(5), 1737-1743.

Netsere, A., & Takala, B. (2021). Progress of soil fertility and soil health management research for Arabica coffee production in Ethiopia. Plant, 9(3), 70-80.

Nong, H. T. T., Unpaprom, Y., Whangchai, K., & Ramaraj, R. (2022). Sustainable valorization of water primrose with cow dung for enhanced biogas production. Biomass Conversion and Biorefinery, 12(5), 1647-1655. https://doi.org/10.1007/s13399-020-01065-6

Pandi, S., Ramaraj, R., Bhuyar, P., Ramaraj, R., & Unpaprom, Y. (2024). Sustainable biobutanol production from Amorphophallus tuber starch via optimized ABE fermentation. Maejo International Journal of Energy and Environmental Communication, 6(3), 70-77. https://doi.org/10.54279/mijeec.v6i3.258825

Pham, T. T., Nguyen, N. H., Yen, P. N. D., Lam, T. D., & Le, N. T. T. (2020). Proposed techniques to supplement the loss in nutrient cycling for replanted coffee plantations in Vietnam. Agronomy, 10(6), Article 905. https://doi.org/10.3390/agronomy10060905

Ramaraj, R., & Dussadee, N. (2015). Renewable energy application for organic agriculture: A review. International Journal of Sustainable and Green Energy, 4, 33-38. doi: 10.11648/j.ijrse.s.2015040101.15

Reansuwan, K., Maneejantra, N., & Unpaprom, Y. (2024). Advancing bioenergy sustainability through hydrogen nanobubble-enhanced anaerobic digestion of tobacco stalks for biogas production. Maejo International Journal of Energy and Environmental Communication, 6(3), 50-61. https://doi.org/10.54279/mijeec.v6i3.258867

Reetsch, A., Schwärzel, K., Dornack, C., Stephene, S., & Feger, K. H. (2020). Optimising nutrient cycles to improve food security in smallholder farming families—A case study from banana-coffee-based farming in the Kagera region, NW Tanzania. Sustainability, 12(21), Article 9105. https://doi.org/10.3390/su12219105

Sophanodorn, K., Unpaprom, Y., Whangchai, K., Homdoung, N., Dussadee, N., & Ramaraj, R. (2022). Environmental management and valorization of cultivated tobacco stalks by combined pretreatment for potential bioethanol production. Biomass Conversion and Biorefinery, 12(5), 1627-1637. https://doi.org/10.1007/s13399-020-00992-8

Taechawatchananont, N., Manmai, N., Pakeechai, K., Unpaprom, Y., Ramaraj, R., & Liao, S. Y. (2024). Potentials of bioethanol production from sunflower stalks: value-adding agricultural waste for commercial use. Biomass Conversion and Biorefinery, 14(11), 11799-11811. https://doi.org/10.1007/s13399-022-03373-5

Takala, B., & Chali, G. (2025). Integrated use of coffee husk compost and inorganic fertilizer enhances soil properties, coffee growth and yield in West Wollega, Ethiopia. Middle East Research Journal of Agriculture and Food Sciences, 5(1), 1-8.

Trujillo-González, J. M., Jiménez-Ballesta, R., Silva-Parra, A., Torres-Mora, M. A., & Navarro, F. J. G. (2024). A comprehensive review of composting from coffee waste: Revalorisation of coffee residue in Colombia. International Journal of Recycling of Organic Waste in Agriculture, 13(3). https://doi.org/10.30486/ijrowa.2024.3056

Vu, P. T., Ramaraj, R., Bhuyar, P., & Unpaprom, Y. (2022). The possibility of aquatic weeds serving as a source of feedstock for bioethanol production: a review. Maejo International Journal of Energy and Environmental Communication, 4(2), 50-63.https://doi.org/10.54279/mijeec.v4i2.248180

Wijaya, I. M. W., Martiningsih, N. G. A. G. E., Jayantini, I. G. A. S. R., Putra, G. B. B., Wiratama, I. G. N. M., & Kenedy, F. V. (2025). Composting of coffee husk waste as circular economy practice in local coffee bean production. International Journal of Recycling of Organic Waste in Agriculture, 14(4). https://doi.org/10.30486/ijrowa.2025.8254