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# Resource Management of a Seed-Based Cascade Biorefinery from Amazon Hass Avocado through Exergy Analysis

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Resource use is a key factor for hindering the adoption of avocado biorefineries, especially energy, as inefficient use of energy resources causes higher operating costs and environmental impacts. As cascade biorefineries have emerged as promising technologies for upgrading avocado waste, the need for efficient systems has become crucial. Nonetheless, barely any work has explored how efficiently these novel systems use mass and energy resources. In that case, in this study the resource management of an avocado cascade biorefinery was performed through an exergy analysis, where a series of performance parameters are calculated, which include efficiency, irreversibilities, and industrial services, among others. The analysis was complemented with CAPE tools, like process simulators. The exergy analysis showed that the process had a poor efficiency of 1.5%, with high losses (1950 MJ/h), especially from waste streams (more than 50% of the total), indicating the cascade configuration is not valorizing fully the raw material. The same result was observed for its stages with efficiencies lower than 10%, with only the seed conditioning having an efficiency above 80%. Moreover, the starch extraction and the biocontrol agent production combined had almost 90% of the total losses. Consequently, the process requires extensive improvements to increase its resource conservation, strategies based on process integration are recommended.

## 1. Introduction

As circular bioeconomy has been emerging as an answer to the increasing concerns regarding the impacts of the actual fossil-based economy (Daimary et al., 2025). For emerging economies, this concept it's an opportunity to diversify their energy sources and economic structures, enhancing sustainable economic development and economic resilience (Valderrama et al., 2020). The biorefineries are essential systems capable of transforming biomass into several valuable products (materials and energy) (Arias et al., 2023). However, commonly biorefineries have high external energy flows for their several processes to transform key fractions of the feedstock, while the material flows have a heterogenous nature, with high volume of residual waste with unused fractions and mass agents (e.g. solvents). In contrast, novel cascade configuration offers further use of both mass and internal flows to their maximum extends (Battista et al., 2020), meaning using resource like energy to adequately under green chemistry principles (Mohammad et al., 2024).

For that reason, the assessment on how these systems use energy and mass resources is necessary, as the complexity and variety of these facilities demand data to implement optimal designs (Tacchini et al., 2022). The exergy analysis is powerful tool that analyses energy quality and resource utilization of systems based on the quantification of thermodynamic irreversibilities (Rosen, 2021). Furthermore, it can be used as a metric of resource conservation as can evaluate the flow (input and outputs) and conversion of resources (Michalakakis et al., 2021), higher the efficiency of a system, better the management of its resources (Meramo & González-Delgado, 2023). The exergy analysis have been applied to several industries, recently to biorefineries, where significant energy losses occur throughout the process (Sciubba, 2025). Works like Fontalvo-morales et la., showcased the benefit of this analysis to extractive avocado biorefineries, finding a efficiency of 50%, with losses up to 7,763 MJ/h, with wastes having the most contribution to these (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 exergy studies have identified significant thermodynamic inefficiencies in avocado extractive biorefineries, they have been limited to conventional processing schemes in which a large fraction of the biomass remains unvalorized. Consequently, it remains unclear whether cascade utilization of avocado seed can enhance resource conservation by reducing exergy destruction and improving the utilization of biomass fractions across successive processing stages. Therefore, this work presents the first exergy assessment of an integrated Hass avocado seed cascade biorefinery combined with simulation in the Aspen plus software. The chemical and physical exergies were quantified for the streams and utilities of the process. After that, from global and local exergy balance, several exergy performance parameters are obtained, such as global exergetic efficiency, efficiency by stages of the process, exergy losses, among others. From this work, the resulting exergy indicators establish thermodynamic benchmarks for cascade avocado seed biorefineries, identify the principal sources of exergy destruction, and reveal opportunities to improve resource conservation through process integration and optimization.

## 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: seed conditioning, starch production, biopolymeric film synthesis, and biocontrol agent production. Avocado seed enter section 1 where they are washed and cut into pieces (~1.5 cm) for sections 2 and 5. In section 2, the starch is produced, where the 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 a moisture below 7% with one part as final starch product.

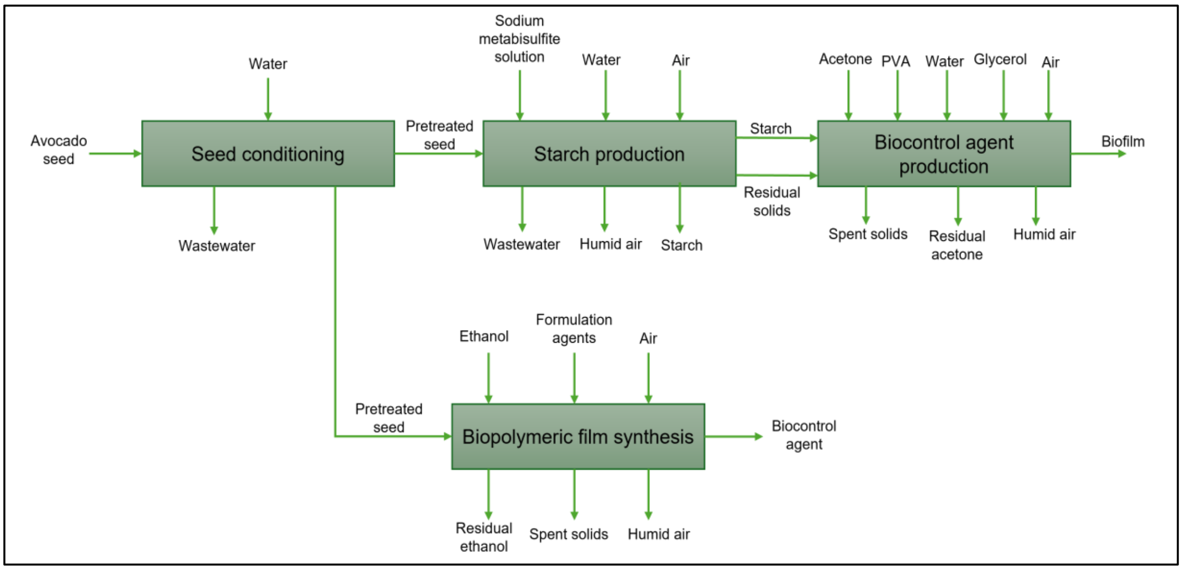


*Figure 1: Process Flow Diagram of the Hass Avocado Waste Cascade Biorefinery.*

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.

### 2.2 Exergetic analysis of a chemical process

The exergy analysis is carried out by quantifying the exergy contained inside streams crossing the process alongside the exergy of utilities or services required for the process to perform. Firstly, the exergy of a stream is calculated by Eq. (1), where the stream's exergy is composed of physical and chemical exergy. Chemical exergy is calculated by Eq. (2), while physical exergy is calculated by Eq. (3). For the chemical exergy, data of standard chemical exergy for chemical species are collected from literature (K. Moreno-Sader et al., 2019).

$$\dot{E}x_{mass} = \dot{E}x_{phy} + \dot{E}x_{chem} \tag{1}$$

$$\dot{E}x_{chem-mix} = \sum_i y_i * Ex_{chem-j} + RT_0 \sum_i y_i * ln(y_i) \tag{2}$$

$$\dot{E}x_{phy} = (H - H_0) - T_0(S - S_0) \tag{3}$$

For the calculation of the physical exergy of the streams of the biorefinery, Aspen Plus® V15 was used, following the suggestion 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 behavior. Furthermore, unit models and operating conditions were determined based on experimental data and literature values (Alviz-Meza et al., 2025). On the other hand, the exergy entering the process by utilities is quantified using Eq. (4) and Eq. (5), taking into consideration the energy source into the stage, like work and heat. Additionally, it is required the assumption of environmental conditions, where $T_0$ is equal to 25 Celsius and $P_0$ to 1 atm (K. Moreno-Sader et al., 2019).

$$\dot{E}x_{work} = \dot{W} \tag{4}$$

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q}_i \tag{5}$$

The quantification of the exergy by the former equations is done both for the exergy getting into and outside the process globally and locally (per stage or unit). For the exergy getting into, Eq. (6) considers exergy from mass and for the utilities. Contrary, the exergy exiting, is in the only in the form of mass, where it is categorized into products and residues, as Eq. (7) shows (Meramo & González-Delgado, 2023).

$$\dot{E}x_{in} = \sum \dot{E}x_{mass-in} + \sum \dot{E}x_{utilities-in} \tag{6}$$

$$\dot{E}x_{out} = \sum \dot{E}x_{products} + \sum \dot{E}x_{residues} \tag{7}$$

From a balance between the exergy crossing the process both globally and locally, the losses or irreversibilities can be quantified, as seen in Eq. (8). These losses include both avoidable and unavoidable, which allows determining the recoverable exergy potential of the process and subprocess. Moreover, with the losses, efficiency can be quantified using Eq. (9), both globally and locally. Lastly, the contribution of each stage to the total irreversibilities is quantified by Eq. (10) (Meramo-Hurtado et al., 2020).

$$\dot{E}x_{losses} = \sum \dot{E}x_{in} - \sum \dot{E}x_{products} \tag{8}$$

$$\eta_{Exergy} = 1 - \left(\frac{\dot{E}x_{losses}}{\dot{E}x_{in}}\right) * 100\% \tag{9}$$

$$\%Ex_{lost,i} = \left(\frac{\dot{E}x_{losses,i}}{\dot{E}x_{total-\text{losses}}}\right) * 100\% \tag{10}$$

## 3. Results and discussion

In figure 2 the exergy performance of each subprocess of the avocado cascade biorefinery is portrayed. In which most of the stages of the biorefinery were strongly inefficient with values of 9.9%, 5.9% and 2.6% for bio-film production, biocontrol agent production and starch extraction, respectively. The poor performance indicates the requiring of improvements for the individual stages of the biorefinery. In contrast, the seed conditioning stage was the most efficient with 88%, as the stage contains only a washing and fractioning, meaning conserving the most exergy entering the stage. However, the stage had important exergy in its waste that can be reused.

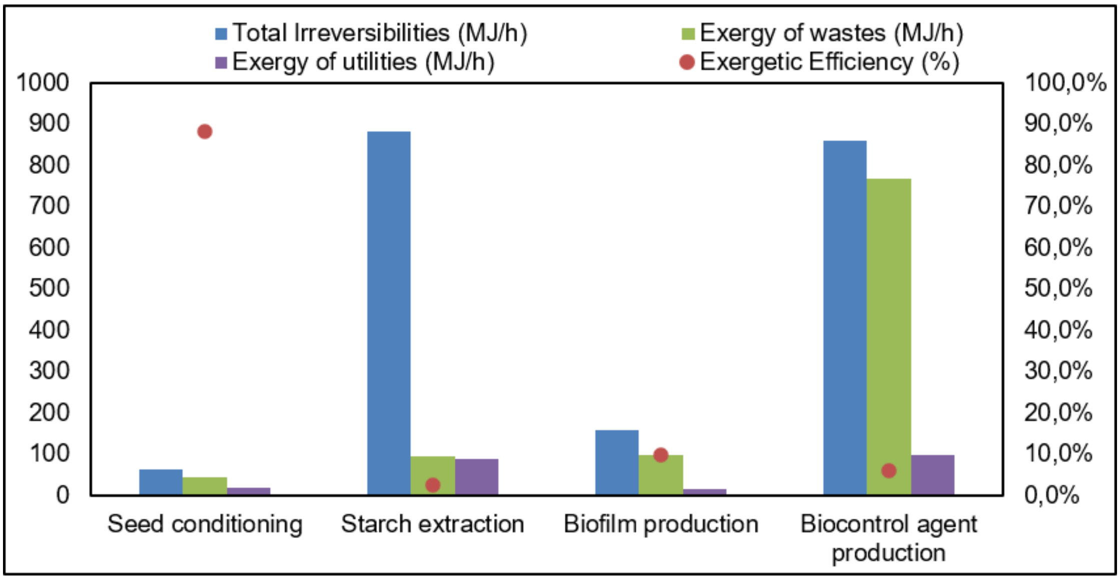


*Figure 2: Exergy parameters by stage for the avocado cascade biorefinery.*

Observing more deeply, highest irreversibilities were obtained in the starch extraction stage with 882.7 MJ/h, followed by 859.4 MJ/h in the biocontrol agent production stage. Both are characterized by important significant changes in temperature and pressure, alongside the generation of important streams of waste. Especially for the biocontrol agent production stage, where the highest exergy lost in waste was present (776 MJ/h), as significant streams of purged solvent and spent solids are ejected from purification units. The most exergy entered as utility was in the starch extraction and the biocontrol agent, in which 89.62 and 97.09 MJ/h were used, respectively. For both the main source was heat, specifically heat for the air used to dry the wet mass (wet starch and wet bioagent emulsion).

For the former stage, atomization drying required more, as several units were used to separate solvent using heat (ethanol), furthermore, the atomization dryer used work for the pump of the bioagent into the dryer. In figure 3 the global exergy performance of the analyzed cascade biorefinery is depicted.

Firstly, the overall efficiency of the process was very low, with 1.5%, characterizing the process as very inefficient. Consequently, the process requires further optimization to reduce losses throughout the whole process, in the form of heat exchange networks or revalorizing waste fractions (optimizing cascading sequence) (K. A. Moreno-Sader et al., 2021).

In comparison, Herrera et al., quantified the efficiency of avocado biorefinery, were the whole avocado is processed, to produce not only a material product but energy carriers, achieving a efficiency of almost 50%, indicating the complete use of valuable fractions of the raw material can increase the overall performance of the process (Herrera-Rodríguez et al., 2025).

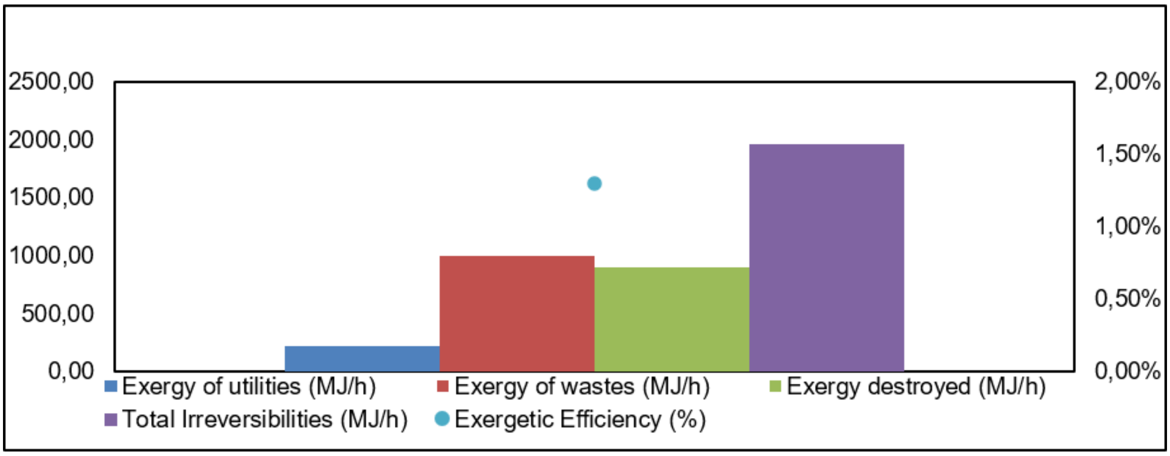


*Figure 3: Global exergy parameters for the avocado cascade biorefinery.*

On the other hand, the exergy of utilities were 221.31 MJ/h, this value is significantly lower than the exergy of mass from the inlet streams of the process (1769.55 MJ/h); the overall operational conditions in the biorefinery were near atmospheric conditions requiring no significant changes in temperature or pression, moreover, the low flow of the streams contributed to lower utilities as well.
The total irreversibilities of the process was 1950 MJ/h, with the exergy related to waste being the main contributor of these losses (1006.24 MJ/h); This value confirms that the valorization of waste is imperative to improve process resource utilization. However, waste contains both substances like solvents that can be easily reused and solids fractions that could require further processing stages to be fully utilized, meaning potential trade-offs can appear. Meanwhile, the permanent degradation of exergy achieved a value of 897.47 MJ/h, indicating strong leak of exergy due to lost heat and other unrefusable forms of energy. These losses are unavoidable and fixed to the configuration of the process carried out; to change it, it would entail substantial change for both operational conditions and process units, such as replacing technologies for others.

## 4. Conclusions

As cascade biorefineries are developed as more complete processes for the valorization of agricultural waste, their energy efficiency is a key factor hindering their adoption. So, in this study the energy management of an avocado cascade biorefinery was performed through an exergetic analysis. The analysis was complemented with CAPE tools, like process simulators. The exergy analysis showed that the process had a poor efficiency of 1.5%, with high losses (1950 MJ/h), especially from waste streams (more than 50% of the total).
Furthermore, only the seed conditioning had an efficiency above 80%, compared to the other stages that did not surpass 10%. The key stages were the starch extraction and the biocontrol agent production, combined had almost 90% of the total losses. Consequently, the process requires extensive improvements, both in relation to exergy related to operational conditions and exergy contained in streams (mass and energy integration).

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