



RESEARCH PAPER

Evaluation of a Circular Economy Model for Coffee Processing Waste Valorization in Sidama, Ethiopia

Daniel Fritschen^{1*}, Habtamu Elias Ololo¹, Dylan Maxwell¹, Abadi Berihu¹, Sidur Rahman¹

¹ Waste Free '23

* Corresponding Author: danfritschen@gmail.com

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Abstract

Background

Coffee processing generates substantial quantities of wastewater, 65,000 tonnes of waste coffee husks [11] produced at nearly 500 mills, and organic residues that frequently create environmental challenges in the Sidama region of Ethiopia. Waste management options available to rural coffee cooperatives are often limited, resulting in uncontrolled disposal, water pollution, and loss of potentially valuable resources.

Methods

Dry coffee husks were converted into biochar using a fan-assisted Top-Lit UpDraft (TLUD) pyrolysis system (ECHO-inspired design) [13]. The biochar was tested according to Quebec criteria and used in field-scale filtration barrels treating coffee processing wastewater (CPWW). Wet organic fractions were processed via vermiculture and BSFL bioconversion. Water quality parameters (pH, BOD, TSS, turbidity) were measured at Hawassa University Environmental Engineering Laboratory.

Results

High quality biochar was produced using the fan-assist TLUD biochar maker from the dry waste coffee husks. The biochar was tested and PAH levels were found to be compliant. Biochar filtration significantly improved wastewater quality, increasing pH from 3.86 to 4.31 in single-pass treatment and an estimated up to ~6.0 under repeated filtration (second-pass system model). Total Suspended Solids (TSS) decreased from 1,800 ppm to 580 ppm (67.8%), and turbidity from 5,360 NTU to 84.4 NTU (98.4%). Vermicompost and BSFL frass produced nutrient-rich soil amendments with estimated NPK values comparable to global literature.

Conclusion

The model demonstrates a scalable, low-cost, decentralized circular economy waste-to-value system that simultaneously addresses water pollution, soil acidification, and rural income generation. Approximately 500 coffee mills exist in the Sidama region, with ~200 having implemented vermiculture systems, indicating strong scalability potential. While improving wastewater quality, additional treatment stages are required to achieve discharge standards. The approach provides a practical and scalable framework for decentralized waste management, localized fertilizer production, and rural enterprise development in coffee-producing regions.

Keywords: *biochar, coffee wastewater, circular economy, Ethiopia, vermicomposting, wastewater treatment, coffee husk, Sidama*

1 Introduction

Ethiopia is the largest coffee producer in Africa and among the world's leading producers of Arabica coffee [14]. Coffee contributes significantly to export earnings, employment, and rural livelihoods [14]. The Sidama region is internationally recognized for high-quality specialty coffee production; however, coffee processing generates substantial waste streams that are often unmanaged.

Wet coffee processing generates coffee processing wastewater (CPWW) with standard water usage and effluent generation averaging 15,000 to 40,000 L per tonne of green coffee produced [15]. CPWW is characterized by high organic loading, low pH, elevated biochemical oxygen demand (BOD), chemical



oxygen demand (COD), suspended solids, and polyphenolic compounds [1,2]. When discharged untreated, CPWW can deplete dissolved oxygen in rivers and negatively impact aquatic ecosystems.

Dry coffee processing generates large quantities of coffee husks. Previous studies estimate that coffee husks may represent approximately 50% of the weight of processed coffee cherries (or roughly 1 kg of husk per kg of green coffee bean produced) and are frequently disposed of through open dumping or burning [3]. Simultaneously, agricultural soils in many coffee-producing regions of Ethiopia are becoming increasingly acidic, reducing nutrient availability and limiting crop productivity [4]. The high and rising cost of imported inorganic fertilizers further exacerbates this challenge for smallholder farmers, increasing production costs and reducing economic viability [21].

A circular economy approach offers opportunities to transform these waste streams into valuable products. Biochar production from coffee husks creates filtration media and high pH soil amendments. Vermicomposting converts organic residues into nutrient-rich compost. Biological conversion technologies such as Black Soldier Fly Larvae (BSFL) offer additional opportunities for feed and fertilizer production.

Waste Free '23 and local partners have been implementing and demonstrating integrated waste valorization systems in Sidama. This paper documents the husk waste biochar characteristics, reports vermiculture suitability, wastewater treatment results, and evaluates opportunities for scaling decentralized waste-to-value systems in coffee-producing communities.

2 Project Context and Methodology

2.1 Project Context

The activities described in this study were implemented through Waste Free '23 and local collaborators in Sidama Region, Ethiopia between 2024 and 2026.

The project focused on:

- Coffee husk biochar production
- Biochar-based wastewater treatment
- Vermicompost production
- Biochar-compost blending
- Farmer demonstrations
- Coffee cooperative engagement

The objective was to establish practical, low-cost technologies capable of reducing waste while creating locally useful products.



Figure 1

Coffee husk stockpiles generated during coffee processing in Sidama Region, Ethiopia. Large volumes of husks are commonly accumulated without productive utilization.

2.2 Biochar Production

Coffee husks were converted into biochar using fan-assisted cone Top-Lit UpDraft (TLUD) reactors developed and promoted by Waste Free '23 (Figure 2). The system consists of a metal cone reactor, solar-powered fan, low-cost air injection system, and operates in batch mode.

The reactor functions under oxygen-limited conditions to promote carbonization while minimizing complete combustion. Operation involves filling the cone with dry coffee husks, creating vertical air channels, top-lighting with kindling, running the fan at full power for the initial ~10 minutes, then adjusting airflow for a clean, smoke-free burn. The process is complete when the combustion front reaches the bottom of the cone, followed by quenching and cooling (see Appendix B for building and operating instructions for the TLUD).

The resulting biochar was characterized through independent laboratory analysis (Bureau Veritas, Montreal; Report C567205, November 2025; see Appendix A for raw data, report, and certification). All measured PAHs and heavy metals were well below Quebec provincial soil quality criteria, confirming its safety for use as a soil amendment and filtration medium [22].





Figure 2
Fan-assisted TLUD reactor converting husks into biochar for wastewater treatment and soil amendment applications.

Table 1. Summary of key chemical properties of the produced coffee husk biochar (Bureau Veritas Report C567205).

Parameter	Measured Value	RDL	Quebec Criteria (A/B/C)	Compliance
Moisture (as-received)	69%	N/A	—	—
PAHs (mg/kg, dry weight)				
Naphthalene	0.31	0.10	5 / 50 / 50	Compliant
1-Methylnaphthalene	0.24	0.10	—	Compliant
2-Methylnaphthalene	0.16	0.10	—	Compliant
1,3-Dimethylnaphthalene	0.18	0.10	—	Compliant
All other PAHs (incl. Benzo(a)pyrene)	<0.10	0.10	0.1-10 (varies)	Compliant
Heavy Metals (mg/kg, dry weight)				
Arsenic (As)	<2.0	2.0	6 / 30 / 50	Compliant
Cadmium (Cd)	<0.10	0.10	1.5 / 5 / 20	Compliant
Chromium (Cr)	4.3	2.0	100 / 250 / 800	Compliant
Copper (Cu)	33	1.0	50 / 100 / 500	Compliant
Lead (Pb)	<5.0	5.0	50 / 500 / 1000	Compliant
Zinc (Zn)	57	5.0	140 / 500 / 1500	Compliant
Barium (Ba)	75	5.0	340 / 500 / 2000	Compliant
Manganese (Mn)	120	2.0	1000 / 1000 / 2200	Compliant

2.3 Wastewater Treatment Demonstration

A biochar column gravity-forced filtration system was constructed to evaluate the treatment of coffee processing wastewater. Coffee wastewater was directed through a filtration system containing coffee husk-derived biochar before discharge. Influent CPWW flows through:

1. Sedimentation zone
2. Biochar filtration bed
3. Collection outlet basin

Water samples were collected from:

1. Reference river water
2. Untreated wastewater
3. Treated wastewater

Laboratory analyses were conducted by Hawassa University Institute of Technology Environmental Engineering Laboratory.



(a)

(b)

(c)

(d)

Figure 3

(a) Biochar in the filtration column. (b) Fine-mesh screen on column top. (c) CPWW poured at the top for treatment. (d) Wastewater passes through biochar media and is discharged at the bottom.

2.4 Vermicomposting Activities

Organic residues were converted into vermicompost using earthworm-based systems. The vermicomposting units were designed using locally available materials and low-cost construction methods. Produced vermicompost was blended with biochar and applied as a soil amendment.



Figure 4

Vermicomposting unit established for conversion of organic waste into agricultural inputs.

2.5 Biochar-Compost Blending

Produced vermicompost was physically blended with biochar generated from coffee husks. Although chemical characterization of the blended material was not conducted during this project, previous studies

suggest that combining biochar with organic fertilizers can improve nutrient retention, soil water holding capacity, and microbial activity [5,6].



Figure 5

Biochar blended with vermicompost for use as a locally produced soil amendment.

3 Results and Discussion

3.1 Wastewater Treatment Performance

Table 2 presents the laboratory results obtained from Hawassa University (see Appendix).

Table 2. Water Quality Parameters Before and After Treatment.

Parameter	Raw CPWW	Treated (Single Pass)	Second Pass (Estimated)	Guideline Reference
pH	3.86	4.31	~6.0	6.5 – 8.5 [23]
TSS (ppm)	1,800	580	~200 (est.)	—
Turbidity (NTU)	5,360	84.4	~30 (est.)	<50 [23],[24]
BOD (mg/L)	3,500	3,080	TBD	5 [23]
DO (mg/L)	0.7	1.2	~2.5 (est.)	>5–6 [23]

The treatment system achieved substantial reductions in suspended solids and turbidity:

- TSS reduction: 67.8%
- Turbidity reduction: 98.4%

The results indicate that coffee husk biochar is effective as a primary treatment medium for removal of particulate matter. However, reductions in BOD were limited, and the treated effluent remained acidic. This suggests that additional passes of the water through a biochar filter are required to achieve the target of water ready for release.

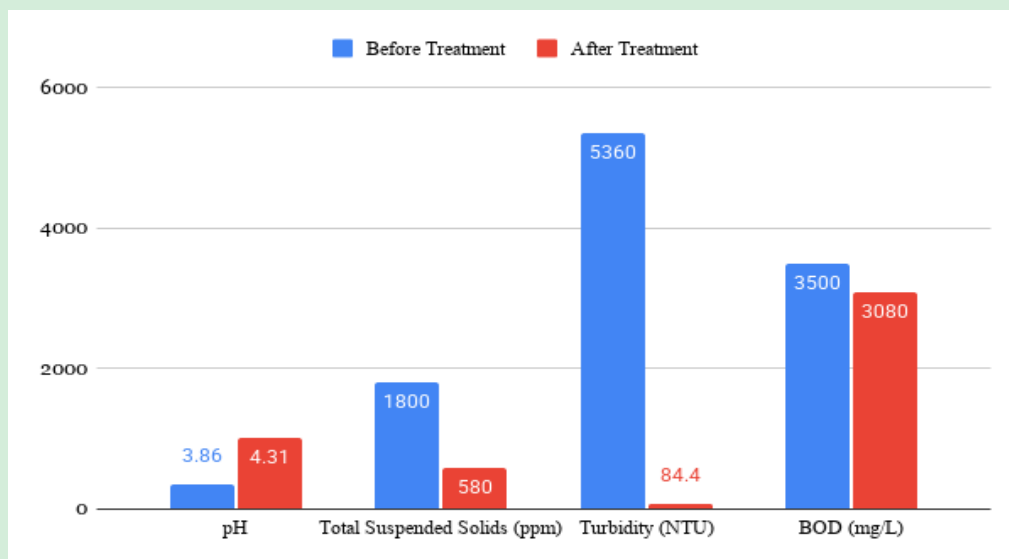


Figure 6

Comparison of wastewater quality parameters before and after biochar filtration treatment. pH rose from 3.86 to 4.31; TSS fell from 1,800 to 580 ppm; turbidity fell from 5,360 to 84.4 NTU; BOD fell slightly from 3,500 to 3,080 mg/L.

3.2 Comparison with Published Studies

The observed reductions in turbidity and suspended solids are consistent with previous investigations reporting effective adsorption and filtration properties of coffee-derived biochars.

Mukarunyana et al. reported that coffee-derived chars can effectively adsorb organic contaminants, polyphenols, and other pollutants from wastewater [7].

Similarly, Zungu et al. demonstrated strong adsorption performance of coffee-waste-derived biochars in water treatment applications [8].

Unlike laboratory-scale systems reported in literature, the present study evaluated a field-scale demonstration under practical operating conditions.

3.3 Vermicomposting and Soil Amendment Production

Vermicomposting activities successfully converted organic residues into stabilized compost suitable for agricultural use. Combining vermicompost with biochar may offer several agronomic advantages:

- Increased nutrient retention
- Reduced nutrient leaching
- Improved soil structure
- Enhanced microbial activity
- Increased water holding capacity

These observations are supported by previous research on biochar-compost interactions [5,6].



3.4 Economic Considerations

A key advantage of the integrated circular system is its low operating cost and potential for positive returns. Coffee husks are generated as a free waste product at processing mills, while vermicomposting utilizes readily available organic residues. The primary upfront investment is in basic equipment, with low ongoing costs due to minimal energy and feedstock requirements. This model supports income generation through the sale of biochar, vermicompost, and blended soil amendments, while reducing waste disposal and fertilizer expenses for farmers.

Table 3. Estimated Initial Investment (per small-scale unit).

Component	Estimated Cost (USD)	Notes
TLUD Reactor	120	Metal cone, locally fabricated
Solar-Powered Fan System	200	Low-cost solar setup
Vermicompost Setup	100	Beds, worms, local materials
Basic Tools & Accessories	40	Buckets, sieves, etc.
TOTAL	460	Scalable for cooperatives

Table 4. Estimated Operational Costs and Potential Revenue (small-scale cooperative unit processing ~5-10 tonnes husks/organics per year).

Item	Cost/Revenue (USD/yr)	Assumptions / Notes
Ongoing Costs		
Labor (part-time)	150 – 300	Local wages for 1-2 people
Maintenance & minor repairs	50	Drums, fans
Transport / Misc.	50 – 100	—
Total Annual Costs	250 – 450	Very low due to free feedstock
Revenue Streams		
Biochar sales (1 tonne)	50 – 100	~\$25 to \$50/tonne local/East Africa market
Vermicompost / Frass sales (1 tonne)	100 – 200	~\$100 to \$200/tonne; high demand for organic fertilizer
Blended soil amendment (1 tonne)	100 – 200	Biochar + vermicompost mix
Total Potential Revenue	250 – 500	Conservative; higher with scale/carbon credits
Net Annual Profit	0 – 50	Highly conservative estimate; excludes carbon credit potential

Notes: Prices based on East African / Ethiopian local markets and similar projects. Revenue can increase through carbon credit participation or sales to organic coffee farms. Actual figures depend on scale, local prices, and market access [19].

3.4.1 Biochar Value for Volcanic Soils and Organic Farming in Sidama



Soils in the Sidama region, often derived from volcanic parent material, are frequently acidic (low pH), which limits nutrient availability (especially phosphorus) and crop productivity [20]. Biochar from coffee husks acts as an effective, low-cost liming agent, raising soil pH, increasing cation exchange capacity (CEC), improving water retention, and enhancing microbial activity — benefits particularly valuable for sustainable and organic coffee farming. When blended with vermicompost, it further reduces nutrient leaching and supports long-term soil health, making it an excellent alternative or complement to imported chemical fertilizers [20].

This decentralized approach not only mitigates environmental pollution but also creates rural enterprise opportunities, aligning with circular economy goals for coffee-producing communities.

4 Future Opportunities

Several opportunities remain for further development.

4.1 Multi-Pass Biochar Filtration

The single-pass gravity filtration through coffee husk biochar achieved substantial improvements in key parameters (see Table 2), particularly for particulate matter. However, the treated effluent remained acidic (pH 4.31) with elevated BOD, indicating the need for additional treatment stages to meet discharge standards.

Modeling of a second-pass system (re-filtration of the single-pass effluent through a similar biochar column) is estimated to further raise pH to approximately ~6.0, reduce TSS to ~200 ppm, and lower turbidity to ~30 NTU. These projections are based on observed first-pass removal efficiencies (TSS: 67.8%, turbidity: 98.4%) and the known capacity of biochar to progressively neutralize acidity through repeated contact with alkaline biochar surfaces [16].

Further passes or longer contact time could bring pH closer to the WHO-recommended range (6.5–8.5) and achieve greater reductions in organic load. Literature on biochar column filtration supports this approach: multi-stage or repeated biochar filtration consistently enhances pH neutralization and removal of residual organics and suspended solids in acidic wastewaters [17,18].

Implementation Recommendation

A simple two- or three-barrel series system (gravity flow from one barrel to the next) would be low-cost, scalable, and suitable for rural coffee cooperatives. This multi-pass configuration would significantly improve compliance with environmental discharge standards while maintaining the decentralized, low-maintenance nature of the system.

4.2 Renewable Energy Production

Future work may evaluate utilization of pyrolysis gases and biomass-derived fuels for decentralized energy production. See Appendix B for the implementation idea.

4.3 Carbon Credits

Biochar production creates opportunities for long-term carbon sequestration and participation in emerging carbon markets.



5 Conclusion

This study documents the results of a decentralized circular economy model for managing coffee-processing waste in Sidama, Ethiopia. Coffee husks were converted into biochar for wastewater treatment, while coffee pulp and other organic wastes were processed through vermicomposting and Black Soldier Fly Larvae (BSFL) systems to produce valuable agricultural inputs.

Field demonstrations and laboratory analyses showed that biochar filtration improved wastewater quality by reducing turbidity, suspended solids, and biochemical oxygen demand while increasing pH. The resulting biochar, vermicompost, and BSFL-derived products can be combined to create locally produced soil amendments suitable for the acidic soils common in Sidama.

The model requires locally built, low-cost equipment, uses locally available waste materials, and creates opportunities for pollution reduction, soil improvement, and rural income generation. With approximately 500 coffee-processing facilities operating across Sidama, there is significant potential for wider adoption.

Future work should evaluate long-term crop responses to biochar-based fertilizer blends, optimize multi-stage wastewater treatment systems, and further quantify economic and environmental benefits. Overall, the results indicate that coffee waste valorization can provide a practical, scalable, and economically attractive solution for sustainable agricultural development in Ethiopia and in all coffee-growing regions.



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Appendix A

4. Lab Analysis of Biochar Properties - [Raw Data](#)
5. Certificate of Analysis - [Revised Report](#)
6. Water Quality Test - [Lab Result](#)

Appendix B

4. [How to Build a Solar Fan-Assisted Cone TLUD](https://wastefree23.org/) – <https://wastefree23.org/>
 5. [Use a Fan-Assisted Cone TLUD to Make High-Quality Biochar](https://wastefree23.org/) – <https://wastefree23.org/>
 6. [Renewable Energy Production; Biochar SHaCK](https://wastefree23.org/) – <https://wastefree23.org/>
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