Comparative Life Cycle Costing and Life Cycle Assessment of Animal Feed Ingredient Production from Grape Stems, Orange Peels, and Olive Cake

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Introduction

Agricultural by-products such as grape stems (GS), olive cake (OC), and orange peel (OP) are often underutilized and managed as waste, presenting both environmental and economic challenges. Transforming these by-products into high-value animal feed (AF) ingredients offers a sustainable solution to reduce waste, enhance resource efficiency, and promote circular economy practices within agricultural systems (Andrianou et al. 2023; San Martin et al. 2023) This study evaluates the environmental and economic viability of GS, OP, and OC as feed ingredients for livestock, employing Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. The aim is to compare the environmental impacts (EI) and costs associated with various processing methods, including non-hydrolyzed (NHY) and hydrolysed (HY) forms for GS and OP, and solid-state fermentation (SSF) for OC, as compared to business-as-usual implementations associated with the conventional AF production and current waste disposal methods. These agro-industrial by-products are assessed for their potential to improve AF production while minimizing environmental harm. The findings of this study aim to provide valuable insights for industry stakeholders seeking sustainable alternatives to conventional feed production, ultimately supporting waste reduction and fostering more sustainable practices in the livestock sector. By quantifying the life cycle impacts and costs of these feed ingredients, the study offers a comprehensive evaluation of their feasibility as cost-effective and environmentally responsible alternatives to traditional AFs.

Methodology

The environmental impact (EI) assessment followed standard LCA procedures (ISO 14040 and ISO 14044) using SimaPro software (version 9.3.0.3), with a functional unit (FU) defined as 1000 kg of animal feed (AF). Two valorization options for GS and OP were analyzed: non-hydrolyzed (NHY) and hydrolyzed (HY) feed ingredients for dairy sheep and cows (GS) and dairy sheep (OP). For OC, the solid-state fermentation (SSF) was used to produce broiler feed. Three business-as-usual scenarios—incineration, composting, and landfilling—were also evaluated, alongside conventional AF production. The system boundary is the "cradle-to-gate". Most data were derived from pilot studies on feed ingredient production, while AF production data were sourced from available software databases. The impact assessment utilized the ReCiPe 2016 (H) method (Huijbregts et al. 2017), combining midpoint and endpoint approaches across 17 impact categories, linking them to human health, ecosystems, and resource depletion. The interpretation phase involved normalizing the impact data and using single scores as Pt for comparison. A comprehensive Life Cycle Costing (LCC) analysis evaluated economic viability, focusing on unit net costs, CAPEX, OPEX, revenues from ingredient sales, and by-product disposal costs. Environmental costs were expressed in monetary terms based on EU28 emissions data (Dilek et al. 2024).

Results and Discussion

Table 1 presents the summary of the LCA and LCC results obtained for three valorization cases. For GS, the NHY variant has relatively low EI (230 mPt/FU) and production costs (0.02 €/kg feed ingredient). In contrast, the HY GS-based feed ingredient results in significantly higher EI (828 mPt/FU), primarily due to the NaOH and electricity consumption, but its cost per kg feed ingredient is higher at 0.05 €/kg. Despite this, NHY GS-based variant is economically favorable with a negative cost of -0.059 €/kg feed ingredient, making it a more feasible option. HY GS variant yields a positive cost of 0.043 €/kg feed ingredient.

For OP, the NHY OP-based feed ingredient demonstrated moderate EI (600 mPt/FU) and a higher environmental cost (0.07 €/kg feed ingredient), while the HY OP-based one showed significantly higher EI (4200 mPt/FU) and increased costs (0.87 €/kg feed ingredient). However, the NHY OP-based feed ingredient is more economically viable, with a cost of 0.09 €/kg of feed ingredient, whereas HY OP variant is much more expensive (1.40 €/kg). Both OP-based methods reduce EI compared to conventional feed production but at a higher operational cost.

For both GS and OP, the higher EI observed with the HY feedstock compared to the NHY variant were largely negligible during the AF production stage. This is because the valorized feed ingredient constitutes only a small fraction (i.e., 10% by weight) of the total AF composition, and the impacts associated with other feed ingredients are significantly higher than those of the valorized ingredients.

Table 1. Comparison of the costs and environmental impacts (Pt/FU)

	GS feed ingredient		OP feed ingredient		OC feed ingredient
	NHY	HY	NHY	HY	SSF
EI	0.230	0.828	0.600	4.200	1.000
Env Costs, €/kg feed ingredient	0.02	0.05	0.07	0.87	0.16
€/kg of feed ingredient produced	-0.059	0.043	0.09	1.40	0.25
€/kg of waste processed	-0.020	0.012	0.01	0.15	0.10
	GS AF		**OP AF**		**OC AF**
EI of AF	91.1	91.7	32.1	35.9	55.1
EI of Conventional AF + incineration	74.9		-8		39
EI of conventional AF + composting	117.9		68.7		69.6
EI of conventional AF + landfilling	116.8		66.6		68.8
	Current waste disposal options				
	Incineration		Composting		Landfilling
€ per kg of waste disposed	0.223		0.835		0.405

For OC, feed production using the SSF process demonstrated moderate EI (1000 mPt/FU) and a cost of 0.16 €/kg feed ingredient. Although SSF results in lower environmental costs than traditional feed production, its economic feasibility is relatively low, with feed ingredient costs of 0.25 €/kg, which is higher than both GS and OP alternatives. Furthermore, all three food waste valorization scenarios demonstrated lower costs compared to the current waste disposal methods. In terms of EI, valorization across all three value chains resulted in fewer impacts than the current practices of landfilling and composting, but not when compared to incineration. The superiority of incineration in the current scenario is primarily due to the significant energy recovery that is achievable through this method. Overall, NHY GS and NHY OP feed ingredients are the most economically viable, with negative costs for GS and a moderate cost for OP, while the HY variants of both by-products offer environmental benefits at a higher cost. Olive cake, processed through SSF, shows a moderate environmental profile but high operational costs, making it less cost-effective compared to the other alternatives. The study suggests that GS and OP valorization, particularly in NHY forms, can be a cost-effective and environmentally beneficial strategy for AF production, supporting circular economy practices in agricultural waste management.

Conclusions

This study provides insights into the potential of using agro-industrial by-products as sustainable alternatives for AF production, supporting circular economy practices. The results highlight that each feedstock offers unique benefits, with GS being economically more viable, OC cake showing moderate environmental advantages, and OP presenting potential for environmental benefit but with higher upfront costs.

Acknowledgment

The research leading to these results has received funding from the EU's PRIMA Program for Research, Technological Development and Demonstration under grant agreement n°2013.

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