

# Techno-Economic Analysis of a Cascade Biorefinery for Valorizing Agro-Industrial Waste: a Case Study of Avocado Hass Seed (*Persea Americana*) from the Amazon Region, Colombia

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This study evaluated the feasibility of a cascade biorefinery of Hass avocado seed for producing biocontrol agents, biofilms, and starch in the Amazon region of Colombia. The feasibility was evaluated through simulation in Aspen Plus® and economic analysis. The total investment capital was estimated at USD 1,624,733. The payback period was 1.39 years, the return on investment was 37.58%, and a net present value of 2.62 MMUSD, confirming the financial solidity of the process. In addition, the results also show a depreciated gross profit of USD 860,232.83, a net profit of USD 610,507.12, and a total product cost of 1.61 MMUSD per year. This research opens new perspectives for developing biorefineries in tropical regions, promoting innovation, and green-technologies adoption.

## 1. Introduction

Agro-industrial waste has become a significant challenge in industrialized global societies, generating large quantities of complex liquid, solid, and gaseous effluents (Squillaci et al. 2021). While traditionally viewed as a major environmental and health concern (Gaur et al. 2022), these wastes are now seen as sustainable resources (Freitas et al. 2021). In this regard, the development of biorefineries to transform agro-industrial waste into valuable bioproducts promotes circular bioeconomy sustainable practices that optimize biomass use (Ahmad et al. 2021). The avocado is one of the most commercialized fruits due to its high nutritional content. Avocado cultivation in Colombia is diverse due to the great variety of regions in the country, obtaining different types of avocados such as 'Hass', 'Lorena', 'Choquette', 'Fuerte', 'Reed', 'Trinidad', etc. (Aguilar-Vasquez et al. 2024). Hass avocado seed (*Persea Americana Mill.*) represents around 13 % of the total weight of fresh fruit, which is considered agricultural waste and discarded (Avhad and Marchetti 2016). Therefore, this work proposes to develop a topology for a cascade biorefinery from the Hass avocado seed from the Colombian Amazon region, prioritizing the production of bioproducts such as biofilms, biocontrol agents, and starch. This study covers the economic viability of the cascade biorefinery, evaluating the process in terms of economic and financial indicators, as in the studies carried out by Herrera-Rodríguez et al. (2022) on the production of oil in northern Colombia from the valorization of Creole avocado pulp, and by Tesfaye et al. (2021) on the extraction of starch from waste avocado seeds.

Limited research has been carried out in the context of the valorization of Hass avocado from an economic perspective, highlighting studies such as the one developed by Dávila et al. (2017) around the avocado's pulp, peel, and seed for producing oil and phenolic compounds, positively concluding about its feasibility. Moreover, Restrepo-Serna et al. (2022) evaluated the Hass avocado's peels and seeds to produce quercetin and catechin, pointing out that these wastes can potentially increase the profit margins of the traditional process. Thus, this research proposes a novel techno-economic evaluation, considering ten economic and three financial indicators, for a cascade biorefinery —not conventional— using only the Hass avocado seed from the Colombian Amazon region for the production of biofilms, biocontrol agent, and starch. Despite the cascade

approach is not novel in the bioprocess's context, we demonstrate that a cascade biorefinery using the Hass avocado seed can be an economically viable scenario.

## 2. Materials and methods

A techno-economic evaluation was carried out to identify a cascade biorefinery's financial and economic indicators from Hass avocado seeds in the Colombian Amazon region in 2024. The mass flows of raw materials and products, and the equipment processing capacity involved in the process were determined through the simulation developed in Aspen Plus®. The economic analysis was performed using Microsoft Excel Office. These calculations were performed following the approach outlined by El-Halwagi (2017b) and applied by Peters and Timmerhaus (1991). The used equation description can be consulted in the work of Garcia-Maza and Gonzalez-Delgado (2024).

### 2.1 Global process description

Figure 1 shows a global block diagram of the cascade biorefinery studied in this work. 240.02 t/y of Hass avocado seeds from the Colombian Amazon region enter the process to produce 108.07 t/y of biocontrol agent, 16.86 t/y of starch, 32.96 t/y of starch-based biofilm (R1, route 1), and 30.13 t/y of biofilm from a second route (R2).

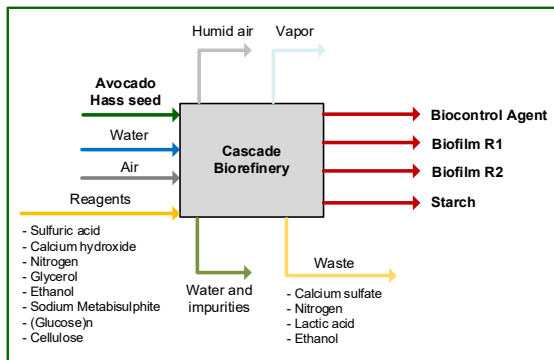


Figure 1: Global block diagram of a cascade biorefinery from Hass avocado seeds.

### 2.2 Considerations for techno-economic evaluation

To establish a cascade biorefinery from Hass avocado seed to produce two biofilms, a biocontrol agent, and starch, it was necessary to collect information on prices of equipment, raw materials, utilities, and products, as well as process profits, labor, taxes, and land costs in 2024. Accordingly, equations from Peters and Timmerhaus (1991) were applied to evaluate the performance of the process from an economic perspective. It starts with the total capital investment (TCI), which is calculated using Eq. (1), where FCI (fixed capital investment) represents the funds required for equipment, civil structures, land preparation, control systems, and facilities, among other aspects, WCI refers to the working capital investment, and SUC means start-up costs, which include legal fees, advertising, and employee training. The costs directly related to the processing capacity, such as buildings, pipes, and purchased equipment (FOB), are calculated using Eq. (2). The costs associated with the operation of the plant (OC) are divided into direct production costs (DPC), fixed charges (FCH), general plant costs (POH) and general expenses (GE), according to Eq. (3). Annualized fixed costs (AFC) are determined using Eq. (4). Total operating costs (TAC) for one year of operation are expressed in Eq. (5), which is derived from annualized fixed costs (AFC) and annualized operating costs (AOC) (El-Halwagi 2017a). Table 1 describes the techno-economic factors taken into account in the analysis.

$$TCI = FCI + WCI + SUC \quad (1)$$

$$FOB_B = FOB_A \left( \frac{Capacity_B}{Capacity_A} \right)^{0.7} \quad (2)$$

$$OC = DPC + FCH + POH + GE \quad (3)$$

$$AFC = \frac{FCI_0 - FCI_s}{N} \quad (4)$$

$$TAC = AFC + AOC \quad (5)$$

Table 1: Techno-economic factors for a cascade biorefinery from Hass avocado seed.

Item	Value
Processing capacity, Hass avocado seed (t/year)	240.02
Hass Avocado seed cost (USD/t)	22.00
Main product flow, biocontrol agent (t/year)	108.07
Biocontrol agent price (USD/t)	20,000.00
Utilities cost: electricity and natural gas (USD/t of Hass avocado seed)	1,541.23
Biorefinery FOB price (USD)	165,060.26
Plant life (years)	15
Salvage value	10 % of depreciable FCI
Construction time	3 years
Location	Colombian Amazon region
Tax rate in 2024	35 %
Discount rate in 2024 (December)	9.5 %
Type of project	Plant on unconstructed land

### 2.3 Economic indicators of the techno-economic evaluation

10 economic indicators were calculated, including gross profit including depreciation (DGP), which was calculated using Eq. (6), and plant profit after tax (PAT), which was derived from Eq. (7). The relationship between process benefits and capital investment (CCF) was also evaluated using Eq. (8). The payback period (PBP) is calculated using Eq. (9). The depreciable investment payback period (DPBP) should be calculated using a cumulative function between two periods, as shown in Eq. (10). The profitability of the project is evaluated with return on investment (ROI) using Eq. (11), while the cumulative sum of all profits during the plant operation period is calculated through the net present value (NPV) in Eq. (12). The first economic potential (EP<sub>1</sub>) represents the profit from subtracting raw material purchase expenses from sales revenue, according to Eq. (13). The second economic potential (EP<sub>2</sub>) is obtained by subtracting industrial process utility costs (U) from the first potential, according to Eq. (14). The third economic potential (EP<sub>3</sub>) is calculated by subtracting annualized operating costs from sales revenue, according to Eq. (15) (El-Halwagi 2017b).

$$DGP = \sum_i m_i C_i^v - TAC \quad (6)$$

$$PAT = DGP(1 - itr) \quad (7)$$

$$CCF = \frac{\sum_i m_i C_i^v - AOC}{TCI} \quad (8)$$

$$PBP = \frac{FCI}{PAT} \quad (9)$$

$$DPBP = y \text{ before PBP occurs} + [\text{non FCI expenses}] \quad (10)$$

$$- \left( \frac{\text{Cumulative NPV } y \text{ before recovery}}{\text{Cumulative NPV } y \text{ after recovery} - \text{Cumulative NPV } y \text{ before recovery}} \right) \quad (11)$$

$$\%ROI = \frac{PAT}{TCI} \times 100\% \quad (11)$$

$$NPV = \sum_n AFC_n (1 + i)^{-n} \quad (12)$$

$$EP_1 = \sum_i m_i C_i^p - \sum_j m_j C_j^{RM} \quad (13)$$

$$EP_2 = \sum_i m_i C_i^p - \sum_j m_j C_j^{RM} - U \quad (14)$$

$$EP_3 = \sum_i m_i C_i^p - AOC \quad (15)$$

## 2.4 Financial indicators of the techno-economic evaluation

Finally, three financial indicators were used to evaluate the operational performance of the process, particularly in terms of profitability before taxes, interest, or depreciation. Earnings before interest and taxes (EBIT) measures the operating profit of a chemical process and is calculated using Eq. (16). Earnings before taxes (EBT) indicates the profit before tax deductions, calculated using Eq. (17). Earnings before interest, taxes, depreciation and amortization (EBITDA) is a measure of the operating cash flow of the company, calculated using Eq. (18) (El-Halwagi 2017c).

$$EBIT = Revenue - AOC + FCH - insurance \quad (16)$$

$$EBT = EBIT - interest/rent \quad (17)$$

$$EBITDA = EBIT + depreciation + amortization \quad (18)$$

## 3. Results and discussion

### 3.1 Techno-economic evaluation analysis

Table 2 presents the results of the techno-economic evaluation, including the direct fixed capital investment (DFCI) and indirect fixed capital investment (IFCI). Additionally, fixed capital investment (FCI), working capital (WCI), start-up (SUC), total capital investment (TCI), salvage value FCI, and annualized fixed costs (AFC) are shown.

*Table 2: Capital costs for the cascade biorefinery from Hass avocado seed.*

Capital costs	Total
DFCI (USD)	492,044.63
IFCI (USD)	363,078.10
Fixed capital investment (FCI; USD)	855,122.72
Working capital (WCI; USD)	684,098.18
Start-up (SUC; USD)	85,512.27
Total capital investment (TCI; USD)	1,624,733.17
Salvage value FCI (USD)	84,786.01
Annualized fixed costs (AFC; USD/year)	51,355.78

Based on the results presented in Table 2, the cascade biorefinery from Hass avocado seed in 2024 required a TCI of USD 1,624,733.17. To put this value in context, the work of Herrera-Rodríguez et al. (2022) presented a TCI 4 times higher for producing Creole avocado oil (*Laurus Persea L*). Tesfaye et al. (2021) presented a FCI of USD 804,885 per year for only producing starch from Hass avocado seeds. While, Davila et al. (2017) obtained FCI values between 20 and 30 times when considering a cascade biorefinery from Hass avocado seeds to produce a phenolic compound extract, ethanol, xylitol, and oil. Therefore, the value obtained is promising. Table 3 shows the contribution of each parameter to the total product cost (TPC) in the cascade biorefinery from Hass avocado seeds. Considering the direct production cost (DPC), the fixed charges (FCH), and the plant overhead (POH) for the total manufacturing cost (TMC), which, together with the general expenses (GE), result in the TPC.

*Table 3: Total product cost for the cascade biorefinery from Hass avocado seed.*

Total Product Cost (TPC)	Total (USD/year)
Direct production cost (DPC)	951,589.94
Fixed charges (FCH)	101,808.02
Plant overhead (POH)	233,280.00
Total manufacturing cost (TMC)	1,286,677.96
General expenses (GE)	321,669.49
Total product cost (TPC)	1,608,347.46

Based on the results presented in Table 3, it is evident that the cascade biorefinery from Hass avocado seed in 2024 generated a TPC of USD 1,608,347.46 per year. The works of Restrepo-Serna et al. (2022), Davila et al. (2017) and Tesfaye et al. (2021) obtained values of 10-12 times our DPC, more than 70 times our DPC and about 0.4 times our DPC, respectively. Due to the scale of the processes, the values of the first two studies were found to be significantly different from our DPC. Tesfaye et al., on the other hand, obtained a lower value because only starch is produced from the Hass avocado seed. Then, these results are also considered attractive for producing biofilm, biocontrol agent, and starch from avocado seeds.

### 3.2 Economic indicators analysis

Table 4 presents the results of the economic indicators calculated for the cascade biorefinery from Hass avocado seed in 2024.

*Table 4: Economic indicators for the cascade biorefinery from Hass avocado seed.*

Indicator	Total
Gross profit (depreciation included) (DGP; USD)	860,232.83
Profitability after tax (PAT; USD)	610,507.12
Cumulative cash flow (CCF; year <sup>-1</sup> )	0.56
Payback period (PBP; years)	1.39
Depreciable payback period (DPBP; years)	2.80
Return on investment (% ROI)	37.58 %
Net present value (NPV; MMUSD)	2.62
Economic potentials 1 (EP1; USD/year)	2,482,000.29
Economic potentials 2 (EP2; USD/year)	2,112,066.91
Economic potentials 3 (EP3; USD/year)	911,588.61

The DGP and PAT were higher than 600 MUSD, which is positive as they are considerably high values. The CCF is less than 1 year<sup>-1</sup>, making the project attractive. The PBP in the present study was 1.39 years (less than 2 years), while the DPBP was 2.80 years (less than 3 years). Moreover, the cascade biorefinery is profitable with a ROI higher than 30 %. On the other hand, it is reflected that the cascade biorefinery from the Hass avocado seed generates an income (NPV) of 2.62 MMUSD with low annual benefits, which indicates that this process has the opportunity for economic improvement. Additionally, economic potentials 1 (EP1), 2 (EP2), and 3 (EP3) are also significantly high, being higher than 2.48 MMUSD, 2.11 MMUSD, and 0.91 MMUSD, respectively. The PBP of this work was among the lowest reported in the studies by Herrera-Rodríguez et al. (2022) and Restrepo-Serna et al. (2022), who reported 1.11 and 1.17, respectively. Restrepo-Serna et al. (2022) presented a better ROI of 54.9% for the production of quercetin and catechin from Hass avocado seeds. For TAP, with a PBP of 2 years and an ROI of 75.12%, Tesfaye et al. (2021) reported comparable values when the seed was used for starch production. This supports the hypothesis that the exclusive use of Hass avocado seed is a profitable source for producing bioproducts.

### 3.3 Financial indicators analysis

Table 5 presents the results of the financial indicators calculated for the cascade biorefinery from Hass avocado seed in 2024.

*Table 5: Financial indicators for the cascade biorefinery from Hass avocado seed.*

Indicator	Total
Earnings before taxes (EBT; USD)	843,985.50
Earnings before interest and taxes (EBIT; USD)	860,232.83
Earnings before interest, taxes, depreciation, and amortization (EBITDA; USD)	1,004,845.40

According to the results, an EBT, EBIT, and EBITDA of over 800 MUSD were obtained, which is positive as they are considerably high values. These results indicate that the proposed cascade biorefinery will be financially self-sustaining, freeing resources for investment in operational improvements, research and development, or debt repayment.

#### 4. Conclusions

This paper highlights the viability of the proposed cascade biorefinery based on Hass avocado seed. This is reflected in favorable economic indicators such as PBP, ROI, and EBITDA. The financial analysis confirms that the project can be self-sustaining with surpluses to improve operations or pay down debt. Also noteworthy is the high gross profit before depreciation (GDP) of over USD 860,000, demonstrating that the process can absorb operating costs and still generate attractive margins. These results open up possibilities for expansion to other derived products in the Colombian Amazon region. In addition, the exclusive use of Hass avocado seeds reinforces the relevance of integrating circular economy approaches in the agroindustry. This research work contributes to the reduction of environmental impacts and the diversification of the national production matrix.

#### Acknowledgments

The authors thank the Universidad de Cartagena and the Colombian Ministry of Science, Technology and Innovation, who funded this work through the project "Evaluation of the sustainability of a cascade biorefinery topology for the use of Hass avocado seeds cultivated in the Amazon region", Code SIGP 100307.

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