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Energy Resiliency of a Seed-Based Cascade Biorefinery from Amazon Hass Avocado through Resilience Exergy Analysis

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Exergy analysis shed light on how efficiently a cascade biorefinery uses available resources, as these systems are essential for enabling a circular bioeconomy and therefore must maximize mass and energy utilization. However, it can overlook the effect of variations on operative parameters that affect process exergy efficiency. For this reason, in this study an exergy resilience sensibility analysis is carried out for a cascade biorefinery for avocado hard waste. The analysis is complemented by simulation tools as source of process data. Several scenarios were analysed based on the biorefinery and its unit's performance. The results showed that the biorefinery is dominated by high irreversibilities and underutilized high-quality waste streams. The process is very sensible to improvement, especially from a combine waste stream valorisation and targeted optimization using heat integration strategies. The first strategy obtained an increase up to 52% when all streams are reused, and a reduction of half of the base losses (1000 MJ/h). The improvement of local exergy efficiency of key stages (starch extraction and biocontrol stages) also has a strong impact on system performance. However, the process has an efficiency limit of approximately 50–52%, were the unavoidable losses dominated the process total losses, addressing these complex inefficiencies can increase the process efficiency near 55%. Nevertheless, achieving such improvements would require structural and operational modifications, as these types of losses are strongly linked to intrinsic process design.

1. Introduction

Recently, Colombia have turn into a major producer of avocado in the world (being number two), with exports in 2021 value at USD 204.6 million (Taramuel-Taramuel et al., 2024). Yet, several challenges are poised to limit its economic potential in the future, especially the poor resources and waste management of the avocado value chain. Resources and wastes from this productive chain are characterized by being rich in nutrients and compounds, that can be used in several sectors, like food, pharmaceutical and cosmetic, among others (Sandoval-Contreras et al., 2023). For that reason, cascade biorefineries are an opportunity to enhance the avocado value chain, by transforming biomass into several valuable products (materials and energy), reducing waste and boosting economic growth of rural regions (Arias et al., 2023).Cascade biorefineries are complex systems designed to maximize biomass processing, and they are characterized with inessive external energy consumption due to need several processes to transform heterogenous materials, like avocado. However, these systems are based on green chemistry principles, requiring to be efficient, safe and environmentally friendly (Mohammad et al., 2024). For that reason, assessment of how these systems can improve their energy is a key factor for its implementation.

Exergy analysis offer the evaluation of system's performance based on the quantification of thermodynamic irreversibilities (losses) (Rosen, 2021). Furthermore, it can evaluate resource utilization as it can convert mass and energy flows into a single metric (Michalakakis et al., 2021). Moreover, the exergy analysis has been applied to several industries, recently to biorefineries, as it can be applied to early development stages, like Fontalvo-morales et al., analysed extractive avocado biorefineries, finding a efficiency of 50%, with losses up to 7,763 MJ/h, with wastes having the most contribution to them (Fontalvo-Morales et al., 2025). Similarly, Herrera et al., found for avocado oil extraction, wastes impacting strongly the process performance with almost 90% of the total losses, achieving a efficiency around 30% (Herrera et al., 2022).

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Although previous studies quantified thermodynamic inefficiencies in avocado biorefineries, they evaluated performance under fixed operating conditions. Consequently, the influence of process variability on thermodynamic performance and the resilience of cascade biorefineries remains unknown. For this reason, this work is the first approximation into the potential implications of uncertainties or variations in key parameters of a cascade biorefinery configuration providing a dynamic measure that eases design modifications and operational strategies to enhance efficiency. Therefore, this study introduces a resilience-oriented exergy assessment of a cascade avocado seed biorefinery complemented with CAPE tools. Unlike conventional exergy analyses, which provide a static measure of thermodynamic performance, the proposed framework incorporates sensitivity analysis to evaluate how variations in key operating parameters influence exergy efficiency and resource conservation. Several exergy parameters are used, such as global exergy efficiency, efficiency by stages of the process, exergy losses, among others. From this work, several insights into the usefulness of resilience sensibility analysis in optimizing and assessing system performance of biorefineries.

2. Materials and methods

2.1 Process description

Figure 1 presents the cascade biorefinery for avocado waste where the system consists of four main subprocesses: seed conditioning, starch production, biopolymeric film synthesis, and biocontrol agent production. Avocado residues enter Section 1 under ambient conditions (25 °C, 1 bar). Seeds are washed and cut into small pieces (~1.5 cm) and split 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 biofilm 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.

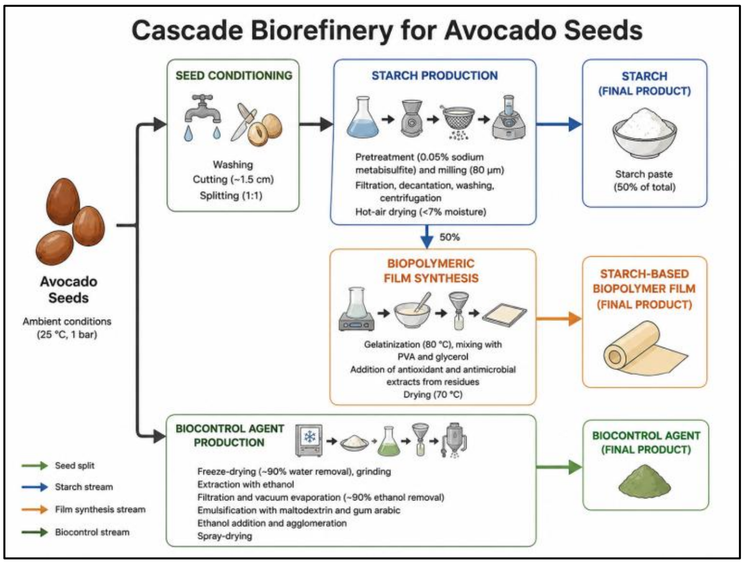

Figure 1: Process Flow Diagram of the Hass Avocado Waste Cascade Biorefinery.

For the mass and energy extended balances, a simulation was carried in Aspen Plus® V15, following the work of 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 (Alviz-Meza et al., 2025).

2.2 Exergy resilience of cascade biorefinery

The assessment carried out is based on previous work by the authors, for a deep exergy analysis of a PVC production process (Aguilar-Vásquez et al., 2025). The analysis focuses on assessing the effects of several key variables or parameters on the global exergy efficiency of the process. For this, the methodology follows one assumption: for each case or scenario, one variable is explored change while others are constant. The selection of these variables is based on the results of the exergy analysis of both the overall process and its individual stages, with priority given to those exhibiting low efficiency or high losses (both avoidable and unavoidable).
From this, key studies are conducted: the effect of reusing residues, how reusing waste flows contributes to increasing efficiency; the effect of local exergy efficiency on global efficiency, observing the improvement of a specific stage can improve process performance; the effect of reducing exergy destruction, study of how the reduction of the unavoidable losses improve the global efficiency; lastly, the effect of the output exergy of the process, highlighting where the most critical losses are located and should be *prioritized* in further studies such as energy integration. For the analysis, Eq. (1) to Eq. (6) are employed, as for the process and stages, the exergy of flows is quantified and how it is used.

$$\dot{E}x_{losses} = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \tag{1}$$

$$\dot{E}x_{in} = \sum \dot{E}x_{mass-in} + \sum \dot{E}x_{utilities-in} \tag{2}$$

$$\dot{E}x_{mass} = \dot{E}x_{phy} + \dot{E}x_{chem} \tag{3}$$

$$\dot{E}x_{utilities-in} = \dot{E}x_{work} + \dot{E}x_{heat} = \dot{W} + \sum \left(1 - \frac{T_0}{T}\right) \dot{Q}_i \tag{4}$$

$$\dot{E}x_{out} = \sum \dot{E}x_{products} + \sum \dot{E}x_{residues} \tag{5}$$

$$\eta_{Exergy} = 1 - \left(\frac{\dot{E}x_{losses}}{\dot{E}x_{in}}\right) * 100\% \tag{6}$$

3. Results and discussion

Figure 2 shows the effect of reusing a waste stream of the biorefinery individually (left) and accumulated (right). The base case had an efficiency of 1.3%, the inclusion of wastes individually had a positive effect on the overall exergy of the process. The valorisation of the waste from the biocontrol agent process increased the overall efficiency substantially up to 39%, alongside a reduction of nearly half the total irreversibilities. The wastes streams of that section had important streams with high mass flow with high exergy value, like solvents (ethanol) and solid residues. Meanwhile, the other processes made minor contributions both to increasing the exergy and lowering the losses. Nonetheless, the accumulated contribution of all the reuses of these streams substantially increased the efficiency of the process, achieving an efficiency of 52%, and a reduction of more than half of the losses of the base case.

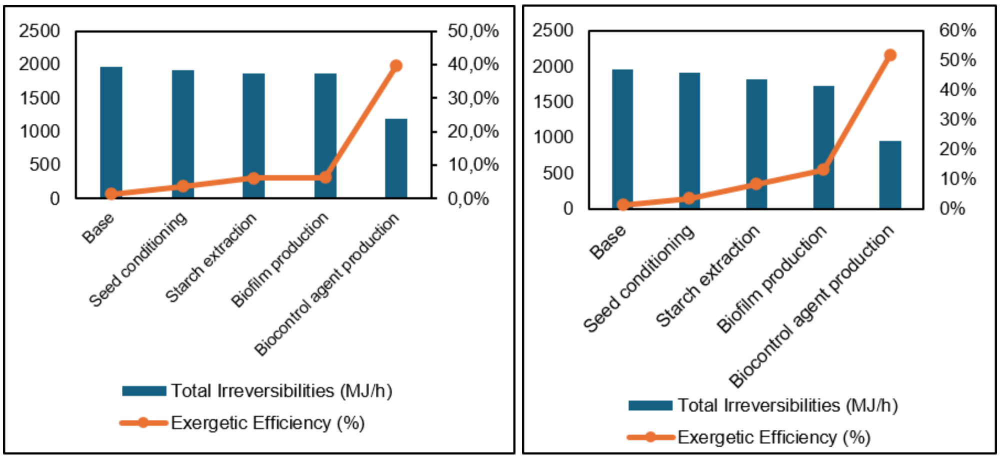

Figure 2: Effect of waste stream reutilization on global exergy efficiency of the Hass Avocado Waste Cascade Biorefinery.

Figure 3 shows the effect of improving local exergy efficiency of key stages on the global exergy efficiency of the cascade biorefinery. Starch extraction and biocontrol agent production had the highest losses of exergy of the biorefinery. The improvement of the performance of both processes had positive effect on the overall process performance. For instance, an optimized starch extraction process could increase the efficiency of the process to 50% alone. Similarly, the bioagent control process had lower impact on the overall performance of the process, as it achieved 22% efficiency. Consequently, improving both stages is required if a more efficient process is desired. However, this implies dealing with unavoidable losses inherent to the stage's characteristics, requiring structural (often costly) changes of the units present in each process, as unavoidable losses required to be suppressed.

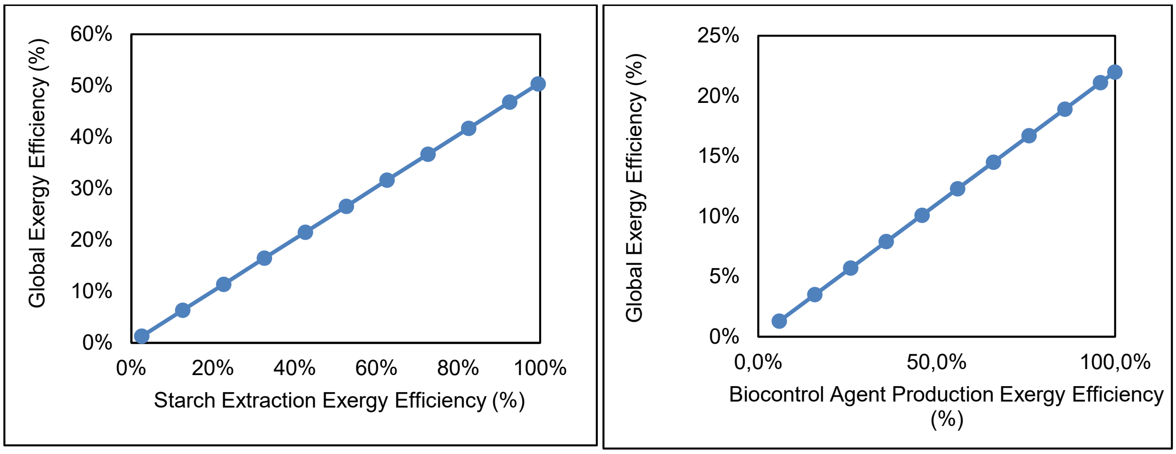

Figure 3: Effect of local exergy efficiency of key stages on the global exergy efficiency of the Hass Avocado Waste Cascade Biorefinery.

Figure 4 shows the potential effect of reducing unavoidable exergy losses on the global exergy efficiency of the biorefinery. the reduction of unavoidable losses improved substantially, the process performance, increasing efficiency from 1.3% to 50%, while simultaneously reducing irreversibilities to 1001 MJ/h (from almost 2000). This improvement is significant compared to that achieved through waste reutilization, which reaches efficiencies close to 52%, there is a high volume of unavoidable losses, because of constant unoptimized heating and cooling of flows. The use of heat could improve the handling of heat load across the process. Although, it could be insufficient, as the nature of these losses is inherent to the configuration and condition of the processes. This may involve changes in flow rates, temperatures, or losses, and may even require altering the structure or configuration of the equipment within a stage, depending on how the process has been subdivided.

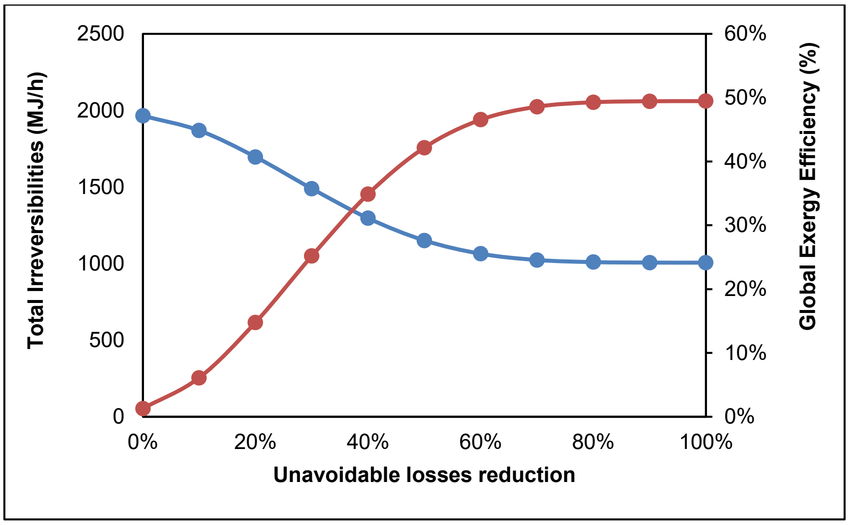

Figure 4: Effect of potential unavoidable exergy losses reduction on the global exergy efficiency of the Hass Avocado Waste Cascade Biorefinery.

Figure 5 showcases the effect of exergy output accumulation on the global exergy efficiency and the relative exergy destruction. As expected, opposite but consistent trends happened: as output increases, both the global exergy efficiency rises strongly while relative exergy losses decrease significantly. The initial changes of the assessed variables are low as waste from stages are low (seed conditioning, starch extraction, biofilm production), maintaining a poor performance with low efficiency and high relative losses close to 100%. However, both curves change rapidly—efficiency increases steeply and losses drop considerably. This indicates that recovering additional exergy, likely from high-quality waste streams (bioagent production waste streams). The process transitions from a highly irreversible regime to a more efficient one, highlighting that improving the utilization of available exergy—especially from key stages—can lead to substantial global gains. Nonetheless, the process reached its ceiling, as the system gets closer to the practical thermodynamic limit determined by unavoidable losses (efficiency of 50%).

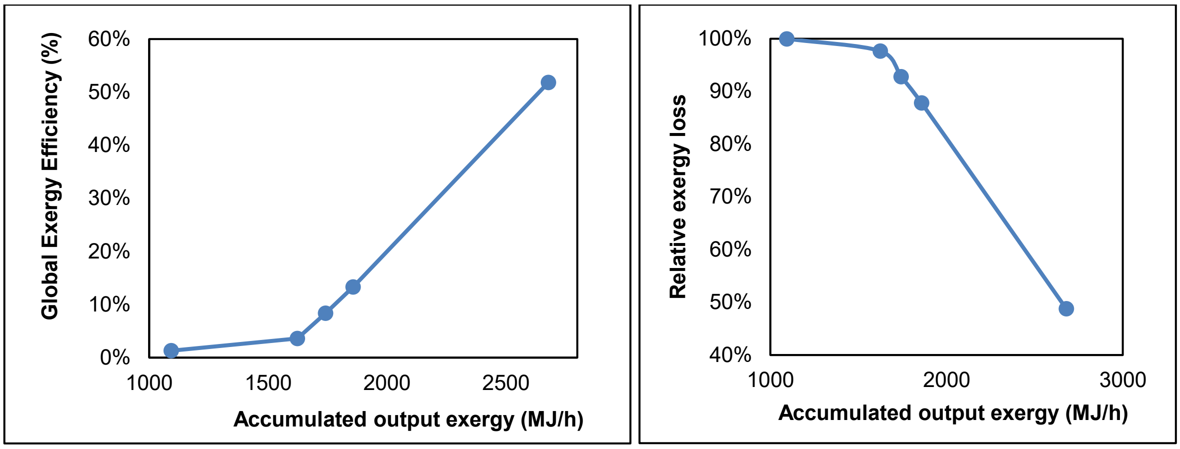

Figure 5: Effect of the accumulated output exergy on global efficiency and total irreversibilities of the Hass Avocado Waste Cascade Biorefinery.

Overall, these results indicated that the process initially operates in a regime dominated by high irreversibilities and poor exergy utilization, highlighting the importance of targeting specific stages with significant exergy destruction or waste generation, as improvements in these areas can produce substantial global benefits. These improve can be done through process integration techniques, like heat and mass integration procedures (Goodarzvand-Chegini & GhasemiKafrudi, 2017), considering stages like bioagent control and biofilm production.

4. Conclusions

In this study an exergy resilience sensibility analysis is carried out for a cascade biorefinery for avocado hard waste. Several scenarios based on the biorefinery performance were analysed. The results showcased that the global exergy performance of the cascade biorefinery is highly sensitive to both waste valorisation strategies and local stage improvements. Firstly, the valorisation of waste streams positively impacted the process efficiency, reaching 39% efficiency for individual stream reuse (biocontrol agent production stage) and up to 52% when all wastes are integrated (all waste streams), while nearly halving total irreversibilities.
On the other hand, local exergy efficiency of key stages also has a strong impact on system performance, for instance, optimizing starch extraction can increase process efficiency by 50%. However, the optimization of key units can entail the reduction of unavoidable losses. In the same idea, the sole reduction of the unavoidable losses can potentially increase the process efficiency near 55%. However, achieving such improvements would require structural and operational modifications, as these losses are strongly linked to intrinsic process constraints. Lastly, the output exergy influence indicated that the process has high recovery potential masked by poor integration and a few dominant loss key stages, further gains would require advanced heat integration and potential redesign of unit operations.

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