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Impact of Compost Produced with Coffee Pulp and *Hermetia Illucens* on Tomato Plant Growth

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This study evaluated the bioconversion of coffee pulp by *Hermetia illucens larvae* in a controlled reactor designed to regulate temperature (27–30 °C), relative humidity (60–70%), and aeration. The system monitored environmental temperature, relative humidity, CO_2 concentration, and substrate temperature. The substrate—coffee pulp with 82.67% moisture, pH 5.32, and 38.58% total organic carbon—was supplied at 1 kg per container with 100 larvae (feeding rate: 115.53 mg dry matter/larva/day), with three replicates and a control without larvae. Larval growth was monitored for 15 days. The highest mass (0.133 ± 0.007 g) and length (18.0 ± 0.42 mm) were observed on day 14. CO_2 concentration peaked at 5553 ppm on day 10, while environmental conditions remained stable throughout the experiment.
The resulting compost exhibited a pH of 9.71, density of 0.53 g/cm³, and 36.04% total organic carbon. The fertilizer was tested in germination assays using *Solanum lycopersicum* (tomato) seeds and coconut coir in various ratios. The 1:3 frass-to-coir treatment yielded the best plant performance: 96 cm height, 23 mm stem thickness, 14 leaves, and 86.67% germination over 27 days. These results demonstrate that black soldier fly larvae can effectively bioconvert coffee pulp into a nutrient-rich organic fertilizer suitable for early-stage plant development, supporting its potential application in sustainable agriculture.

1. Introduction

The coffee industry generates significant quantities of organic waste, particularly coffee pulp, which constitutes approximately 617 kg of solid residues and nearly 6000 L of wastewater per ton of processed coffee (Diyarma, 2019; Abd Manan et al., 2024). These by-products are rich in organic matter—including carbohydrates, proteins, fibers, and polyphenols (Heeger et al., 2017)—and are characterized by high biochemical and chemical oxygen demand, contributing to water and soil pollution (Ijanu et al., 2020; Laili et al., 2022).
Bioconversion using black soldier fly (*Hermetia illucens*) larvae has emerged as a promising strategy for managing agro-industrial waste. These larvae can efficiently degrade a variety of organic substrates while producing valuable by-products such as protein-rich biomass and frass—a residue that can serve as an organic fertilizer (Van Huis et al., 2013; Liu et al., 2022). Studies have demonstrated that H. illucens can reduce the mass of organic waste significantly and improve the physicochemical properties of the resulting fertilizer (Ma et al., 2018; Lardé, 1990).
Despite its potential, the application of coffee pulp as a substrate for BSF larvae remains underexplored due to its high polyphenol content, which may affect larval growth and development. This study evaluates the growth performance of *H. illucens* larvae on coffee pulp and examines the quality of the resulting fertilizer. Furthermore, the agronomic potential of the frass is assessed through a germination test using tomato (*Solanum lycopersicum*) seeds.

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2. Materials and Methods

2.1 Design and Construction of the Laboratory-Scale Reactor.

The bioreactor is a controlled system that includes a growth chamber made of a polypropylene container with dimensions of 67.6 × 85.5 × 39.0 cm and a maximum capacity of 18 kg. The control module incorporates an STC 3028 device (-20 to 80°C, 0 to 100% RH), an electric heating element, and an ultrasonic humidifier HUM-24V (15 mL/h). Air inlet and outlet are regulated with a dual analog timer EBCHQ®, and three Phoenix® air fans with a flow rate of 170 m³/h and 3000 RPM are included. The monitoring module consists of an M135 air quality sensor for detecting harmful gases, a CCS811 CO_2 sensor with a sensitivity range of 400 to 8192 ppm, a DHT11 sensor for ambient temperature and relative humidity (0–50°C, 20–95% RH), and four K-type thermocouples Max 6675 (0–1024°C) for verifying the temperature in the substrate-larvae containers. The programming was conducted using Arduino® libraries.

In the study, coffee pulp from the Manizales region in Colombia was used, with a feeding rate of 115.53 mg dm/larva/day. Larval growth in terms of mass and length was evaluated over 15 days. The reactor's environmental temperature was programmed between 27 and 30°C, and relative humidity was maintained at 60–70%. Bioconversion indicators and the percentage of waste reduction were selected to evaluate the process using Equations 1 and 2 (Gold et al., 2020) (Villa et al., 2021)(Z. Liu et al., 2022)(Parodi et al., 2021):

$$Bioconversion\ rate\%dm = \left(\frac{larvaegain\ g}{feedmass\ g}\right) * 100 \qquad (1)$$

$$Waste\ reduction\ efficieancy\ \%dw = \left(\frac{1 - residuemass\ g}{feedmass\ g}\right) * 100 \qquad (2)$$

2.2. Chemical Composition of Substrate and Fertilizer

To characterize the coffee pulp and the fertilizer obtained through biodegradation, the following analyses were conducted: pH using the potentiometric method, moisture content using the gravimetric technique, total organic carbon content using the colorimetric method (ICONTEC, 2022), and phosphorus content using the Olsen method (Recena et al., 2022).

2.3. Germination and Growth Evaluation of Tomato Plants

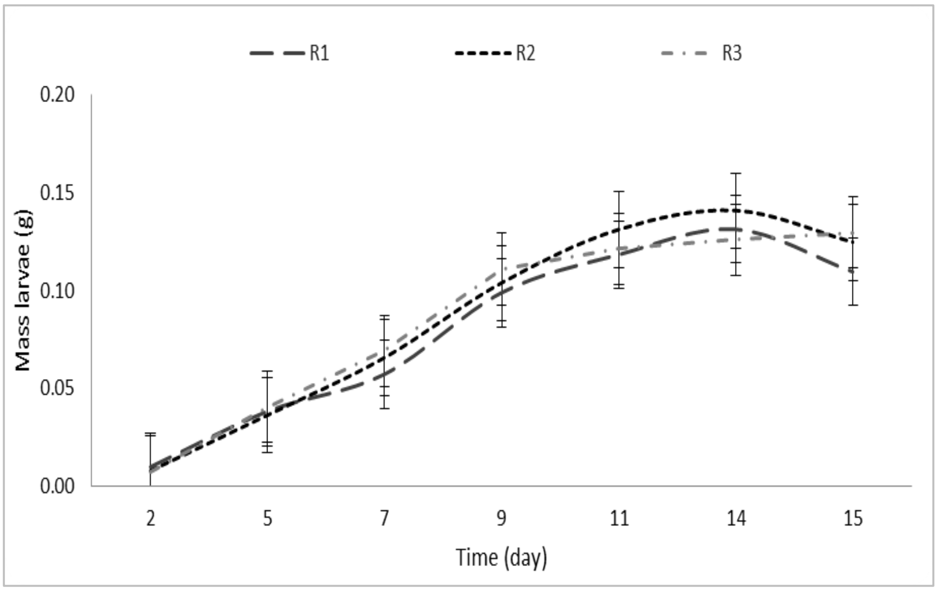
For the germination and growth test of tomato seeds and seedlings, *Solanum lycopersicum* seeds were used. Soil conditioning for cultivation included BSF derived fertilizer and coconut coir in five ratios: 1:0, 3:1, 1:1, 1:3, and 0:1. The coconut fiber and frass mixtures were previously sanitized at 45°C for 24 hours. In each 3.3-ounce seedling tray, three seeds were sown, and each treatment had ten replicates. A vernier caliper was used to measure the size and thickness of plant structures, leaves and stems, on a daily basis.

3. Results

The experiment was conducted using five-day-old *Hermetia illucens* larvae. A total of 100 larvae per kilogram of coffee pulp (moisture content: 82.67%) were introduced into each treatment. The setup included three replicates (R1, R2, R3) and a control without larvae. The samples were incubated for 15 days in a controlled laboratory reactor under a temperature range of 27–30°C and a relative humidity of 60–70%. Larval length and mass were measured every three days.

As shown in Figures 1 and 2, larval growth increased steadily over time, reaching a maximum average mass of 0.133 ± 0.007 g and length of 18 ± 0.42 mm on day 14. A slight decrease was observed on day 15 (0.121 ± 0.010 g and 17.7 ± 0.38 mm), likely due to the mobilization of internal reserves (lipids and proteins) for metabolic processes and pupation.

The biotransformation process achieved a waste reduction efficiency of 45.81% ± 4.48 and a bioconversion rate of 1.63% ± 0.87. These values, although slightly lower than those reported by Casallas et al. (2024) (56.56% and 66.89% over 21 days), suggest that extending the residence time could enhance waste degradation. Similarly, the bioconversion rate was lower than the range of 9.01% to 19.80% reported by Barrantes et al. (2024) for food waste mixtures, highlighting the influence of substrate type and duration on conversion efficiency.



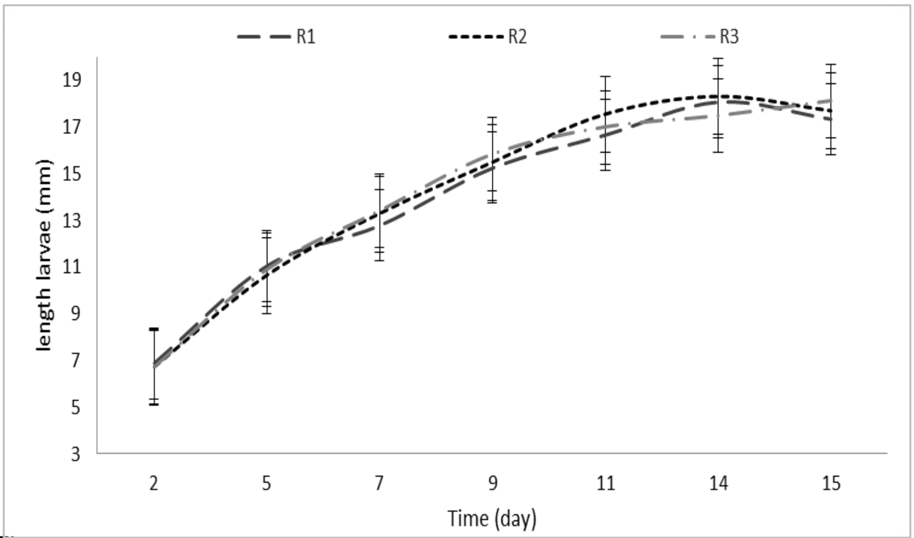


Figure 1 and 2: Black soldier fly larvae growth (g), (mm).

Table 1: characterization of organic fraction of BSF larvae

Parameter	Allowed values in fertilizers (Colombia)	Coffee pulp	Fertilizer BSF	Blank*
Density (g/cm^3)	(<0.6)	1.84	0.53	0.36
pH	(4-9)	5.32	8.96	8.94
%TOC	(> 15)	38.58	40.41	39.50
% Moisture	(< 20)	82.67	75.96	82.26
%Ashes	(< 60)	7.45	22.70	17.51
% P	(> 1)	<0.001	<0.001	<0.001

*Blank: degradation without larvae

Table 1 presents the physicochemical characterization of the coffee pulp and the resulting frass (larval fertilizer). The process improved key parameters such as pH and organic carbon content, aligning with the standards of NTC 5167:2022 for use as fertilizer in Colombia. However, moisture content and phosphorus levels remained outside the recommended ranges, indicating the need for post-treatment strategies like drying or nutrient fortification. Continuous monitoring of CO_2 levels in the reactor showed fluctuations between 400 and 5000 ppm (Figure 3), with average ambient temperatures of 29–30°C. These elevated CO_2 levels may result from inadequate aeration, as fans operated for only 5 minutes every hour. Future optimization of the aeration cycle is necessary to maintain CO_2 concentrations within ideal ranges (400–1000 ppm) for larval development and microbial activity.

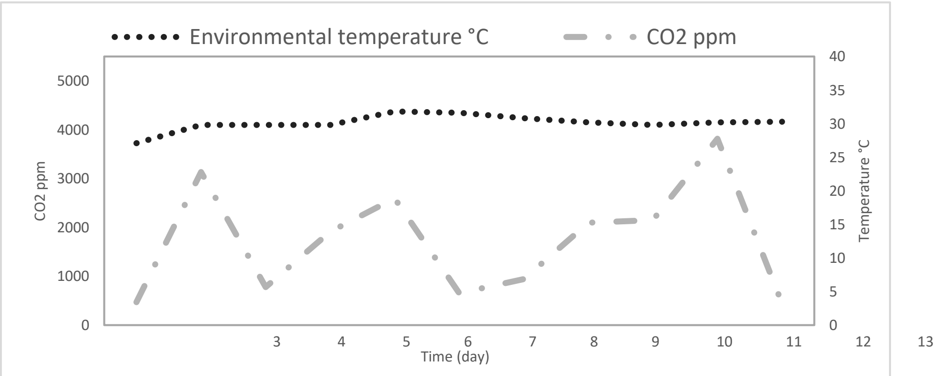


Figure 3: Monitoring temperature and CO_2 concentration in the reactor

In the germination assay, *Solanum lycoper*sicum seeds were sown in mixtures of frass and coconut coir in five different ratios. After 27 days, the 1:3 frass-to-coir mixture yielded the best plant development: an average height of 96.23 mm, 14 leaves, 1.9 mm stem diameter, and 86.67% germination rate. Treatments with 1:1 and 3:1 ratios also showed promising results. Notably, the 1:0 treatment (pure frass) failed to support seed germination, likely due to phytotoxicity or excess salt concentration. The results are shown in Table 2.

Table 2: Germination test results using BSF fertilizer for tomato plants (Solanum lycopersicum)

Treatment	Frass*: Coconut Coir Ratio	Germination (%)	Height (mm)	Number of Leaves	Stem Diameter (mm)	Number of Flowers
1	1:0	0.00%	-	-	-	-
2	3:1	93.33%	31.20	3	1.1	NA
3	1:1	76.67%	68.22	8	1.4	NA
4**	1:3	86.67%	96.23	14	1.9	NA
5	1:1	93.33%	65.05	9	1.4	NA

*Frass: biomass, fertilizer produced by larvae and black soldier fly.

The organic fertilizer (frass) proved to be effective for the development and growth of the plants. The treatments with the highest proportion of organic fertilizer presented the worst conditions, since the treatment (1) with 100% fertilizer did not present germination, the treatment (2) with 75% of frass content presented a germination of 93.33%, but its growth was slow, the treatment (3) with 50% of fertilizer composition presented the lowest germination, but it was the second treatment that had the best growth conditions, followed by the treatment (4) with 25% content, where the plants concluded the experimentation with a height of 68.22 mm, number of leaves 8 and stem diameter of 1.4 mm. It is possible to verify the difference in growth in Figure 4. .
In the study of (Fan et al., 2023), organic fertilizers provide fertility to the soil in the long term, contributing to agricultural production, and it is also considered that this is related to the improvement of soil conductivity. Nur Fardilla Amrul et al., 2022, mentions that the organic fertilizer obtained from BSF larvae has characteristics that are assimilated with the immature organic fertilizer, due to its short time, the author recommends a complementary process such as vermicomposting or anaerobic digestion.

Figure 4: Growth of tomato seedlings with BSF fertilizer

4. Conclusions

This study demonstrated the potential of black soldier fly (*Hermetia illucens*) larvae to bioconvert coffee pulp into an organic fertilizer suitable for agricultural applications. Specifically, the 1:3 frass-to-coconut coir mixture supported successful seed germination and early growth of *Solanum lycopersicum* (tomato), indicating its potential use in seedling production. Although larval growth was not significantly affected by the polyphenol content of coffee pulp, the maximum reported larval size was not reached, suggesting that further optimization—such as extending the residence time or supplementing the substrate—may be required. Stable temperature conditions (27–30°C) proved essential for efficient waste reduction and larval development.

The reactor's aeration system showed limitations, with CO_2 concentrations reaching up to 5000 ppm. Future studies should aim to define the optimal CO_2 thresholds for larval performance to improve aeration strategies and maintain favorable environmental conditions.

Overall, the bioconversion process effectively reduced organic waste while producing a nutrient-rich fertilizer that meets several requirements established by Colombian standards (NTC 5167:2022). These findings underscore the feasibility of converting agro-industrial by-products such as coffee pulp into valuable biofertilizers, contributing to sustainable agriculture and circular economy models.

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