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Technical Bottlenecks of a Cascade Avocado Waste Biorefinery Based on Water, Energy and Product Evaluation (E-WEP)

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Circular bioeconomy has arisen as a promising opportunity for economic and sustainable growth in agricultural regions. Biorefineries have become a center of interest as they are a cornerstone in this new economic system. Among them, the cascade biorefineries are a more complete system to fully valorize waste and organic material. However, these systems operational and efficiency have not been studied, identifying main bottlenecks and potential improvements. For this reason, in this study the technical performance of a cascade biorefinery system for valorizing avocado waste is implemented. The biorefinery had multiple outputs, as starch, biofilms and biocontrol agent were considered as products. The analysis WEP showed that the process has regular mass and energy management requiring further improvement. As the process had low yield (20%) and poor material reuse (11%) tied to the products intended, furthermore, the wastewater production is the worst aspect of the process (9%), to the contrast of the water intake and cost, that were particularly acceptable with performance above 65%. Likewise, energy indicators had similar results, as energy intake was acceptable (65%), but the management was poor with an NER performance of 15%. These highlights reaffirmed the necessity of further optimization of cascade systems, especially using integration techniques with more rigorous sustainability assessments.

1. Introduction

Biorefineries are essential units to achieve a circular bioeconomy, thanks to their versatility to transform biomass into a wide array of products (materials and energy) (Daimary et al., 2025). Circular bioeconomy represents a crucial engine for sustainable development and climate change mitigation by harnessing renewable resources for economic development (Jander et al., 2025). Especially for countries like Colombia, with huge biological potential, can offer rural impoverished zones economic growth and social development. Among these biorefineries, cascading processing have emerged as promising approach to maximize valorization of agro-industrial waste, like avocado seeds from south Colombia (Solarte-Toro et al., 2021). Nonetheless, the adoption of these technologies still has some major challenges for commercial use, with factors like feedstock selection, product portfolio, scaling-up, among others, as key factors (Mohammad et al., 2024). For this reason, the use of technical analysis provides a diagnosis of the process performance, identifying important bottlenecks of different topologies and giving important data useful for optimizing and improving designs. Methods like the water-energy-product (WEP) analysis can offer a comprehensive assessment of process design, interconnectivity, material flows, and operational feasibility; furthermore, with CAPE tools, material and energy conservation is assessed through a rigorous benchmarking (Aguilar-Vásquez et al., 2023).
Recently, Valdez-Valdes et al., analyzed a small-scale biorefinery that produced starch, polylactic acid film and starch film using WEP analysis, finding for these three products, good yield, energy use and water consumption, at the same time, high water production and low waste material reuse (Valdez-Valdes et al., 2025). That work showed that technical assessment can offer a comprehensive understanding of the main bottlenecks of the process, pinpointing potential improvements. However, energy management was not evaluated as the net energy ratio was not benchmarked. To address this gap, this study presents the first E-WEP-based technical

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assessment of a Hass avocado seed cascade biorefinery, explicitly incorporating net energy ratio benchmarking to evaluate energy management alongside conventional material and water performance indicators. This biorefinery produces starch, starch biofilm and a biocontrol agent as products. The analysis is based on data obtained from computer-aided simulation software, as the cascade biorefinery process was modelled to obtain extended material and energy balances. From this, key performance indicators are evaluated to assess efficiency of resource use though a benchmark evaluation. This analysis provides quantitative assessment of resource utilization of an avocado seed cascade biorefinery, identifies process bottlenecks, and establishes engineering benchmarks to support process optimization and future scale-up.

2. Materials and methods

2.1 Process description

Figure 1 presents the cascade biorefinery for avocado waste, illustrating the units and material flows. The system consists of four main subprocesses: (i) seed conditioning, (ii) starch production, (iii) biopolymeric film synthesis, and (iv) biocontrol agent production. Avocado residues enter Section 1 under ambient conditions (25 °C, 1 bar). Seeds are washed and cut into pieces (~1.5 cm) and split 1:1 between Sections 2 and 5. In Section 2, seeds contact 0.05% sodium metabisulfite at ambient temperature, are milled to 80 µm, filtered to remove coarse solids, decanted, washed, and centrifuged. The wet starch paste is hot-air dried to <7% moisture and split 50:50, one part as final starch product. The other starch portion moves to Section 3, gelatinized at 80 °C with water, and mixed with PVA and glycerol. Filtration residues undergo acetone extraction, filtered and concentrated, then added to the biopolymer for antioxidant and antimicrobial properties. The mixture is dried at 70 °C to form the starch-based biopolymer film. In Section 4, pretreated seeds are freeze-dried to remove ~90% water, ground, and extracted with ethanol to isolate bioactive compounds. The liquid phase is filtered and concentrated via vacuum evaporation, removing up to 90% ethanol. The dry bioactive paste is emulsified with maltodextrin and gum arabic, ethanol is added for agglomeration, and the mixture is spray-dried to obtain the final biocontrol agent.

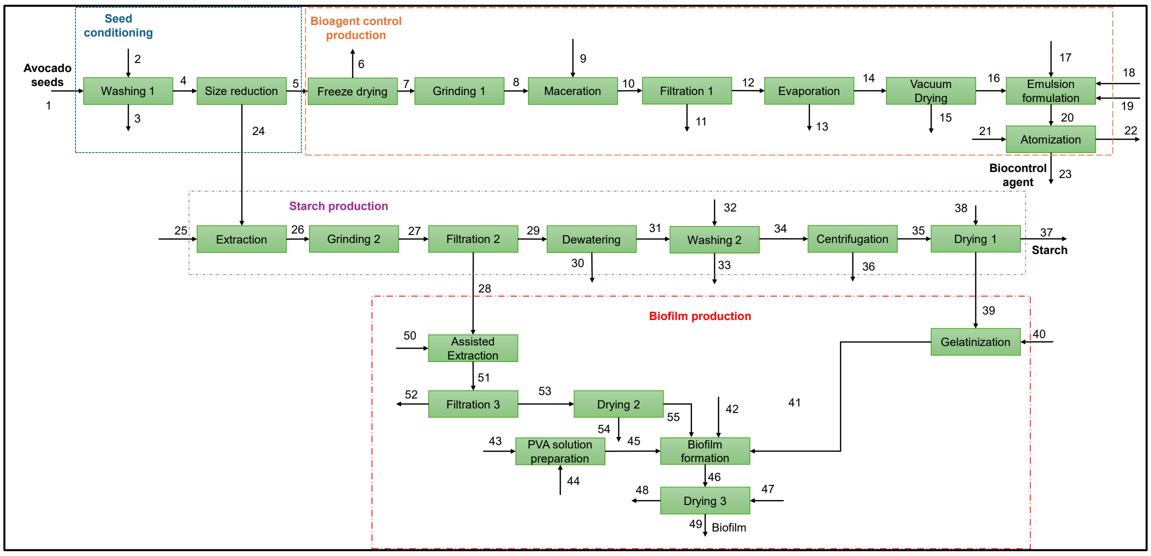

Figure 1: Process Flow Diagram of the Hass Avocado Waste Cascade Biorefinery.

The simulation was carried in Aspen Plus® V15, as suggested by Alviz-Meza et al., with Non-Random Two-Liquid (NRTL) model and Redlich-Kwong (RK) equation of state selected as thermodynamic package for liquid and vapor phase behaviour. Furthermore, unit models and operating conditions were determined based on experimental data and literature values. Lastly, the same raw material input was set at 2645.4 tons per year, corresponding to 50 % of the estimated avocado waste availability in the selected region (Alviz-Meza et al., 2025).

2.2 Water-Energy-Product (WEP) Technical Assessment

In table 1 the metrics used to assess process technical performance are shown. The WEP analysis is based on a “big picture first, details latter” approach in which a set of process parameters are recollected an assessed using a benchmarking framework (best-worst case scenarios). The indicators are considered to provide comprehensive insights of the process energy and mass utilization (raw materials, water and product) (Aguilar-Vásquez et al., 2023). Furthermore, can be used alongside process integration techniques as it showcases the global handling of resources that can be potentially optimized using these methods (mass, energy and properties) (Sousa et al., 2024). For benchmarking, a Min-Max mathematical method is used to quantify efficiency of each of these metrics, where both min and max scenarios are considered or assumed based on data find in literature and achievable targets.

Table 1: Technical WEP indicators, descriptions and equations.

Variable	Description	Formula
Production Yield (%)	Amount of product obtained per unit of feedstock	$\gamma_i = \frac{mass\ flow\ of\ product}{mass\ flow\ of\ main\ feedstock} * 100\%$
Index of Reused Unconverted Material (%)	Percentage of a raw material reused respect to the flowrate of unconverted raw material	$IRUM = \frac{reused\ material\ i\ mass\ flow}{unconverted\ material\ i\ mass\ flow} * 100\%$
Fractional Water Consumption (m^3/t)	Volume of water consumed to obtain the products	$FWC = \frac{volume\ flow\ of\ freshwater}{mass\ flow\ of\ product}$
Wastewater Production Ratio (%)	Quotient between the amount of freshwater required by the process and the wastewater produced	$WPR = \frac{wastewater\ volumetric\ flow}{freshwater\ volumetric\ flow}$*100%
Total Cost of Freshwater ($/day)	Toral cost of freshwater consumed per unit of time	$TCF = flowrate\ of\ freshwater\ consumed * cost\ of\ freshwater$
Energy Specific Intensity (MJ/t)	Energy consumed per tonne of product	$R_{ESI} = \frac{total\ energy\ consumed}{product\ mass\ flow}$
Net Energy ratio (Dimensionless)	Quotient between the energy content of the products and energy enters the process	$NER = \frac{product\ calorific\ power * product\ mass\ flow}{total\ consumed\ energy + (feedstock\ calorific\ power * feedstock\ mass\ flow)}$
Energy Usability Index (Dimensionless)	Quotient between the energy content of the products and the energy required for its production	$EUI = \frac{product\ calorific\ power * product\ mass\ flow}{total\ consumed\ energy}$
Total Cost of Energy ($/day)	Total cost of energy consumed per unit of time	$TCE = total\ energy\ consumed * cost\ of\ energy$
Natural Gas Consumption Index (m^3/t)	Amount of natural gas consumed per tonne of product	$NGCI = \frac{total\ natural\ gas\ consumed}{product\ mass\ flow}$
Electric Energy Consumption Index (kWh/t)	Amount of electric energy consumed per tonne of product	$EECI = \frac{total\ electricity\ consumed}{product\ mass\ flow}$

In the case of the best- and worst-case scenarios for this analysis, the same scenarios proposed by Valdez-Valdes et al., were used as basis to assess the process (Alviz-Meza et al., 2025). For instance, to the production yield 100% and 0% were considered as the best and worst cases, respectively. For fractional water consumption, a 1.27 m^3/t was the best-case scenario, whereas 3.19 m^3/t was the contrary. On the other hand, the best-case scenario for wastewater generation was 0 compared to 95% lower limit. Similarly, a 0.48 per day is the best−case scenario for the total cost of freshwater to 15.60 per day as the worst.
Energy-specific intensity was 18 GJ/t in the best-case scenario and for the worst-case scenario, was 45 GJ/t. Similarly, the electric energy consumption index was 7.6 kWh/t in the best case and 30.6 kWh/t for the worst-case scenario. Contrary, for natural gas consumption, in the best-case scenario is 100% but in the worst-case scenario, its efficiency dropped to only 9.8 %. However, in comparison with the work mentioned, the NER was used as indicator for energy conservation, with the best case being 1 and the worst case 0.25.

3. Results and discussion

In table 2 are shown the technical indicators obtained for the cascade biorefinery using WEP method. These indicators were quantified using key operational parameters collected from the process, such as raw material flow, water intake, wastewater flows, products output, energy requirements, among others. For the process 29.62 kg/h of fresh avocado hard waste was used, in which 5.9 kg/h ended in the form of products (biofilm, starch and biocontrol agent). Furthermore, the water intake was 0.3 m^3/h with a wastewater flow of 0.26 m^3/h. Lastly, the energy consumption was 4,301.5 MJ/day, in which 55% was electricity use and 38.10% was in the form of heat, from the processes involved in the biorefinery.

Table 2: Results of the technical evaluation of the cascade biorefinery from Hass avocado waste.

Indicator	Units	Value
Production Yield	%	20.03
Fractional Water Consumption (FWC)	m^3/t	1.90
Total Cost of Freshwater (TCF)	USD/day	2.86
Wastewater Production Ratio (WPR)	%	86.35
Index of Reused Unconverted Material (IRUM)	%	11.51
Total Cost of Energy (TCE)	USD/day	148.89
Energy Specific Intensity (ESI)	MJ/t	24,737.22
Natural Gas Consumption Index (NGCI)	m^3/t	6.58
Electric Energy Consumption Index (EECI)	kWh/t	0.00
Net Energy ratio (NER)	Dimensionless	0.13833
Energy Usability Index (EUI)	Dimensionless	0.60

Figure 2 shows technical performance of WEP indicators evaluated of the cascade biorefinery of interest, including NER. The EUI indicator was excluded from the analysis, as recommended by authors like Garcia-Maza et al., as it is complicated to assess through normalization due to lack of data (García-Maza et al., 2024). From the analysis several key points can be highlighted as potential opportunities for improvement. First, the production yield was strongly low, as only 20% of the raw material is converted into products (as seen in table 2). This yield is expected, as the process only uses fractions of avocado like starch and bioactive, leaving important fractions unused. In comparison, Valdez-Valdez et al., obtained a yield around 79%, the topology assessed had processes that converted large unused fractions into products, like polylactic acid, increasing material efficiency (Alviz-Meza et al., 2025). This underscores the need to identify potential use of every fraction of the raw material and a potential use, extracting more value from the same raw material; at the same time, the further processing of residual or unconverted fractions can increase complexity in the biorefinery system, a value of 100 reuse of valorization can be not feasible without tradeoffs (Bianchi et al., 2024). Similarly, the use of IRUM presented the same tendency as the production yield, low value of around 12%, pinpointing poor material handling of the topology. The use of fractions from one section into another section improved this indicator as solids filtrated from section 2 where to produce the biofilm. Nonetheless, the limited use of unconverted raw material affected the process of mass efficiency. These indicators supported the need for substantial developments in raw material management.

The case of the water use, indicators showcased both strength and weakness in this resource management. For one instance, the process has high efficiency in FWC and its costs, 67 and 84%, respectively, suggesting

that the process functions effectively with minimal water use (1.9 m^3/h as stated in table 2). The low water footprint is advantage as the process needs to be in regions where water access can be difficult.
However, the same process discharges most of this water as wastewater, with a performance lower than 10%, suggesting the use of water reuse or regeneration. The proper handling of wastewater streams can ease the cost and access to water for the units of the process. Furthermore, WPR can highlight the potential environmental impact that the process has, as some of these streams carry substances that can affect ecosystems.

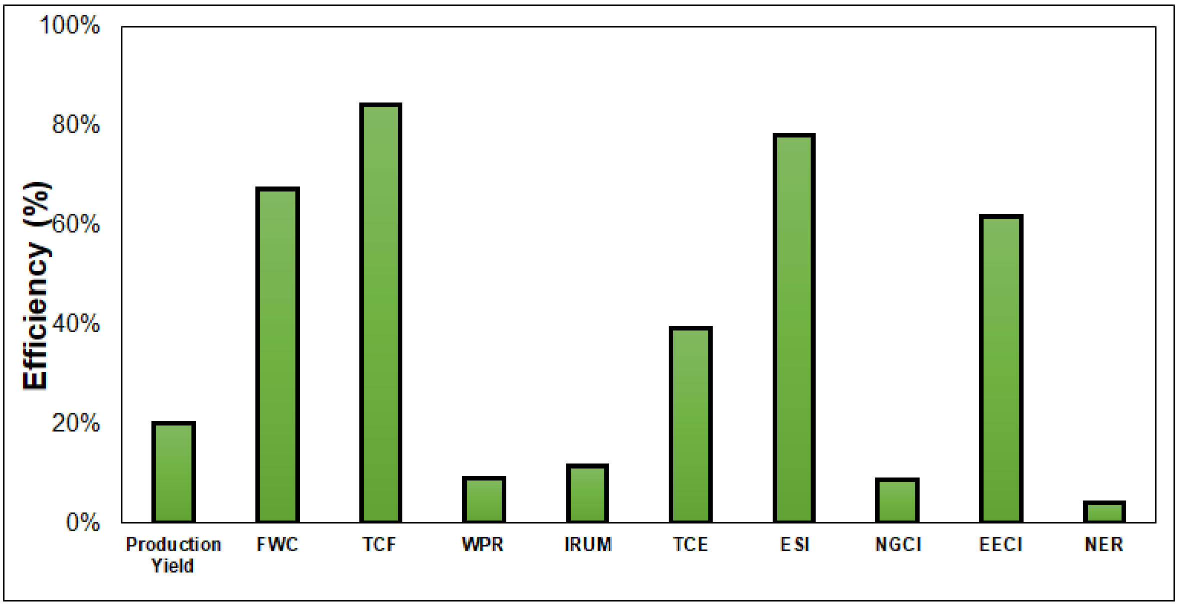

Figure 2: Technical performance of WEP indicators evaluated for a Hass avocado hard waste cascade biorefinery.

Meanwhile, the indicators related to energy have both adequate and poor performance, with the ESI having an adequate performance of 65%, but lower than the 90% from Valdez-Valdes et al., or the 74% of a Creole-Antillean avocado biorefinery from Garcia-Maza et al., obtained in their work. ESI can reflect potential atmospheric impact, as emissions of greenhouse gas can be emitted to supply energy. The process adequate ESI showcased that the process could have a good environmental footprint related to gas emission. Additionally, TCE performance was regular with 45%, and the use of more expensive types of energy impacted on the total cost. The same can be seen on the NGCI and the EECI, in which their relation is inverse, the process has lower natural gas use, requiring higher electricity input, affecting both cost and supply, as reliance on national grid can energy management of the biorefinery. The last indicator, the NER, showed a poor performance with a value of around 15%, indicating poor energy management. As this indicator is defined by the ratio between energy related to inputs and outputs, a lower NER showcase a poor energy management. Similar results were found by Piedrahita-Rodriguez et al., for a Multifeedstock biorefinery as energy demands of these processes are quite high (between 4.8 and 5.6 MJ/kg) but process analyzed had higher capacity (Piedrahita-Rodríguez et al., 2022). Consequently, the biorefinery had an opportunity to improve its management using exergy analysis, as not only does the quality need to be assessed fully but understanding the flow and use inside the biorefinery (Herrera-Rodríguez et al., 2025). Thanks to all the above, the use of integration techniques can be recommended to enhance the resource conservation of the process. For water, use of mass integration can potentially reduce water intake as effluents can be recycled or regenerated for further use. Additionally, heat integration can support the reduction of heat losses of intermediate streams, optimizing energy use through the whole process. Lastly, the cascade systems need to be expanded to further valorize solids waste of the process as high value fractions are still left unused.

4. Conclusions

The analysis of the technical performance of a cascade biorefinery system for valorizing avocado waste highlighted the main bottlenecks of its implementation. The biorefinery assessed has multiple outputs, as starch, biofilms and biocontrol agent were considered. The analysis showed that the process of mass and energy management required further improvement. As the process had low yield (20%) and poor material reuse (11%), furthermore, the wastewater production is the worst aspect of the process as several streams are expelled without additional use (9%). In contrast, water intake and cost were particularly acceptable with performance above 65%. Likewise, energy indicators had similar results, as energy intake was acceptable (65%) but the management was poor with a NER performance of 15%. These highlights reaffirmed the necessity of further optimization of cascade systems, especially using integration techniques.

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