Towards Optimizing Biorefinery Systems with CO_2 Capture: A Circular Economy Approach for Valorizing Olive Pomace in Spain

Á. Galán-Martín[1,2], D. Pérez-Almada[1,2], I. Romero-Pulido[1,2], C. Marzo-Gago[1,2]

[1]Department of Chemical, Environmental and Materials Engineering, University of Jaén, Jaén, 23071, Spain
[2]Institute of Biorefineries Research (I3B), University of Jaén, Jaén, 23071, Spain
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Presenting author email: galan@ujaen.es

The transition towards a sustainable circular economy is driving innovations in biorefinery development, particularly in utilizing biomass residues to produce bioenergy and bio-based products. Biorefineries, which convert biomass into multiple forms of energy and materials, play a critical role in reducing dependence on fossil fuels and enhancing resource efficiency. In addition, with the increasing urgency of the need for carbon dioxide removal (CDR) to meet our climate goals by compensating residual and hard-to-abate emissions, the role of biorefineries becomes even more crucial. By integrating carbon capture and storage (CCS) technologies, biorefineries can deliver valuable bio-based products that replace traditional fossil fuel sources and serve as carbon sinks, trapping CO_2 for long periods. This dual approach of resource recovery and carbon sequestration makes biorefineries a key component in the transition toward a more sustainable future.

A particularly promising feedstock in this context is exhausted olive pomace (EOP), a by-product of olive oil production, which has significant untapped value as feedstock for biorefineries. Spain, the world's largest olive oil producer, generates large quantities of this EOP, which, if not properly managed, can pose environmental challenges. However, EOP contains valuable compounds that can be extracted and converted into products used in various industries.

This study explores the technical, economic, and environmental potential of using EOP in a biorefinery cascading process designed to extract high-value compounds such as antioxidants, lignin, and bioethanol. By converting EOP into these bio-based products, Spain can reduce waste, contribute to the circular economy, and decrease reliance on fossil resources. The findings support Spain's transition toward a sustainable, bio-based economy, aligning with European Union goals to reduce waste and achieve climate-neutral objectives.

Building upon recent advances in EOP bioconversion technologies (Gómez-Cruz et al., 2021), this research integrates simulation tools with life cycle assessment (LCA) to evaluate the biorefinery's environmental impacts, scalability, and economic viability. We analyze several biorefinery scenarios, focusing on the use of renewable energy for heating and cooling, as well as for powering production processes. Additionally, we examine the integration of CCS systems to assess their potential role in reducing the biorefinery's carbon footprint. (Figure 1).

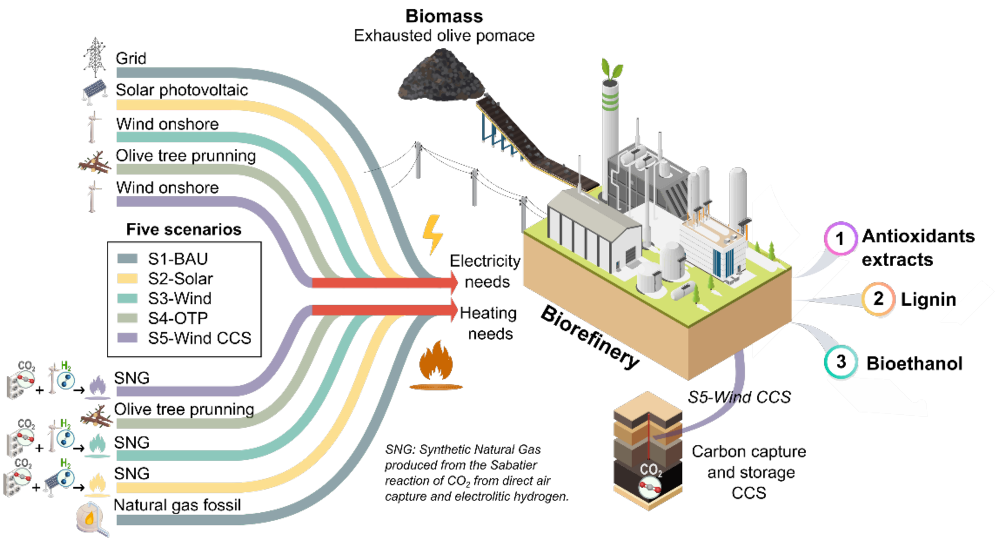

Figure 1 Schematic overview of the biorefinery system scenarios explored in this study (Pérez-Almada et al., 2025).

The results demonstrate that valorizing EOP into a biorefinery optimizes the value derived from olive oil production waste and contributes to sustainability by reducing carbon emissions. The integration of CCS technology in certain scenarios leads to a substantial reduction in CO_2 emissions. In particular, one scenario relying on wind power, hydrogen and integrating CCS achieved the most significant reduction in carbon footprint, even reaching a negative carbon footprint on cradle-to-gate. This result accounts for both the biogenic CO_2 embedded in the bioproducts and the CO_2 that is geologically sequestered, capturing emissions from the combustion of synthetic natural gas (SNG) and fermentation processes. However, the biogenic CO_2 that would be released extractives during the end-use phase of the bio-based products would contribute to emissions returning to the atmosphere. When considering only the CO_2 permanently sequestered, the carbon footprint shifts to a positive value, though this still represents a substantial reduction of 84.31% compared to the baseline scenario where the biorefinery is powered with electricity from the grid and natural gas. This highlights the potential of combining biomass conversion with CO_2 capture technologies to create biorefineries that can actively contribute to climate change mitigation.

Nevertheless, integrating renewable hydrogen and CCS into the biorefinery would also bring undesired consequences. From the economic perspective, our assessment reveals that integrating these technologies would increase operational costs, which could be partially offset by selling carbon removal credits. Additionally, the study reveals trade-offs between different environmental impact categories. While scenarios incorporating CCS show substantial benefits regarding global warming potential, they also introduce higher resource depletion impacts and slightly higher impacts on human health. These findings underscore the importance of a holistic approach to sustainability, where environmental, economic, and social impacts are carefully balanced.

In conclusion, integrating the data generated from this study into comprehensive optimization models is essential for creating effective roadmaps to valorize domestic biomass resources. By incorporating insights from life cycle assessments (LCA), techno-economic analyses, and CO_2 capture, these models can address critical questions about what, where, and when to deploy biorefineries. Such integrated optimization will ensure that biorefinery systems are not only economically feasible but also environmentally and socially responsible. This approach is vital for supporting the effective transition towards a sustainable and circular bioeconomy. Providing actionable guidance for the strategic deployment of biorefineries aligns with the SUSBIOR project's goals (Figure 2), contributing to developing climate-neutral biorefinery systems essential for Spain’s transition to a sustainable European economy.

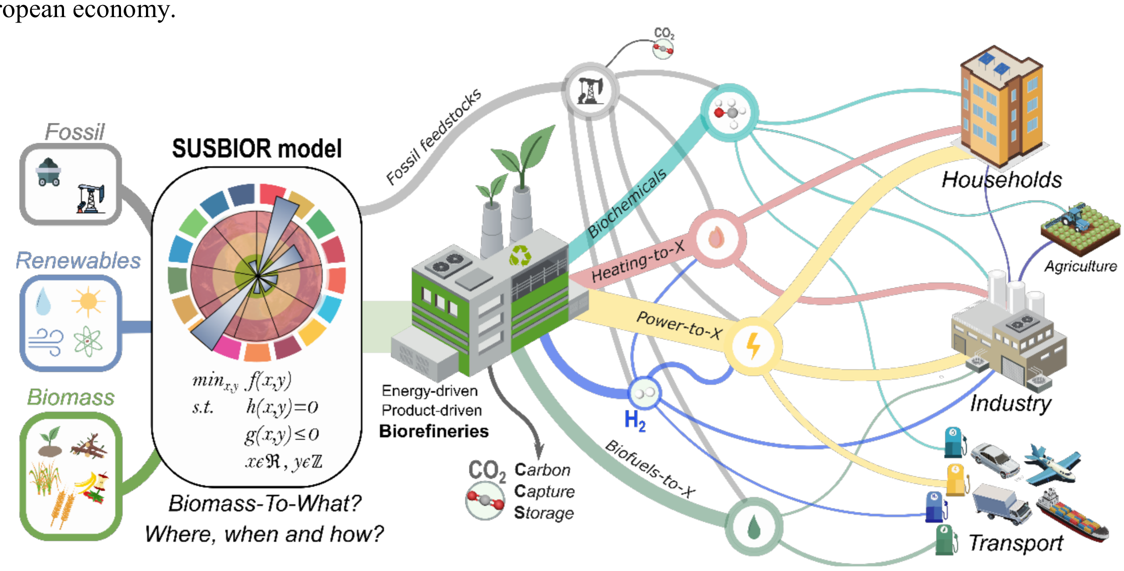

Figure 2 Overall concept of the SUSBIOR project (SUSBIOR, 2024)

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