CHEMICAL ENGINEERING TRANSACTIONS
VOL. 127, 2026

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Laura Capelli, Marzio Invernizzi, Selena Sironi

ISBN 979-12-81206-28-1; **ISSN** 2283-9216

DOI: 10.3303/CET26127038

Potential Environmental Impacts Assessment of a Seed-Based Cascade Biorefinery from Hass Avocado in South Colombia

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Biorefineries are central facilities for the adoption of bioeconomy to countries like Colombia, enhancing production chains for agricultural products like avocado. The environmental impacts of several avocado biorefinery configurations have been studied, however, the design of cascade configurations have been neglected. For this reason, an environmental analysis was carried out for an avocado hard waste cascade biorefinery using WARGUI. The process data was extracted from a simulation tool. The avocado cascade biorefinery demonstrated a good environmental performance, as it had negatives rates for output and generation of PEI. As a green process, the topology showed promising results compared to similar processes. Toxicological impacts were negligible, although inclusion of product streams slightly increased total PEI due to their intrinsic footprint (especially biofilm due to formation agents). Furthermore, energy need to be closely analysed as it can contribute strongly to PEI emission, also, fuel selection significantly influenced atmospheric impacts, with coal exhibiting the highest burdens and gas the lowest, particularly in GWP and AP categories. Moreover, the implementation of cleaner fuels and resource efficiency strategies, such as solvent recovery and mass integration, is essential to further improve process sustainability.

1. Introduction

The increasing demand for avocado fruits and derivates has generated a substantial increment of the amount of waste (seed, peel and even pulp). This waste has been related to land and water contamination due to poor disposal management. However, these wastes are characterized by being rich in carbon compounds and phytochemicals, such as oil, carbohydrates, acetogenins, and dietary fiber, etc; valuable in like food, pharma and cosmetic, among others (Sandoval-Contreras et al., 2023). Cascade biorefineries offer a pathway to valorize fully these materials by manufacturing tailored products for each fraction (material and energy). these systems can not only offer a strategy to deal with these impacts but an economic opportunity to drive economic growth and social improvement (Leong et al., 2021). Nonetheless, this novel technology for the avocado waste processing needs to be environmentally sustainable, as it is crucial for the adoption of these technologies in rural locations (Wagh et al., 2024).
For that reason, the application of environmental impact quantification techniques aids the development of more sustainable process (Mahmud et al., 2021). Among several of these tools, the Waste Reduction Algorithm (WAR) assesses the potential environmental consequences of chemical processes, based on metrics or indicators quantified by mass and energy flows of the process (Shadiya et al., 2012). Furthermore, It easy to use as it requires less information, only of manufacturing phase of a product's entire life cycle (Sammons et al., 2009), and its main advantage is that estimates of output and the generation rates of potential environmental impacts (in eight categories of impacts) which cannot be performed by other methods such as life cycle analysis (Herrera-aristizábal et al., 2017). Several works have been carried out into analyzing biorefineries or bioprocesses, like the production of modified microbeads from chitosan (Bertel et al., 2019), nanoparticles (S. I. Meramo et al., 2018), biorefinery of shrimp (Moreno-Sader, Martinez-Consuegra, et al., 2021), among others.

Paper Received: 3 March 2026; Revised: 23 June 2026; Accepted: 15 July 2026
Please cite this article as: Aguilar-Vásquez E.A., González-Delgado Á.D., 2026, Potential Environmental Impacts Assessment of a Seed-Based Cascade Biorefinery from Hass Avocado in South Colombia, Chemical Engineering Transactions, 127, 223-228 DOI:10.3303/CET26127038

For the case of avocado, several topologies have been assessed, like Herrera et al., analyzed production of biochar and oil from avocado creole finding performance adequate for implementation in rural areas (low impacts) (Herrera-Rodríguez et al., 2023). Similarly, Valdez-Valdes et al., found for a extractive-based biorefinery (avocado oil, biopesticide, chlorophyll) was environmentally friendly, with energy as the main source of impacts (Valdez-Valdes et al., 2024).
Although previous studies have demonstrated the environmental viability of avocado-based biorefineries, they have primarily focused on whole-fruit valorisation or the recovery of isolated products, leaving the environmental performance of cascade utilization of avocado seed largely unexplored. To address this gap, this study presents the first WAR-based environmental assessment of a Hass avocado seed cascade biorefinery producing starch, biofilm, and a biocontrol agent. By integrating process simulation with environmental impact assessment, the study identifies environmental hotspots associated with waste streams, products, and energy consumption, providing engineering guidance for the design of more sustainable cascade biorefineries.
The analysis is performed using WARGUI software complemented with simulations tools as source of process data. The impacts are analyzed using five cases were the contribution of stream wastes, products and energy on the total impacts of the process are observed. The potential findings contribute to the design of biorefinery systems, as it can pinpoint crucial improvement towards sustainable facilities that maximize value among the avocado productive chain.

2. Materials and methods

2.1 Process description

Figure 1 presents the cascade biorefinery for avocado waste, units and material flows. 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 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 a moisture below 7%, then 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 for agglomeration, and the mixture is spray-dried to obtain the final biocontrol agent.

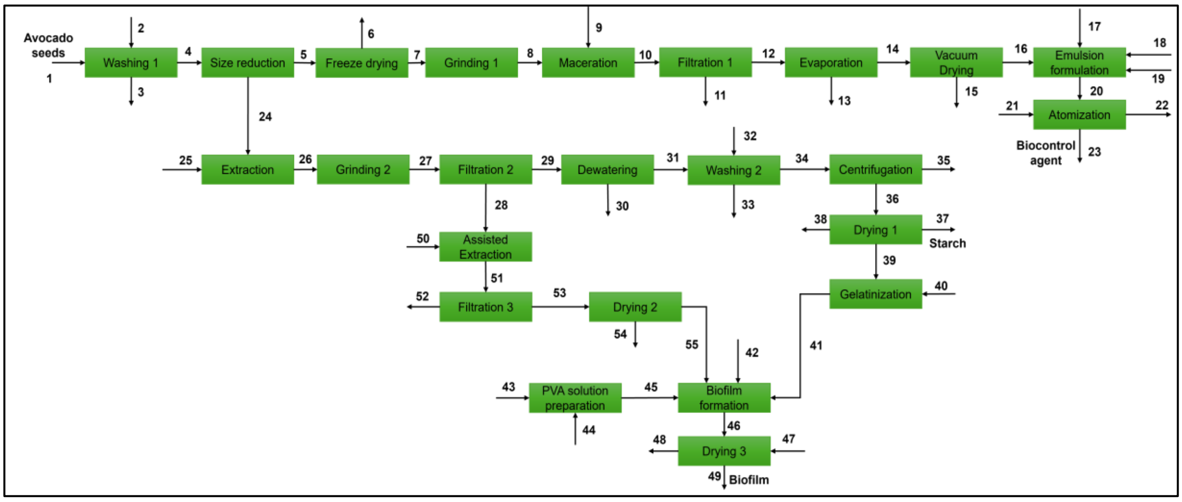

Figure 1: Process Flow Diagram of the Hass Avocado Waste Cascade Biorefinery.

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 behavior.

Furthermore, unit models and operating conditions, were determined based on experimental data and literature values (Alviz-Meza et al., 2025).

2.2 Environmental analysis through WAR GUI

The environmental assessment of the cascade biorefinery of interest was carried out using the WAR GUI (graphical user interface) software, which is based on WAR. This software assesses the potential Environmental impact done by a system, considering each mass and energy flow across those same boundaries (PEI balance) (Cabezas et al., 1999). From the balance, the rate of emission (output PEI) and generation (consumption) are provided for a system. For that reason, it is requiford to know the inputs and outputs of the process (and its composition), as well as the energy required for its operation. Additionally, flows entering and exiting the process need to be categorized as either product, raw material, or waste (S. Meramo et al., 2022). Furthermore, the software offers 8 categories of impact to assess the process, divided into toxicological and atmospherically, both based on chemical properties substances.

The first includes human impact, Human Toxicity Potential by Ingestion (HTPI) based on acute oral lethal dose (LD_{50}); Human Toxicity Potential by Inhalation or Dermal Exposure (HTPE) estimated by Threshold Limit Values (TLV). Ecological impact, which consists in the Aquatic Toxicity Potential (ATP) quantified by the Lethal concentration (LC_{50}) and Terrestrial Toxicity Potential (TTP), also based on the acute oral lethal dose (LD_{50}) (Herrera-Aristizábal et al., 2018). Similarly, the second category is subdivided into two subcategories, two of which are global and the other are local. The first includes the Global Warning Potential (GWP) measuring carbon emissions (aCO_2) and the Ozone Depletion Potential (ODP) that measure Ozone concentration.

The locals consist in the Photochemical Oxidation Potential (PCOP) and the acidification Potential (AP), estimated by the emission rate of (OH^-) and (H^+) of the substance to ethylene and SO_2, respectively. The software has a database for common substances, and its properties are required to quantify the categories mentioned, which are selected considering the compounds of interest in the biorefinery (Herrera-Aristizábal et al., 2018). However, when a substance is no present in the database, it was to feed into the WARGUI software by collecting those properties alongside the molecular weight, formula, CAS number, among others.

On the other hand, to visualize the results of the estimation total impacts indicators and by each specific category, bar charts were made, considering four cases of study as seen in table 1, these cases provide a good diagnosis of the environmental performance of the process, as considers the contribution of different components of the process.

Table 1: Cases analyzed for the environmental analysis of an avocado cascade biorefinery

Cases analyzed	Considerations
Case 1	Only residues considered, products and energy excluded
Case 2	Only residues and products considered, energy excluded
Case 3	Only residues and energy considered, products excluded
Case 4	Residues, products and energy considered
Case 5	Source of energy

Moreover, a fifth case is considered in which the process PEI output rate is quantified for only the energy use of the biorefinery. Three fuels are considered, as they are available in software, coal, gas and liquid fuel (oil). This case can be helpful to provide insights on fuel use and its impacts on the environmental performance (Bertel et al., 2019).

3. Results and discussion

Figure 3 shows the results of the total Total PEI rates of impacts of the avocado cascade biorefinery studied. Firstly, the generation rate was low for each of the cases with a maximum value of 0.67 PE/h for case 4.

In comparison with cases 1, 2 and 3, the process products had a significant impact as the cases of 2 and 3 had negative rate with -0.93 and -0.67 PEI/h, meaning suffering an increase of PEI. It is confirmed when looking at the change in the output rate, where the emission of PEI increased from case to case, but the change is more significant for cases 2 and 4, when products are considered.

This consideration is key as products like the biofilm used compound with a higher PEI footprint, like PVA and Glycerol. Nonetheless, these values indicated that the cascading biorefinery of avocado seed is environmentally sustainable as the process can produce the products with a low generation of PEI. Compared to similar bioprocesses, rates are very low, as Herrera et al., obtained generation rates of 60 PEI/h for an oil extraction process with an 97kg of avocado capacity (Herrera et al., 2022).

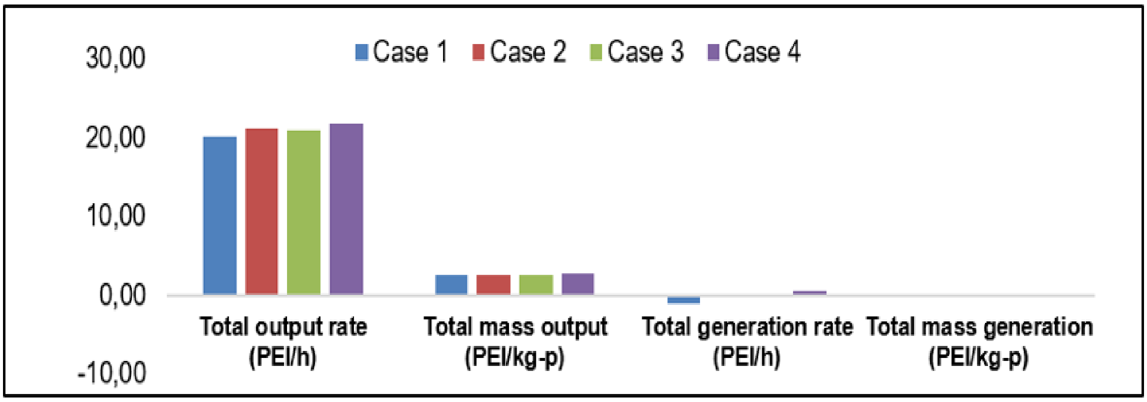

Figure 2: Total PEI rates of impacts per case for an avocado cascade biorefinery.

Figure 3 shows the rate of toxicological impacts generated and output of impacts of the avocado cascade biorefinery studied. The main toxicological impact is the ATP category as the generated rate of PEI is slightly positive for the case 2, 3 and 4 (0.000001, 0.008 and 0.01 PEI/h, respectively). Similar tendencies were found in the case of HTPI, HTPE, TTP, where cases 1 and 3 had negative values in contrast to positive values of cases 2 and 4.

The difference is the streams of products, as cases 2 and 4 considered their contribution, meaning the compound released from the biorefinery can minimum negative impact on the environment. Overall, the toxicological categories demonstrated that the process had no significant environmental impact both for humans and ecosystems.

However, the process can further improve its performance by adopting resource conservation strategies like mass integration, where streams of wastewater and spent solvents can be further reused.

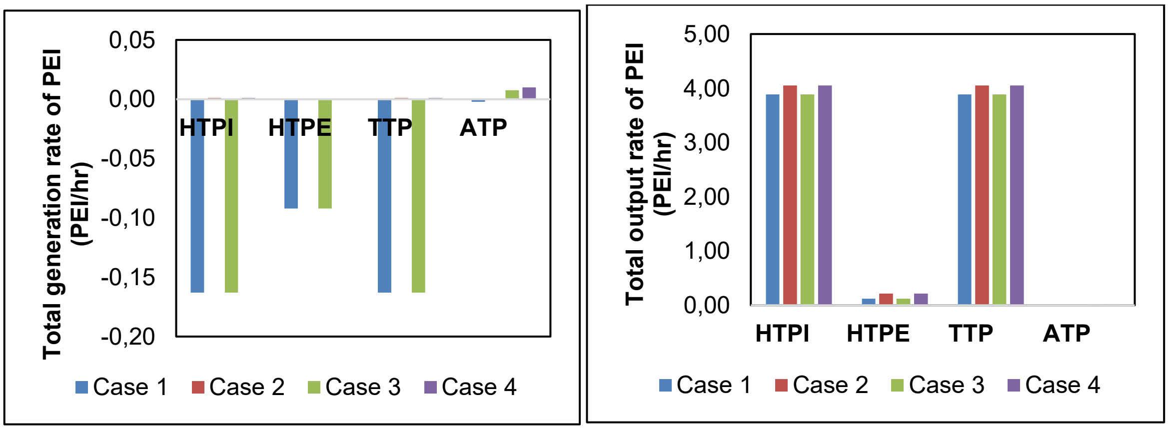

Figure 3: Total output and generated atmospheric impacts for an avocado cascade biorefinery.

Figure 4 shows the global (GWP and ODP) and local (PCOP and AP) atmospheric impacts of impacts of the avocado cascade biorefinery studied. The process had positive rates for the GWP, AP and PCOP categories when the energy and products are considered, indicating a strong contribution of the residues, products and energy into the potential atmospheric impacts of the biorefinery. However, when the output rate is observed only the AP and GWP and ODP are affected for cases 3 and 4, indicating the main contributor for these categories was the energy of the process.

Contrary to the PCOP category, the increase between cases 1 and 3 to 2 and 4 was only 0.5, indicating the contribution of the residues was the highest, this can be corroborated due to the expulsion of solvents like ethanol and acetone without reuse. Still, the generation rate for this category showed that the process with a proper reuse/regeneration system can maintain a low impact performance. Lastly, the integration of waste, especially spent solvents, can improve the environmental performance of the process (Moreno-Sader, Martínez-Consuegra, et al., 2021).

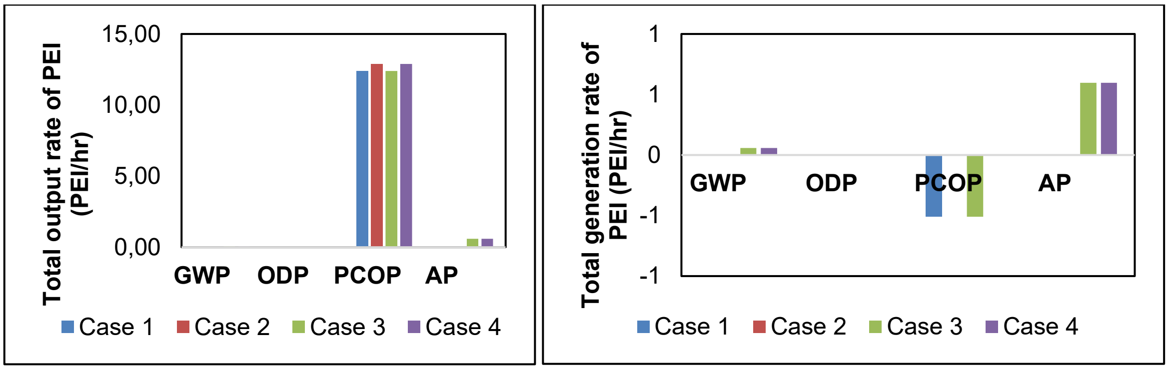

Figure 4: Total output and generated toxicological impacts for an avocado cascade biorefinery.

Figure 5 shows the PEIs for the atmospheric and toxicological categories according to the type of fuel used to satisfy the energy requirements. Coal had the worst performance of the fuels, followed by the liquid fuel, and lastly, the gas with the best performance. The difference between fuels is expected as coal's chemical structure and energy content lead to more emissions like SO_2, NO_2 and CO_2 or volatile organic compounds (VOC) compared to gas and oil (González-Delgado et al., 2023). The most impacted categories are associated with gas emissions, like AP, GWP, however, ATP and TTP and HTPI also appear affected by the typo of fuel employed. These categories can be affected as compounds expelled from the combustion can lodge inside ecosystems like the VOCs. Consequently, the choice of fuel in these facilities is a key factor, as they are in rural settings, solids fuels can be used as cheap source of energy but can lead to further impacts unintentionally.

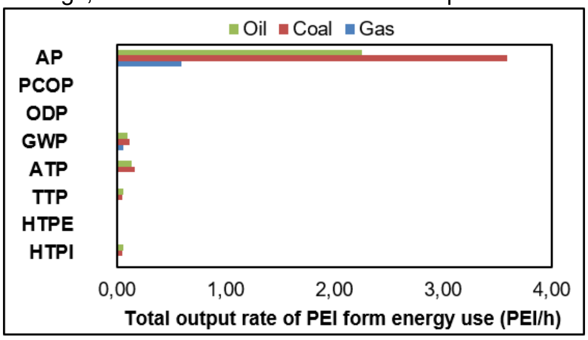

Figure 5: Output rate of PEI regarding energy source.

4. Conclusions

The waste reduction algorithm (WAR) was implemented to evaluate the environmental performance of a cascade biorefinery that processed avocado hard waste. The avocado cascade biorefinery demonstrated good environmental performance, as expected to a green process, indicating promising results if implemented in key producing regions as compared to similar processes. Fuel selection significantly influenced atmospheric impacts, with coal exhibiting the highest burdens and gas the lowest, particularly in GWP and AP categories. Toxicological impacts were negligible across all cases, although inclusion of product streams slightly increased total PEI due to their intrinsic footprint. Overall, the implementation of cleaner fuels and resource efficiency strategies, such as solvent recovery and mass integration, is essential to further improve process sustainability.

Acknowledgments

The authors gratefully acknowledge the financial support provided by the Universidad de Cartagena and the Colombian Ministry of Science, Technology, and Innovation (Minciencias). This work was funded under the project SIGP 100307 and contract 442-2023.

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