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ORIGINAL PAPER

Orange Peel Waste Valorization: An Integrated Assessment of Environmental and Economic Sustainability in Animal Feed Production

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Abstract

This study examines the environmental and economic sustainability of producing a feed ingredient from waste orange peels (OP), for use in animal feed, focusing on two waste valorization strategies: one involving hydrolyzed and the other non-hydrolyzed OP. Life cycle assessment (LCA) and life cycle costing (LCC) methodologies were employed to assess the environmental impacts and economic feasibility. LCA data were derived from lab-scale experiments and existing literature, using the ReCiPe 2016 (H) method to quantify environmental impacts per tonne of animal feed. Key findings show that hydrolyzing OP results in higher impacts compared to non-hydrolyzed variant, primarily due to the saccharification-hydrolysis process, though this difference becomes negligible at the animal feed production stage. Sensitivity analysis reveals that variations in input materials, except for transport distance—particularly for the non-hydrolyzed variant—have limited effects on LCA outcomes. Comparisons with business-as-usual scenarios (landfilling, composting and incineration) show that while waste valorization reduces environmental impacts, it does not surpass incineration due to energy recovery potential. LCC analysis indicates that producing non-hydrolyzed feed ingredient is significantly more cost-effective than the hydrolyzed variant. Overall, the LCA and LCC results suggest that while OP waste valorization offers notable environmental benefits, non-hydrolyzed feed ingredient production is the more economically viable option, contributing to sustainable feed production. This study highlights the importance of integrating both environmental and economic considerations in waste valorization strategies and provides guidance for waste management companies and animal feed manufacturers to support circular economy practices.

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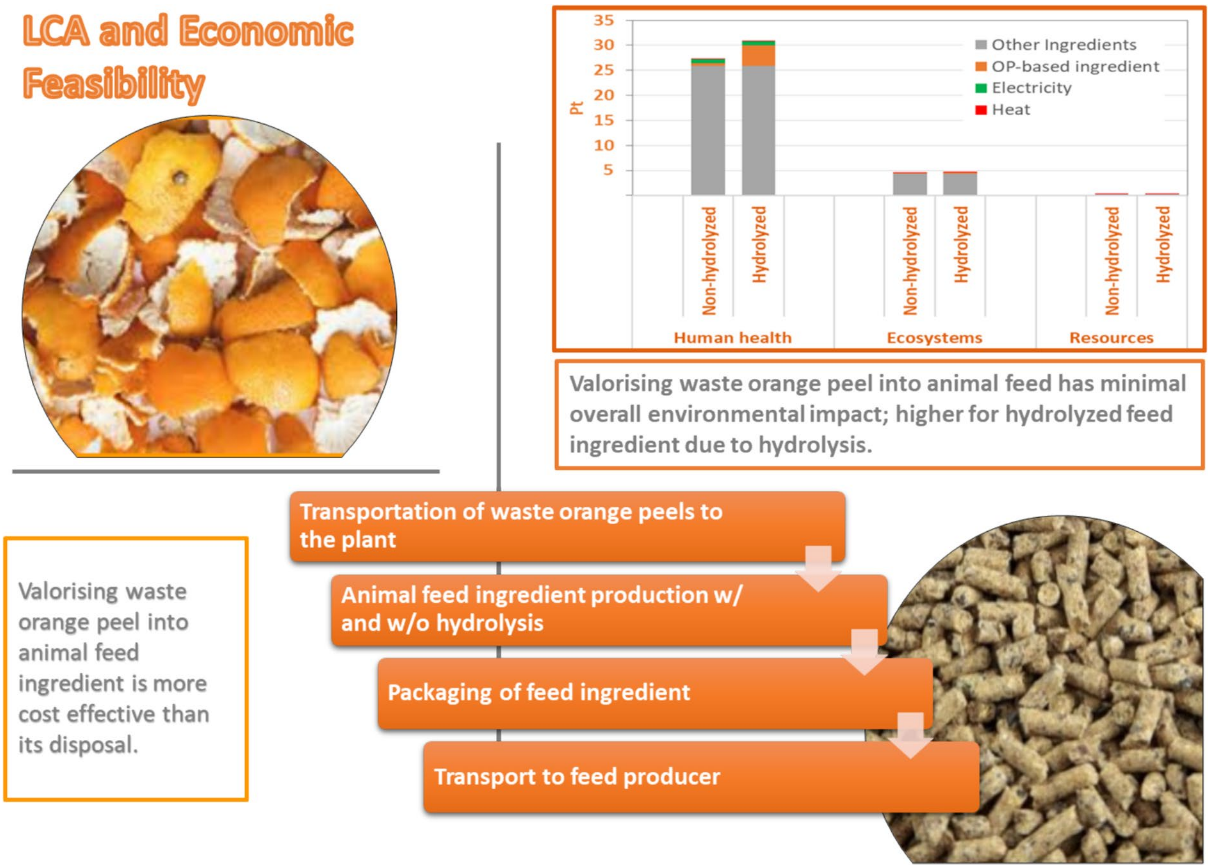
Graphical Abstract



Keywords LCA · LCC · Waste orange peel · Waste valorization · Animal feed

Statement of Novelty

This study uniquely explores the environmental and economic sustainability of using waste orange peels (OP) for animal feed production. By comprehensively assessing environmental impacts and economic feasibility, it evaluates OP-based animal feed production as a waste valorization strategy. Moreover, the inclusion of comparisons with conventional waste disposal methods (incineration, composting, and landfilling) provides valuable insights into the advantages of this approach. The findings underscore the critical importance of integrating both environmental and economic considerations to achieve sustainable outcomes.

Introduction

The increasing demand for animal products is placing additional pressure on the availability and sustainability of animal feed sources. In response to this challenge, researchers are exploring innovative strategies, such as incorporating food waste into animal feed for cattle, poultry, and fish. This approach aligns with the growing trend towards circular systems, which prioritize waste minimization and the creation of a closed loop where resources are used efficiently and sustainably [1].

Oranges are among the most consumed fruits worldwide, and the orange juice industry generates significant waste. Studies estimate that more than half of the original fruit weight is wasted as byproducts after juice extraction [2]. These byproducts primarily consist of peels, seeds, and leftover membrane residues. Orange peels (OP), a major source of organic waste in the juice industry, typically end up in landfills, harming the environment and squandering a valuable resource. European policies discourage landfilling, promoting the search for sustainable solutions. The Newfeed Project, supported by the PRIMA program under grant agreement No. 2013, is an initiative exploring the potential of converting these by-products into secondary animal feed through circular economy schemes. This method addresses waste management challenges while providing the livestock industry with a sustainable feed source [3, 4]. Repurposing food waste in this manner could reduce environmental impacts and contribute to more sustainable and efficient circular food production systems, enhancing the long-term competitiveness and sustainability of the livestock sector.

However, despite these potential benefits, Yoo et al. [5] identified economic challenges associated with using OP as animal feed due to several drawbacks. They noted that while OP can be dried for use as a dry feed additive, the high water and sugar content, along with pectin, make drying expensive. An alternative method involves producing pellet-type feedstock by dewatering OP with NaOH or CaO treatment. However, disposing of the filtrate, which contains high organic concentrations, poses challenges for wastewater treatment.

Within the framework of the Newfeed Project, a new valorization process has been proposed, involving the saccharification of OP and the aerobic fermentation of the liquid portion of the resulting hydrolysate. This innovative approach, outlined by Andrianou et al. [6] aimed to develop alternative animal feed ingredients, and established a circular economy in livestock production by transforming waste OP from the food industry into high-value secondary feedstuff. The process was optimized through factorial design. Nevertheless, the environmental and economic impacts of implementing the optimized valorization strategy remain unclear. Roy et al. [7] emphasized the need for comprehensive studies that evaluate the environmental, economic, and social implications of food waste valorization strategies in transitioning to a circular economy. Menna et al. [8] proposed a combined framework of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to analyze food waste prevention and valorization, demonstrating the potential for a deeper understanding of the impacts associated with various waste management strategies [8].

The valorization of agricultural waste has been widely studied, particularly in converting byproducts into biostimulants, biofertilizers, and biopolymers. Puglia et al. [9] analyzed the environmental impacts of products derived from agricultural waste, showcasing their role in promoting sustainable agricultural practices. Similarly, Ufitikirezi [10] emphasized the importance of integrating LCA and techno-economic assessments to evaluate the efficacy and sustainability of agricultural waste valorization technologies. These studies aim to minimize environmental impacts while maximizing economic benefits. Other examples of waste valorization include transforming plastic waste into construction materials, a process that contributes to sustainability by reducing waste and optimizing resource use [11].

Food processing byproducts, such as fish waste and dairy whey, have also been successfully valorized into valuable products. Alfio et al. [12] explored the sustainable recovery of omega-3 fatty acids from fish waste, using LCA to evaluate the environmental impacts of this process. Meanwhile, Das et al. [13] introduced a novel membrane-integrated technique for valorizing dairy whey, analyzing its environmental effects via LCA.

This investigation aims to analyze the environmental impact of the different stages of OP-based animal feed production as optimized by Andrianou et al. [6] and assess whether this production is environmentally and economically sustainable, using LCA and LCC methodologies. The LCA covers the feed ingredient production stage from waste OP (Stage 1) and the production of animal feed for dairy sheep using the OP-based feed ingredient (Stage 2). Comparisons are also made with conventional animal feed production for dairy sheep, as well as the disposal of OP through incineration, composting, and landfilling, in order to evaluate the sustainability of valorization strategies.

Our focus is on the downstream processes of feed production from OP, specifically the use of OP as a feed ingredient. This focus aligns with the research objectives of assessing the environmental impacts associated with utilizing a waste byproduct in animal feed production. While upstream processes, such as orange cultivation and juice production, also contribute to the overall environmental footprint, concentrating on downstream processes allows an in-depth investigation of the value-added activities related to the waste stream generated during juice production and its conversion into a feed ingredient.

Data for LCC analysis were sourced from lab-scale experiments for feed ingredient production and existing literature for animal feed production. The LCC study covers capital expenditure (CAPEX), operational expenditures (OPEX), and the environmental cost of OP-based feed ingredient production, as well as expected revenues expected from selling the produced feed ingredient. However, it does not include the animal feed production stage, as the related cost figures (CAPEX and OPEX) for the other feed ingredients used in the dairy sheep diet are not publicly available.

This research is expected to provide insights into the environmental and economic sustainability of OP-based animal feed production, contributing to the development of sustainable feed production practices in the livestock industry.

Methodology

Environmental Impact Assessment—LCA

The LCA study was performed according to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO 2006b). SimaPro (9.3.0.3) software was utilized to model and compute the life cycle impacts of the valorization chains. An LCA analysis comprises four distinct phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, each of which is explained below.

Goal and Scope Definition

The functional unit (FU) was defined as one tonne of animal feed produced. As shown in Fig. 1, two options; the production of hydrolyzed and non-hydrolyzed OP-based animal feed and three business-as-usual scenarios were considered. In both Option 1 and Option 2, the feed ingredient produced in Stage 1; hydrolyzed or non-hydrolyzed, is utilized for the animal feed production in Stage 2. The process chain applied for the production of the hydrolyzed OP-based animal feed ingredient that involves saccharification-hydrolysis-fermentation is called "the process of hydrolysis".

The system boundary of "cradle to gate" was considered for both the animal feed ingredient (Stage 1) and animal feed production (Stage 2) stages (Fig. 1). However, while comparing the impacts of the animal feed containing the OP-based feed ingredient with the business-as-usual case that is the production of conventional animal feed, the end-of-life (EOL) stage of waste OP (i.e. incineration, composting, and landfilling) was also included within the system boundary as indicated in Fig. 1. It should be noted that the upstream processes associated with the production of oranges and orange juice, which generate the waste OP, are excluded from the assessment. Figure 2 shows the flow diagrams for converting waste OP into hydrolyzed (Option 1) and non-hydrolyzed (Option 2) OP-based feed ingredients.

In the production of non-hydrolyzed feed ingredients, the feedstock is milled and dried using a rotary drum waste dryer at 100–140 °C for 9–15 h. This process aims to eliminate microbial growth while preserving the feedstock's composition. For hydrolyzed feed ingredients, the feedstock undergoes enzymatic hydrolysis at pH 5.5 and 50 °C to break down cellulose and pectin. Following hydrolysis, microfiltration separates the material into two fractions: a liquid, rich in sugars (hydrolysate) and a hydrolyzed solid residue (dewatered hydrolyzed OP). The hydrolysate is directed to fermentation for yeast production, while the dewatered hydrolyzed OP is combined with the fermentation effluent. This mixture is then dewatered using a plate and frame filter press. Finally, drying is applied using

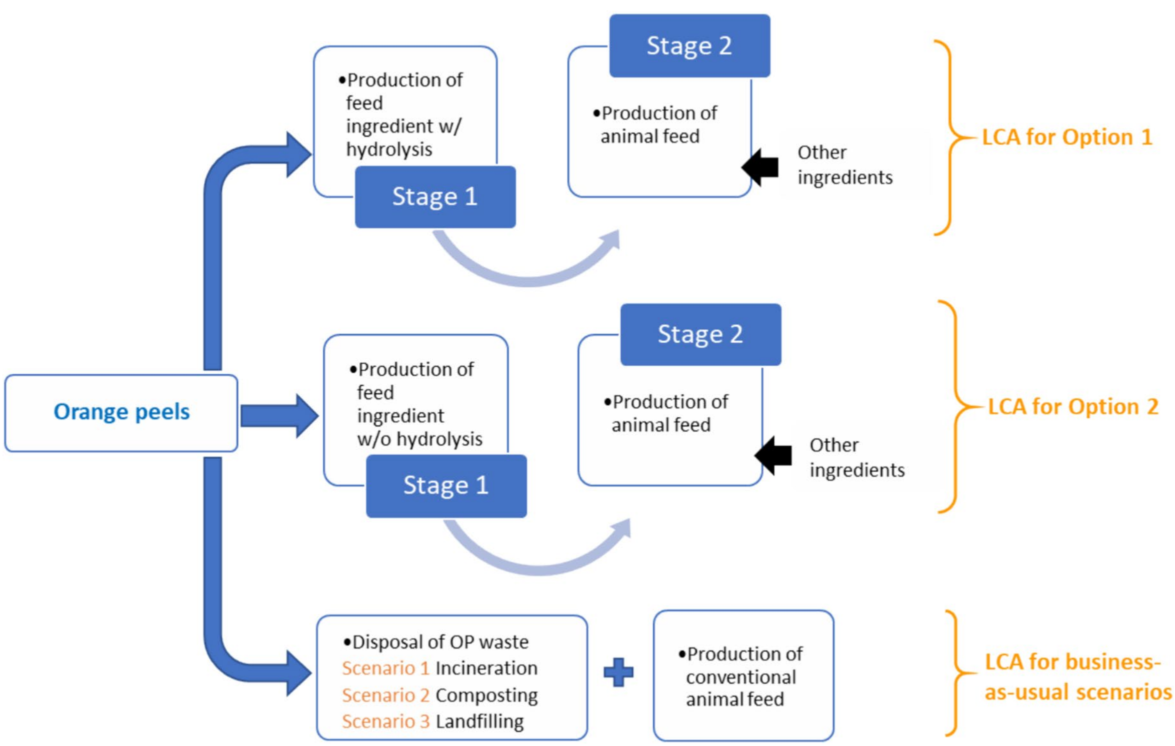


Fig. 1 Waste valorization and disposal options explored in the study

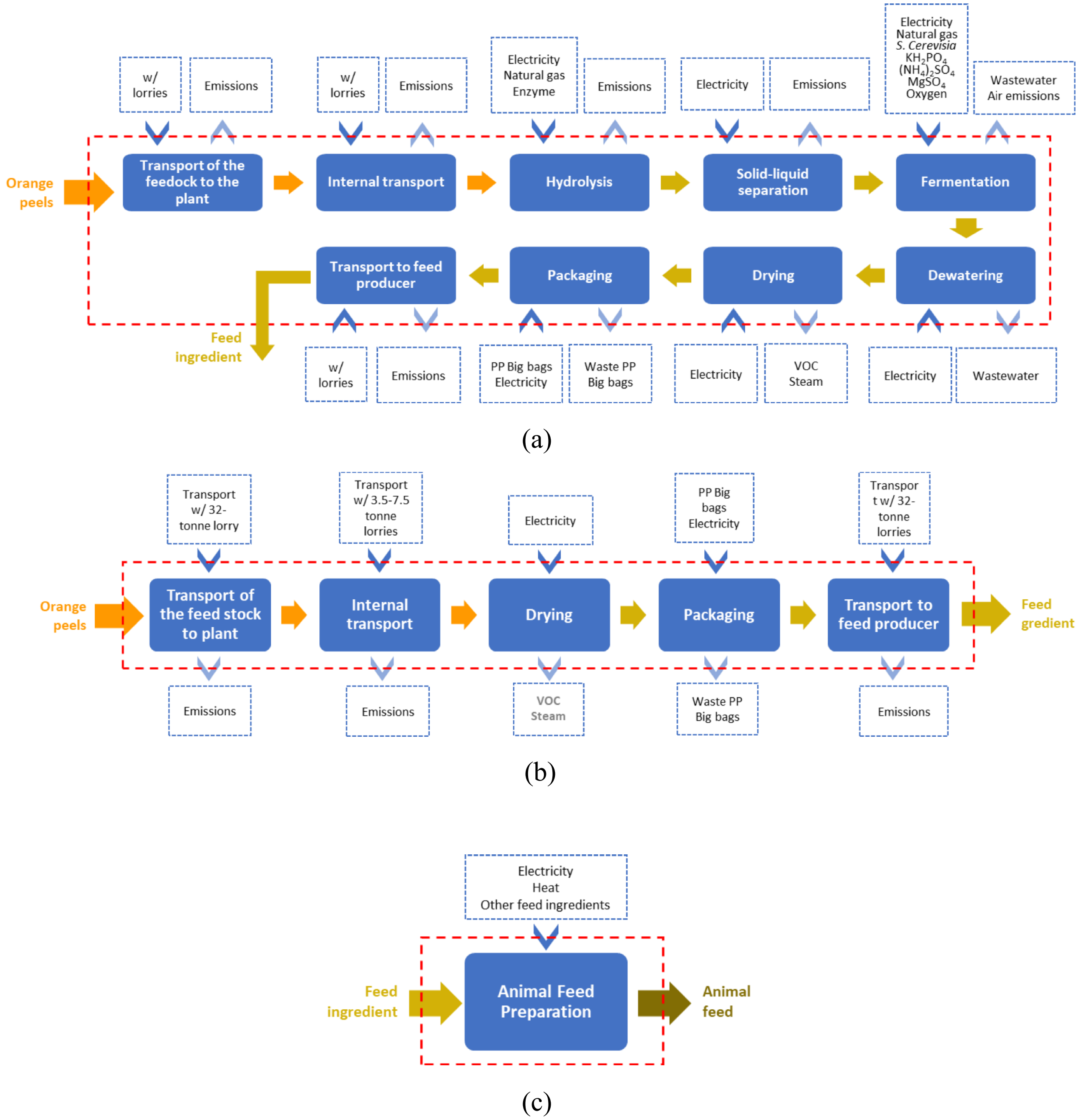


Fig. 2 Valorization process flow chart for the production of **a** hydrolyzed OP-based feed ingredient, **b** non-hydrolyzed OP-based feed ingredient, **c** animal feed

biomass-based energy, following a similar approach as in the production of non-hydrolyzed feed ingredients [6].

In comparing the value chain of OP-based animal feed with the current situation, we considered scenarios involving the production of conventional animal feeds alongside current waste disposal practices of as incineration, composting, and landfilling for the OP food wastes (Fig. 1). These scenarios were then compared with the value chains of OP-based animal feed, including both "hydrolyzed" and "non-hydrolyzed" feed ingredients.

Inventory Analysis

Table 1 presents the inventory data used for the production of the OP-based feed ingredient (Stage 1 of Option 1 and Option 2). As shown, some of the inventory data involves

Table 1 Inventory data for Stage 1 (for the FU of 1 tonne of animal feed produced)

Activity #	Activity	Option 1 Hydrolyzed OP-based feed ingredient production		Option 2 Non-hydrolyzed OP-based feed ingredient production	
1	Transportation to the plant with lorry 32 t EURO6 * 100 km				
		OP	680 kg	OP (84.5% moisture)	680 kg
2	Internal transportation with lorry 3.5–7.5 t EURO6 * 0.5 km				
		OP	680 kg	OP (84.5% moisture)	636 kg
3	Saccharification and hydrolysis (at 50 °C)				
	Inputs	OP	680 kg	–	–
		Tap water	729 L		
		Electricity	109 kWh		
		Enzyme	5.304 kg		
	Outputs	Hydrolyzed OP	1409 kg		
	Avoided Products	Enzyme	1.061 kg		
		Tap water	145.8 L		
4	Solid–liquid Separation (Dewatering) (Microfiltration)				
	Inputs	Hydrolyzed OP	1409 kg	–	–
		Electricity	3.14 kWh		
	Outputs	Dewatered hydrolyzed OP	61.3 kg		
		Hydrolysate	1348 kg		
5	Fermentation				
	Inputs	Hydrolysate (at 30 °C)	1348 kg	–	–
		Electricity	26.68 kWh		
		Yeast (*S. Cerevisiae)*	0.372 kg		
		KH_2PO_4	7.045 kg		
		$(NH_4)_2SO_4$	2.817 kg		
		$MgSO_4$	0.564 kg		
		Air	18.95 kg O_2		
	Outputs	Liquid phase	1319.2 L		
		Yeast	26.68 kg		
		Emission (CO_2)	27.3 kg		
	Avoided products	KH_2PO_4	1.409 kg		
		$(NH_4)_2SO_4$	0.564 kg		
		$MgSO_4$	0.113 kg		
		Tap water	263.8 L		
6	Dewatering (Plate and frame filter press)				
	Inputs	Yeast	26.68 kg	–	–
		Hydrolyzed OP	61.3 kg		
		Electricity	2.6 kWh		
	Outputs	Dewatered OP-based ingredient	88 kg		
		Filtrate	1055.3 L		
7	Drying				
	Inputs	Dewatered OP-based ingredient	88 kg	Feedstock (OP) (50% dry matter)	636 kg
		Biomass energy	11.73 kWh	Biomass energy	84.8 kWh
	Outputs	Dried OP-based feed ingredient	88 kg	Dried OP feed ingredient	99 kg
		Water evaporated	242 kg	Water evaporated	526 kg

Table 1 (continued)

Activity #	Activity	Option 1 Hydrolyzed OP-based feed ingredient production		Option 2 Non-hydrolyzed OP-based feed ingredient production	
8	Packaging				
	Inputs	OP-based feed ingredient	110 kg	OP-based feed ingredient	110 kg
		Electricity	0.0176 kWh	Electricity	0.0158 kWh
		Number of big bags used	2.2	Number of big bags used	2
		Mass of big bags used	0.51 kg	Mass of big bags used	0.46 kg
		Big bag carry capacity	50 kg/bag	Big bag carry capacity	50 kg /bag
		Big bag empty weight	0.233 kg/bag	Big bag empty weight	0.233 kg/bag
	Outputs	OP-based feed ingredient, packed	110 kg	OP-based feed ingredient, packed	110 kg
		Waste big bags	0.051 kg	Waste big bags	0.046 kg
	Big Bag Production				
	Inputs	LDPE	12.7 kg	LDPE	12.7 kg
		HDPE	10.7 kg	HDPE	10.7 kg
		Diesel	0.0681 kg	Diesel	0.0681 kg
		Ethanol	2.1432 kg	Ethanol	2.1432 kg
		Ethylene acetate	0.453 kg	Ethylene acetate	0.453 kg
		1-Propanol	1.8753 kg	1-Propanol	1.8753 kg
		Toluene	0.643 kg	Toluene	0.643 kg
	Emissions	Abietic acid	0.00812 kg	Abietic acid	0.00812 kg
		Butyl acetate	9.7005 kg	Butyl acetate	9.7005 kg
		Toluene	3.9917 kg	Toluene	3.9917 kg
		Ethanol	1.9401 kg	Ethanol	1.9401 kg
		Butanol,2 methyl-1	3.9917 kg	Butanol, 2 methyl-1	3.9917 kg
		CO	0.008068 kg	CO	0.008068 kg
		Nonmethane VOC	0.0011 kg	Nonmethane VOC	0.0011 kg
		CH_4	3.2619E-5 kg	CH_4	3.2619E-5 kg
		NO_2	0.0041 kg	NO_2	0.0041 kg
		Soot	0.0005 kg	Soot	0.0005 kg
		NO	1.5657E-5 kg	NO	1.5657E-5 kg
		CO_2	0.40944 kg	CO_2	0.40944 kg
		Benzo(a)pyrene	3.9143E-6 kg	Benzo(a)pyrene	3.9143E-6 kg
		SO_2	0.0005 kg	SO_2	0.0005 kg
9	Transport to Feed Producer with lorry 32 t EURO6 * 100 km				
		OP-based feed ingredient, packed	110 kg	OP-based feed ingredient, packed	110 kg

the transportation of waste orange peel to the processing plant, its processing for feed ingredient production, and the packaging and transportation of the feed ingredient from the production plant to the animal feed-producing plant. All the inventory data originate from pilot studies, except for the data concerning the packaging of the feed ingredient and its transportation from the feed ingredient production plant to the animal feed production plant. The inventory data for these latter steps are based on assumptions considering common practices.

Table 2 Inventory data for Stage 2 (for the functional unit of 1 tonne of animal feed produced)

Activity #	Activity	Item	Animal feed production with hydrolyzed or non-hydrolyzed OP-based feed ingredient	Conventional animal feed production
1	Feed preparation			
	Inputs	OP-based feed ingredient	110 kg	0 kg
		Electricity	280 MJ	280 MJ
		Heat	120.6 MJ	120.6 MJ
		Corn grain	300 kg	300 kg kg
		Barley grain	200 kg	200 kg
		Wheat bran	120 kg	200 kg
		Soybean meal	110 kg	110 kg
		Sunflower meal	120 kg	150 kg
		Limestone	5 kg	5 kg
		Monocalcium phosphate	5 kg	5 kg
		Salt	5 kg	5 kg
		Vitamin and mineral premix	25 kg	25 kg
	Output	Packed animal feed	1000 kg	1000 kg

Table 2 provides a comprehensive breakdown of the animal feed formulations under consideration for dairy sheep, encompassing both the OP-based feed and the conventional diet for comparative analysis. For all feed ingredients other than OP-based ones, consistent with the consequential LCA approach employed, readily available unit processes from the Ecoinvent 3 and Agri-footprint 5 databases were utilized in constructing the relevant LCA models. In instances where data was unavailable within these databases, alternative database(s) within the SimaPro software suite were utilized. Detailed listings of the specific unit processes and the corresponding databases employed are provided in Table SI.1 and Table SI.2, available in the supplementary information.

The feed ingredients considered in constructing the pertinent LCA models for Stage 2 are detailed in Table 2. To maintain consistency and facilitate comparability, preference was given to "market" units over "processing at plant" units whenever available in the databases. "Market" units encompass both the production of the ingredient at the plant and its transportation to the animal feed production plant. The feed preparation process encompasses all the procedural steps involved in animal feed production, including crushing, mixing, pelletizing, cooling, and packaging.

Assumptions, along with their respective sources (where applicable) are presented in Table 3. The assumptions made in this table are based on standard industry practices and regional data relevant to the processes being analyzed. For example, the choice of lorries with capacities greater than 32 tonnes for feedstock transportation reflects common practice in bulk logistics, and the 100 km distance is a reasonable estimate based on typical transportation routes for industrial operations. The assumption that unloading and intermediate storage have a negligible impact is supported by the general understanding that these stages typically contribute less to environmental impact compared to other more energy-intensive processes. Internal transport within the plant is assumed to use smaller lorries (3.5–7.5 tonnes), consistent with short distances between production units. The electricity mix assumed for various stages (e.g., medium voltage RER for saccharification, hydrolysis, and fermentation) is justified by typical grid energy sources in the region, with the added assumption that oxygen for fermentation is included in the electricity consumption, as is common in aerobic fermentation processes. Reusing filtrate in the saccharification step is a sustainable practice aimed at minimizing water consumption, while the use of bag filters in drying ensures dust recovery, reflecting industry standards for air quality control. The packaging assumption regarding big bags and their associated waste is based on typical packaging practices, with the empty weight and 10% waste rate aligning with standard packaging for bulk materials. For the transport to the animal feed producer, a similar approach to the initial transport assumption is used, considering large-scale logistics. In Stage 2, the electricity and heat consumption values are adopted from animal feed processing data, which provides a benchmark for energy usage in similar production settings. Finally, the disposal of waste and end-of-life treatments (composting, incineration, and landfill) is consistent with common waste management practices in the EU27 region. Overall, the assumptions are supported by industry norms, regional data, and sustainability goals that guide the process design and environmental impact assessment.

Table 3 Assumptions considered

Process/Unit	Assumption	Source
Stage 1		
Transport of the feedstock to the plant	Transport type: Lorry (> 32 tonne)	
	Distance: 100 km	
Unloading and intermediate storage of the feedstock in the plant	Negligible impact	
Internal transport	Transport type: Lorry (3.5–7.5 tonne)	
	Distance: 0.5 km	
Saccharification and hydrolysis, solid–liquid separation (microfiltration), fermentation, dewatering, packaging	Electricity mix type: medium voltage (RER)	
Fermentation (aerobic)	The oxygen required is considered within the electricity consumption	
Dewatering	Filtrate (to be reused in the saccharification step to replace tap water)	
Drying	The bag filters of the drying equipment ensure that all dusts are recovered	
Packaging	Big bags' empty weight is 0.233 kg/bag (assuming 1000 conventional carry bags correspond to 10 big bags) Big bag material is assumed as for traditional plastic bags	[14]
	Electricity used during filling: 0.008 kWh/bag	
	10% big bag waste	
Transport to an animal feed producer	Transport type: Lorry (> 32 tonne)	
	Distance: 100 km	
Stage 2		
Electricity	Adopted from animal feed processing (i.e. for 0.94 kg feed 0.296 MJ electricity mix)	Ecoinvent 3
Heat	Adopted from animal feed processing (i.e. for 0.94 kg feed 0.127 MJ heat from residential heating system)	Ecoinvent 3
Disposal of waste OP		
EOL for feedstocks	- Waste treatment, composting of food waste, EU27 - Waste treatment, Incineration of waste, food, EU27 - Waste treatment, Landfill of waste, food, EU27	Ecoinvent 3

OP Orange peel, *EOL* End-of-life

Table 4 Midpoint impact categories

Symbol	Midpoint Impact Category	Symbol	Midpoint Impact Category
GW	Global warming	TE	Terrestrial ecotoxicity
SOD	Stratospheric ozone depletion	FET	Freshwater ecotoxicity
IR	Ionizing radiation	MET	Marine ecotoxicity
OF-HH	Ozone formation-human health	HCT	Human carcinogenic toxicity
FPF	Fine particulate matter formation	HNCT	Human non-carcinogenic toxicity
OF-TE	Ozone formation-terrestrial ecosystems	LU	Land use
TA	Terrestrial acidification	MRS	Mineral resource scarcity
FE	Freshwater eutrophication	FRS	Fossil resource scarcity
ME	Marine eutrophication	WC	Water consumption

Impact Assessment

Stage 3 of LCA, known as the impact assessment phase, focuses on evaluating the potential environmental impacts associated with the life cycle stages identified in earlier phases. In this phase, the ReCiPe 2016 (H) (Midpoint and Endpoint, V1.06) Method is used to assess and quantify these impacts. This method employs characterization factors to convert inventory data—such as emissions or resource use—into impact values on 18 midpoint impact categories (Table 4), reflecting their potential effects on the environment. These midpoint indicators are then aggregated into three endpoint impact categories: human health, ecosystems, and resources, using a combined midpoint/endpoint approach score [15]. The characterization process calculates the contribution of each input or emission to the total environmental impact (Table SI. 3). To facilitate comparison across categories, results are normalized using the normalization scores provided in Table SI.4 to a common scale, enabling the synthesis of findings. The impact assessment concludes with the aggregation of the normalized values, where single scores are derived by applying weighting factors specific to each category (Table SI. 5). This approach ensures that results are presented in a unified, interpretable format. Throughout the process, the methodology adheres to ISO 14040 standards, ensuring that the assessment is consistent, transparent, and scientifically rigorous.

Interpretation

In the interpretation phase of LCA, which represents the final stage of the evaluation process, the gathered impact data is carefully analyzed and assessed to draw meaningful and actionable conclusions about the environmental effects of the processes under study. In this phase, environmental impacts are reviewed, key findings are highlighted, and results are compared and presented understandably. Additionally, uncertainties and data gaps are examined to identify which life cycle stages contribute most to the environmental impacts. Interpretation helps clarify the results and guides decision-making by synthesizing and reporting the findings.

Sensitivity Analysis

To fully comprehend how different input parameters influence the outcomes of LCA, a thorough investigation of numerous factors was conducted, as delineated in Table 5. This analysis allows for a nuanced understanding of how alterations in these parameters may affect the results of the LCA process. The decision to increase most parameters by 10% was made to observe moderate variations and assess how these changes influence the overall results without introducing extreme deviations. A 10% variation is often considered a reasonable and realistic range for such parameters, ensuring that the analysis remains applicable to real-world scenarios.

For transport distance, the choice to test both a 1.5 and 10 times increase was intended to capture a broader range of possible scenarios, particularly because transport distances can vary significantly depending on the logistics involved in different contexts. The larger increments help explore extreme cases that could have a disproportionate effect on the environmental impacts, especially for factors like fuel consumption and emissions. By considering both moderate and more extreme variations, we aim to provide a well-rounded sensitivity analysis that accounts for a spectrum of potential real-world conditions. Such insights are invaluable for informed decision-making.

The selection of RER and GRIDM for the electricity mix type aimed to capture the impact of different energy sources used in electricity generation. Both RER and GRIDM are specific to Europe; however, the RER dataset focuses exclusively on renewable energy sources, such as biomass, hydropower, solar, and wind. In contrast, the GRIDM dataset represents the electricity grid mix of the EU-27 countries, encompassing data from regions with diverse energy compositions, including those with a greater reliance on fossil

Table 5 Parameters and alternative values considered for the sensitivity analysis of results

Parameter	Default value of the parameter	Alternative value/s of the parameter
Electricity Mix Type	Electricity, medium voltage {RER}| market group for | Conseq, S (RER)	Electricity grid mix 1 kV-60 kV, AC, consumption mix, at consumer (GRIDM)
Transport Type	Transport, freight, lorry > 32 tonne, euro6 {RER}| market for transport, Conseq, S (LORRY)	Transport, freight train {Europe}| market for | Conseq, S (RAIL)
Electricity Consumption	153.7 kWh (for hydrolyzed OP) 84.8 kWh (for non-hydrolyzed OP)	10% increase 10% decrease
Transport Distance	100 km	150 km 1000 km
Most influencing parameters	Current enzyme consumption of 5.304 kg (for 1 ton of hydrolyzed OP-based animal feed)	10% increase 10% decrease
	Current electricity consumption of 84.8 kWh (for non-hydrolyzed OP)	10% increase 10% decrease

RER Renewable energy resources-based electricity in Europe, *GRIDM* Regional grid mix electricity in Europe, *RAIL* Transport by railway, *LORRY* Transport by road freight fuels, such as coal and natural gas. By examining the effects of variations in parameters such as electricity mix type, transport type, consumption levels, and distances traveled, we gain a nuanced understanding of their impact on the overall LCA results. Such insights are invaluable for informed decision-making.

Economic Analysis—LCC

To assess the economic performance of the proposed value chain and its long-term financial viability, a life cycle cost–benefit analysis was conducted for both of the scenarios and the business-as-usual case calculating their net present value (NPV). The calculation of NPV at time t was done using the following equation:

$$NPV = \sum_{t=0}^{n} \left(\frac{CAPEX + OPEX - Revenues}{(1+r)^n} + Environmentalcost \right) \quad (1)$$

where:

n: life span of the plant.

r: interest rate.

An interest rate of 3% was applied as the discount rate to discount all future cash flows of an investment to derive its NPV. The lifetime of the system was taken as 20 years. As shown in Eq. 1, the net cost includes life cycle financial costs (CAPEX and OPEX), environmental costs, and financial benefits of the proposed value chain (revenues due to selling the produced feed ingredient) compared to conventional animal feed production. CAPEX estimation primarily involves a comprehensive consideration of both direct and indirect cost items, each calculated as a percentage of the total CAPEX as outlined in Table SI.6. Direct costs encompass expenses for purchased equipment, its installation, instrumentation, piping, and electrical equipment. Purchased equipment costs were gathered from equipment suppliers. Given that the purchase equipment cost data was for a lower capacity, a scale-up factor was used to determine the adjustment necessary for transitioning from the current production capacity of the equipment to the increased production capacity.

In the CAPEX calculation, scaling up from the pilot plant size (producing 200 kg feed ingredient produced per day) to the field size (1000 kg feed ingredient produced per day) was performed by applying the "0.6 Rule" which originates from the relationship between equipment cost and capacity increase [16]:

$$\frac{Cost_2}{Cost_1} = \left(\frac{Size_1}{Size_2} \right)^m \quad (2)$$

where m is the scaling factor.

Tribe and Alpine [16] explained that the scale coefficient (m) may vary depending on the technology nature and ranges between 0.5 and 1. In this study, to comprehensively represent the specific plant and technology under evaluation, a scaling factor of 0.8 was adopted for m [17]. This choice was influenced by the approach of Arfan et al. [17], who applied a similar scaling factor of 0.8 in a comparable process. We found that this value provided a more accurate representation of the CAPEX calculation for our specific case, ensuring the results were more aligned with the characteristics of the process and technology involved.

Additional CAPEX considerations such as land procurement, architectural planning, and building construction are not factored into the CAPEX calculations as these are highly case-dependent [18].

OPEX included expenses for electricity, steam, and chemicals based on unit costs presented in Table SI.7. OPEX was considered nil for the construction year. Revenues are generated from selling the feed ingredient to animal feed producers. These revenues were calculated based on the selling prices of the hydrolyzed and non-hydrolyzed feed ingredients, as well as the assumed daily production capacity of a feed-producing facility with an annual capacity of 1,200,000 kg. The selling price for the non-hydrolyzed feed ingredient is €0.28 per kg, while the selling price for the hydrolyzed feed ingredient is €0.44 per kg. Given the assumed annual production capacity of 1,200,000 kg of OP-based feed ingredients, the revenue estimates were obtained by multiplying the respective selling prices by the quantity of feed ingredient produced. The methodology used for OPEX calculation relies on unit prices for variable costs, while fixed costs are determined as a certain percentage of CAPEX. Variable costs encompass expenses such as raw materials and utilities, which vary by production levels and are calculated using unit prices (Other assumptions include a yearly production of feed ingredient totaling 120,000 kg/year, and the number of operational days per year set at 120). Conversely, fixed costs, represent stable expenditures such as labor (2% of CAPEX), repair and maintenance (4% of CAPEX), and laboratory expenses (15% of CAPEX), allocated based on predetermined percentages. Other assumptions include a yearly production of feed ingredient totaling 120,000 kg/year, and the number of operational days per year set at 120.

The environmental cost includes the economic loss of well-being due to an impact as well as the cost of mitigation measures. For the calculation of the environmental cost, the absolute values of the impacts in all mid-point categories were multiplied by their respective environmental unit price (Table SI.8).

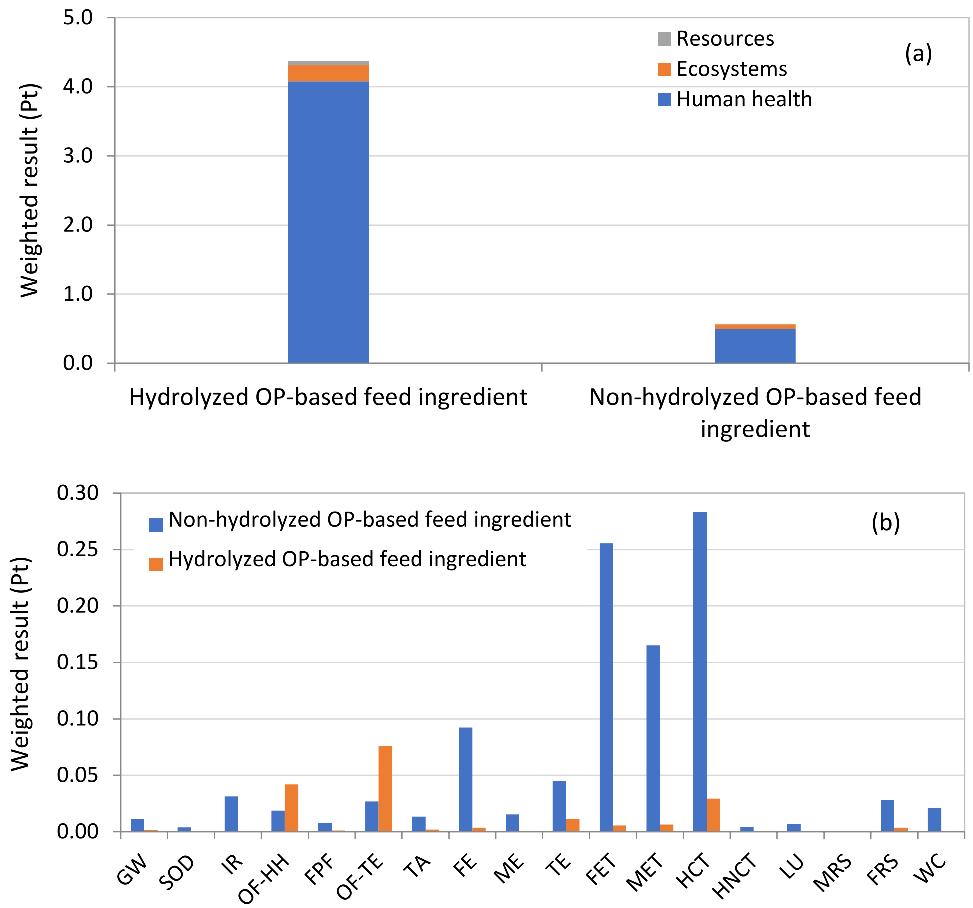


Fig. 3 Environmental impacts of the hydrolyzed and non-hydrolyzed OP-based feed ingredients at (**a**) endpoint, (**b**) midpoint impact categories

Results and Discussion

LCA Results

OP-Based Feed Ingredient Production

Figure 3 illustrates a comparison between the impacts associated with the production of 110 kg of hydrolyzed and non-hydrolyzed OP-based feed ingredients that are required for the production of 1 tonne of animal feed. As shown in Fig. 3(a), the total environmental impacts associated with the hydrolyzed OP-based feed ingredient are substantially greater, being nearly 8 times higher than those of the non-hydrolyzed variant. This is particularly evident in the endpoint impact category of the human health category. The distribution of these impacts among the midpoint impact categories provided in Fig. 3(b) shows that in the case of the hydrolyzed OP-based feed ingredient production, the highest impact is on the human carcinogenic toxicity (HCT) category followed by freshwater ecotoxicity (FET) and marine ecotoxicity (MET). On the other hand, in the case of the non-hydrolyzed OP-based feed ingredient production, ozone formation-terrestrial ecosystem (OF-TE) and ozone formation-human health (OF-HH) appeared as the most influenced mid-point impact categories.

Figure 4(a) illustrates the process contributions of various process stages to these impacts. It is evident that the "saccharification-hydrolysis" process has the highest contribution to the impacts in the hydrolyzed OP case, while "drying" appears as the primary contributor for the non-hydrolyzed OP (Fig. 4b). A more detailed analysis of the results reveals that the use of the enzyme during the saccharification-hydrolysis process is the most influential parameter, with a share of about 50% of the total impacts and 35% of the impacts on the HCT category (Fig. SI.1) This high contribution from the saccharification-hydrolysis process is attributed to several factors, including the energy-intensive nature of the process and the use of water during the process. This finding aligns with the conclusions of Garafao et al. [19] who demonstrated that the duration of the hydrolysis and the associated electricity consumption are the primary factors affecting the environmental sustainability of the fish-waste recovery by enzymatic hydrolysis process. Enzymes are essential catalysts in breaking down complex carbohydrates into simpler sugars, a crucial step in bioconversion processes. However, their production and utilization often involve

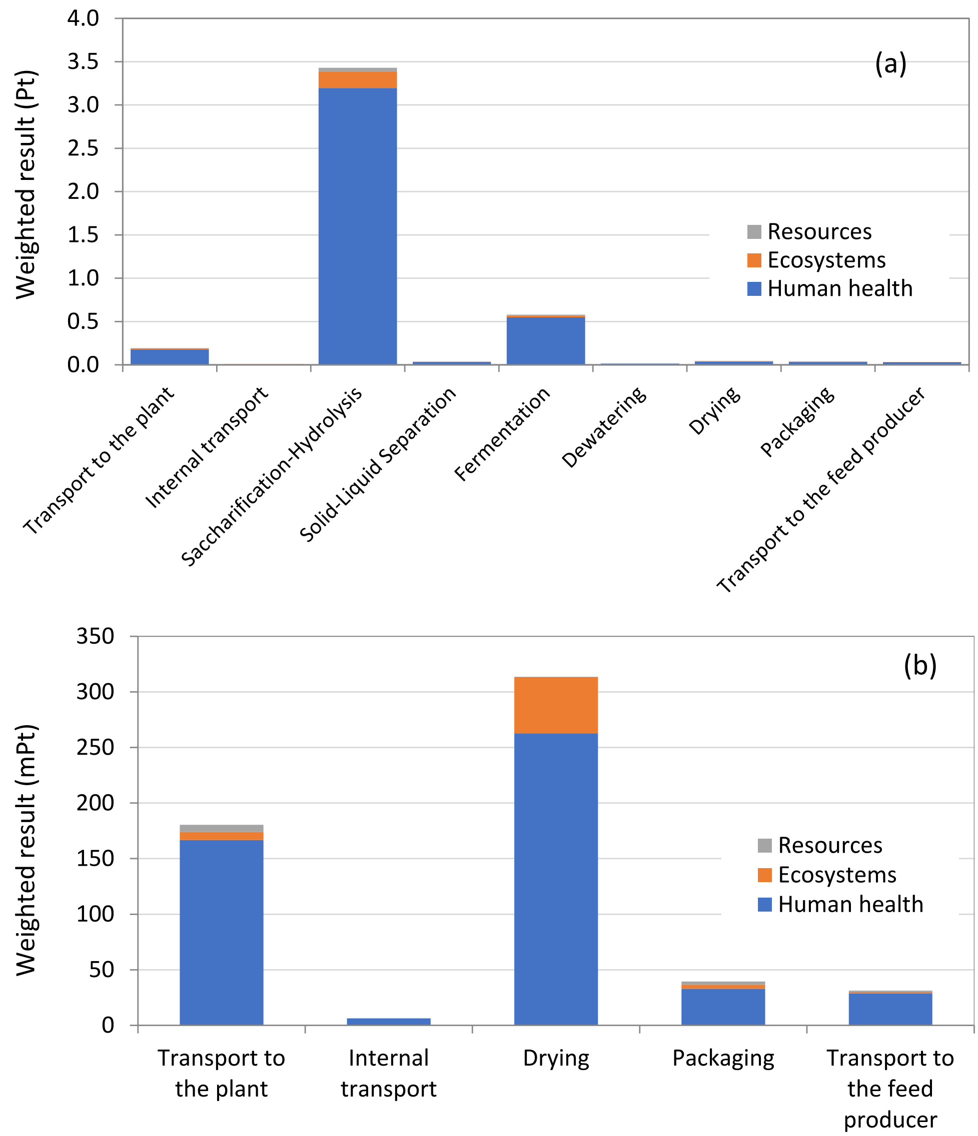


Fig. 4 Process contribution to the normalized impacts **a** hydrolyzed **b** non-hydrolyzed 110 kg OP-based feed ingredient

energy-intensive processes, such as fermentation and purification, which contribute to environmental impacts.

Regarding the non-hydrolyzed OP-based feed ingredient, the most influential parameter on the total impacts, as well as the impacts on the OF-TE, is identified as electricity consumption (Fig. SI.2). The significant impact of drying in the non-hydrolyzed OP case appears to be due to the energy requirements for removing moisture from the feedstock. It seems that 54% of the total impacts, and a striking 94% of the impacts in the OF-TE category, are attributed to the electricity used for drying. This process requires substantial electricity input, and the associated environmental burdens align with observations from similar studies. For example, Joglekar et al. [21] and Siddique et al. [20] pointed out drying as an energy-intensive step in feedstock processing, contributing to significant environmental impacts. The high electricity demand for moisture removal, as noted in this study, is a common theme in the literature, emphasizing the need for alternative drying technologies or energy recovery approaches to reduce these impacts.

The distinction in midpoint impact categories between hydrolyzed and non-hydrolyzed OP-based feed ingredients also finds support in studies focusing on feedstock processing. While the HCT category is dominant in hydrolyzed variants due to enzyme usage and associated processes, ozone formation-related categories (OF-TE and OF-HH) are pronounced in non-hydrolyzed variants. This reflects the direct relationship between electricity consumption and emissions linked to ozone formation, as previously documented in LCA studies of industrial processes [21].

Overall, these findings emphasize the need for process optimization, specifically targeting enzyme utilization efficiency and energy management during hydrolysis, to enhance sustainability in valorizing OP waste. Future

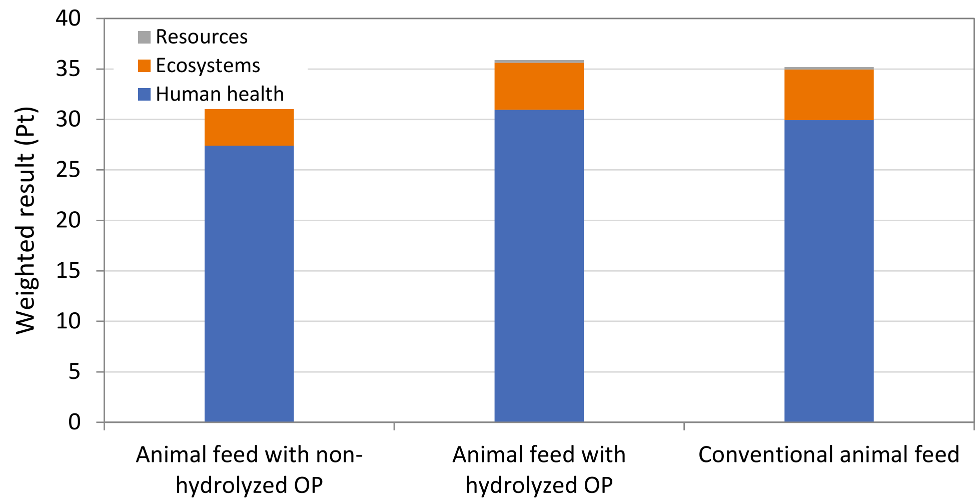


Fig. 5 Environmental impacts of 1 tonne of animal feed containing 110 kg of hydrolyzed and non-hydrolyzed OP-based feed ingredient and conventional animal feed across endpoint impact categories

research could build on these insights by exploring specific interventions, such as reducing enzyme production impacts, optimizing energy efficiency, and employing renewable energy sources, to reduce the environmental footprint of these processes.

OP-Based Animal Feed Production

Figure 5 depicts the environmental impacts associated with the production of 1 tonne of animal feed for dairy sheep, using both hydrolyzed and non-hydrolyzed OP-feed ingredients. The comparison suggests that there were no significant differences in environmental impacts between the two animal feeds when considering their overall impacts. The environmental impacts of the animal feed containing hydrolyzed OP-based feed ingredient were found to be approximately 9% higher compared to the feed containing OP-based non-hydrolyzed feed ingredient. However, as presented in Fig. 3(a), when focusing solely on the production of feed ingredients, there was a notable difference between the environmental impacts of hydrolyzed and non-hydrolyzed variants. This suggests a significant difference in the environmental footprint at the ingredient level, but not at the animal feed level. When all the ingredients are incorporated into the production of the animal feed, the dominant effects of other components within the feed blend tend to mitigate the observed difference between hydrolyzed and non-hydrolyzed variants. This observation aligns with the findings of Dilek et al. [22], who noted that the environmental impacts of grape stem-based feed ingredients in animal feed were minimal, largely due to their small proportion in the overall feed, with the majority of the impacts coming from other feed components.

When comparing the environmental impacts of animal feeds containing hydrolyzed and non-hydrolyzed OP-based feed ingredients with those of conventional animal feed, it is observed that the feed containing the non-hydrolyzed ingredient has lower impacts, while the feed with the hydrolyzed variant shows slightly higher impacts (Fig. 3). This suggests that incorporating the hydrolyzed feed ingredient does not result in a reduction in environmental impacts, unlike the non-hydrolyzed variant. While the use of OP-based ingredients allows for a reduction in the quantities of the other two ingredients compared to conventional feed (Table 2), the additional processing involved in hydrolysis, which requires more energy and chemicals, offsets these reductions, resulting in slightly higher environmental impacts for the feed with hydrolyzed OP. This finding aligns with the results of Scherhaufer et al. [23], who reported that the production of food ingredients from food side flows is only advantageous if the emissions from processing are lower than those from the products being replaced.

Figure 6 reveals that the most affected impact category in both "non-hydrolyzed" and "hydrolyzed" cases is the human health impact category, followed by ecosystems. As depicted in Fig. 6, the primary contributor to impacts in both human health and ecosystem impact categories is the other ingredients in the animal feed formulation. Ingredients such as corn grain, barley grain, wheat bran, etc., are incorporated into the animal feed (Table 3). Fig. SI.3 in the SI provides a breakdown of the impacts associated with each feed ingredient individually. Figure 6 clearly shows that the contribution of the OP-based feed ingredient to the overall impacts is considerable (about 12%) only in the case of hydrolyzed OP-based feed ingredient, and the impacts due to the utilization of electricity and heat are relatively negligible.

Scenarios

Comparing the environmental impacts of the three business-as-usual scenarios with the impacts of OP-based animal feed production options is crucial for a comprehensive

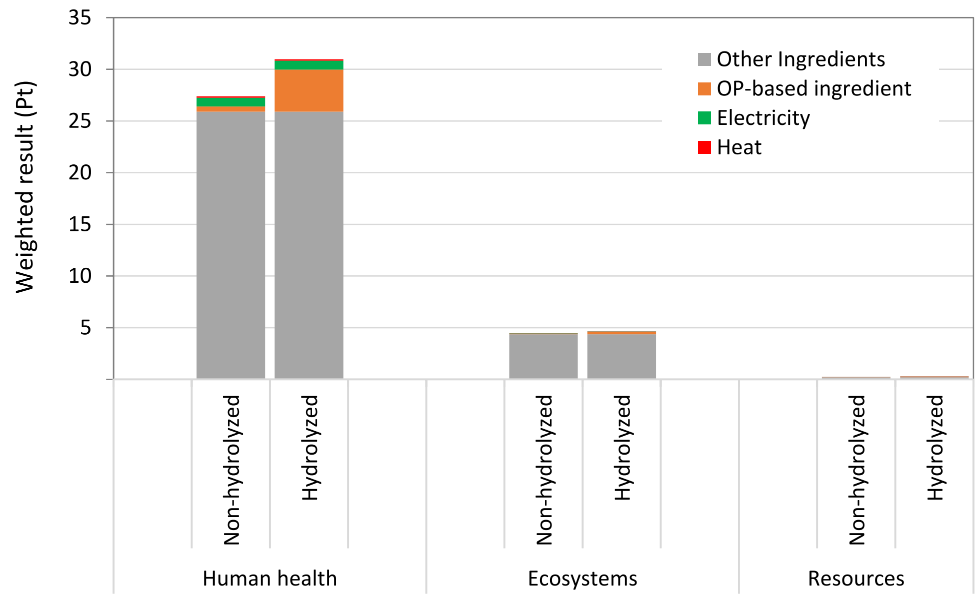


Fig. 6 The contribution of OP-based feed ingredient and other ingredients to the environmental impact of 1 tonne of animal feed (containing 110 kg of feed ingredient) production

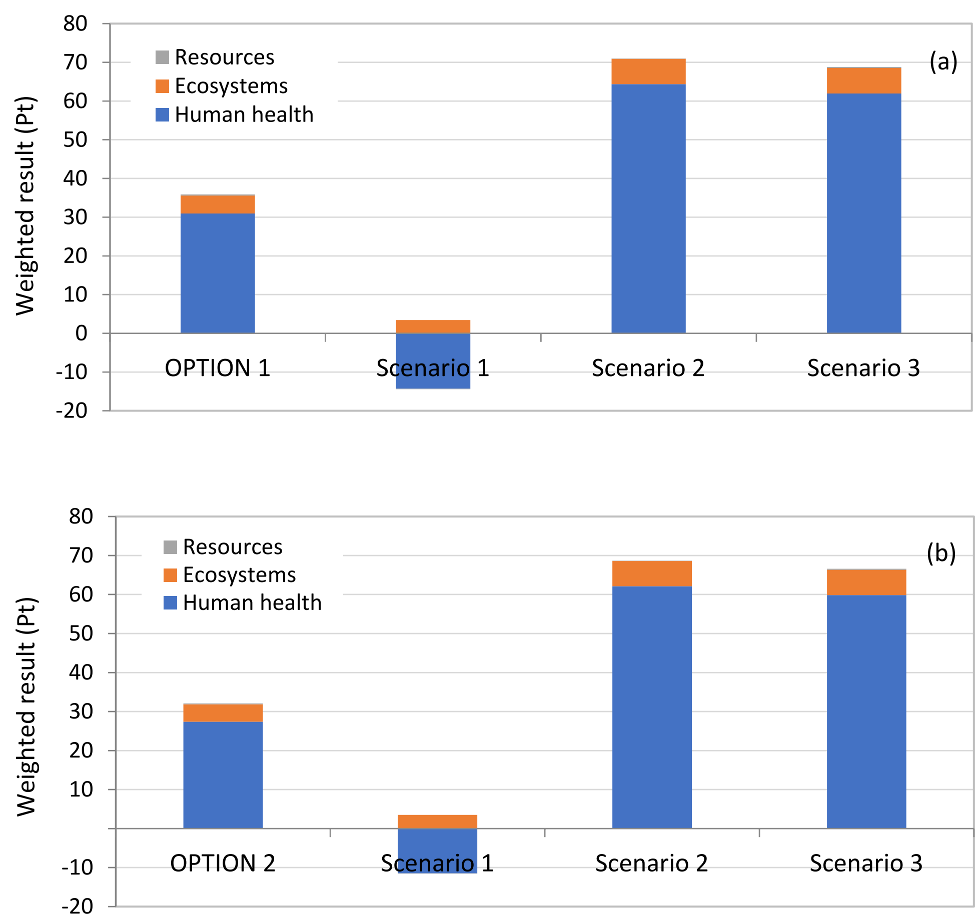


Fig. 7 Comparison of the cradle-to-gate environmental impacts of; (**a**) the hydrolyzed and (**b**) non-hydrolyzed OP-based animal feed with those of the business-as-usual scenarios (for 1 tonne of animal feed that is produced using 680 kg of OP when hydrolyzed or 636 kg of OP when non-hydrolyzed)

assessment. Business-as-usual scenarios encompass situations where OP is disposed of and animal feed is produced with conventional ingredients, i.e., without OP-based feed ingredient. Disposal options include incineration with heat recovery, composting, and landfilling. Therefore, the comparison is made between the environmental impacts of 1 tonne of OP-based animal feed production (from 680 kg of OP for the hydrolyzed and 636 kg of OP for the non-hydrolyzed case) and the environmental impacts of conventional 1 tonne of animal feed production without OP-based ingredients, along with the environmental impacts of disposing of the respective amounts of OP by landfilling (Scenario 1), composting (Scenario 2), or incineration (Scenario 3). This holistic approach provides a more accurate understanding of their comparative environmental performance. Figure 7(a) and (b) illustrate the impacts of the OP waste valorization options compared to those of the business-as-usual scenarios, which include incineration with heat recovery, composting, and landfilling, for Option 1 and Option 2, respectively. As shown, the environmental impacts of the business-as-usual scenarios, particularly landfilling and composting, are nearly twice as high as those associated with both hydrolyzed and non-hydrolyzed OP-based animal feed production. In contrast, the impacts of incineration with heat recovery (Scenario 1) are significantly lower compared to other waste valorization scenarios. In fact, incineration has a positive impact on the human health category and minimal impacts on the other two categories. This positive outcome is attributed to the consideration of heat recovery in the incineration process. These findings align with those observed in the valorization of grape stem as an animal feed ingredient [22]. Dilek et al. [22] found that grape stem valorization leads to lower environmental impacts than landfilling and composting, though it still falls short of the environmental benefits of incineration, which provides significant energy recovery.

Sensitivity Analysis

Sensitivity analyses were conducted for five parameters for both hydrolyzed and non-hydrolyzed feed ingredients, with the single score results presented in Fig. 8. For the hydrolyzed feed ingredient, sensitivity to the most influential parameter—enzyme use (Fig. SI.1) was found to be

Fig. 8 Sensitivity results for (**a**) hydrolyzed, (**b**) nonhydrolyzed feed ingredient production (Default: Enzyme use, 5.304 kg/FU; Electricity mix type, RER; Electricity consumption, 153.1676 kWh/FU for hydrolyzed, 84.8158 kWh/FU for non-hydrolyzed; Transport type, Lorry; Transport distance, 100 km)

significant. A 10% reduction in enzyme use led to a decrease reduction in the total impact score from 4.37 to 4.16. This result emphasizes the importance of enzyme efficiency in the OP-based feed ingredient production process. Enzyme optimization could, therefore, represent a valuable opportunity for reducing the environmental impacts of hydrolyzed feed ingredient production. Similar findings in the literature have indicated that enzyme improvements can enhance feed production efficiency while also lowering environmental impacts [23]. Therefore, it may be beneficial for the industry to focus on optimizing enzyme use as a means of minimizing overall resource consumption.

The variation in electricity consumption also had a significant impact on the results. A 10% increase in electricity consumption raised the impact score from 4.37 to 4.54, demonstrating sensitivity to this parameter. This suggests that the energy source used during the hydrolyzed feed ingredient production plays a critical role in determining its environmental footprint. Specifically, switching from the default RER electricity mix to GRIDM resulted in a higher impact score, underscoring the importance of renewable energy sources. This observation is in line with other studies that have shown the substantial effect of energy sourcing on the carbon footprint of industrial processes [23]. Therefore, shifting to greener electricity sources could substantially reduce the environmental impact of OP-based feed ingredient production [24].

Transport distance was also found to influence the total impact, particularly for the non-hydrolyzed feed ingredient. A 50 km increase in transport distance resulted in a 3% rise in the impact score for hydrolyzed feed ingredient, while for the non-hydrolyzed variant, the same increase in transport distance led to a more pronounced 20% rise (Fig. 8a and b). These findings highlight the importance of transport logistics in determining the environmental footprint, with road-based transportation significantly affecting the total impact. Although changing the transport type from lorry to railway did not show a significant effect, increasing the transport distance from 100 to 1000 km caused substantial increases in total impact scores for both hydrolyzed and non-hydrolyzed feed ingredients. This suggests that long-distance transportation, especially by road, can greatly contribute to environmental impacts, and efforts to optimize logistics or switch to more sustainable transport modes may offer opportunities for significant reductions in impact.

When it came to the feed production stage, it was observed that sensitivity to the previously mentioned parameters was virtually nonexistent, with the exception of the long transport distance. As noted in Sect. "OP-based animal feed production", this outcome was attributed to the dominant environmental effects of the other feed ingredients. This is primarily due to the greater influence of these ingredients compared to the OP-based ingredient, which constitutes only 10% of the animal feed.

These results suggest several practical implications for the feed industry. Optimizing enzyme usage, transitioning to renewable energy sources, and minimizing transport distances could lead to substantial reductions in the environmental impact of feed production. However, future studies could explore additional parameters, such as raw material sourcing or production efficiency, to provide a more comprehensive understanding of the environmental footprint.

Life Cycle Costing

In every decision-making scenario involving LCA, evaluating the economic implications of alternative products or processes is crucial. However, economic considerations often lie beyond the traditional scope of LCA methodology, requiring a delicate balance between economic factors

Table 6 Purchased equipment costs for the OP-based feed ingredient production (for 1 tonne of feed ingredient production)

Equipment	Non-hydrolyzed				Hydrolyzed			
	# of units	Unit Price, €	Purchased cost for a pilot plant[a], €	Total purchased cost for a full-scale plant[b], €	# of units	Unit Price, €	Purchased cost for a pilot plant[a], €	Total purchased cost for a full-scale plant[b], €
Bioreactor[c]					1	18,000	18,000	
Dryer	1	30,000	30,000		1	30,000	30,000	
Auxiliary (cooling)		–	–		1	26,510	26,510	
Auxiliary (heating)		–	–		1	45,000	45,000	
Automation systems	1	20,000	20,000		1	58,000	58,000	
Total			50,000	**181,195**[d]			177,510	**643,278**[d]

[a]for capacity of 200 kg/d; [b]for capacity of 1000 kg/d; [c]for saccharification and fermentation processes (2m^3)

[d] with a scaling factor of 0.8 $\frac{\mathrm{CAPEX1}}{\mathrm{CAPEX2}} = (\frac{\mathrm{Capacity1}}{\mathrm{Capacity}})^{\mathrm{m}}$ (Arfan et al. [17])

and life cycle performance. When producing a feed ingredient from waste, it is imperative to address not just the environmental impacts of the waste valorization process but also its associated costs. Consequently, an economic analysis was undertaken to compare the costs and benefits of OP waste valorization options, to pinpoint the optimal approach between the two valorization options.

The economic assessment of the OP waste valorization scenarios primarily involves evaluating its CAPEX, OPEX, and environmental costs, in addition to the revenues generated from selling the final animal feed ingredient produced. The estimations for all cost items and the revenues were done for a basis of 1 tonne of feed ingredient production or for a full-scale plant that has a production capacity of 1 tonne of OP-based animal feed ingredient per day.

The direct and indirect CAPEX elements for producing feed ingredients were computed based on the total purchased equipment cost detailed in Table 6. The purchased costs listed in the table reflect the plant's CAPEX required to produce 200 kg/day of OP-based feed ingredient and the total purchased costs are the costs upscaled to the capacity of 1 tonne/day.

Analysis of the cost breakdown reveals that for non-hydrolyzed OP-based feed ingredient production, the dryer constitutes the largest portion of the total purchased equipment costs. Conversely, in hydrolyzed OP-based feed ingredient production, automation costs take precedence. Referring to Table 6, the total purchased equipment cost amounts to €181,195 for non-hydrolyzed production and €643,278 for hydrolyzed production. Correspondingly, the total CAPEX figures stand at €241,593 for non-hydrolyzed production

Table 7 CAPEX for the OP-based feed ingredient production scenarios (for 1 ton of feed ingredient production)

Cost items	% of CAPEX	Non-hydrolyzed €	Hydrolyzed
Direct costs			
Purchased equipment	75	181,195	643,278
Purchased-equipment installation	7	16,912	60,039
Instrumentation	5	12,080	42,885
Piping	5	12,080	42,885
Electrical equipment	3	7,248	25,731
Indirect costs			–
Engineering and supervision	3	7,248	25,731
Start-up expenses	2	4,832	17,154
Total CAPEX	100	241,593	857,704

Table 8 Fixed and variable OPEX for 1 tonne of feed ingredient production

OPEX		Non-hydrolyzed			Hydrolyzed		
Variable OPEX							
Item	Price	Quantity		€/yr	Quantity		€/yr
Electricity	0.15 €/kwh	771	kwh/d	13 876	1397.3	kwh/d	25 151
Water	1 €/m^3	–	–	–	5301.5	kg/d	636
Enzyme	0.39 €/kg	–	–	–	38.6	kg/d	1 791
S. Cerevisiae	1.2 €/kg	–	–	–	3.4	kg/d	487
KH_2PO_4	2 €/kg	–	–	–	51.2	kg/d	12 296
$(NH_4)_2SO_4$	0.68 €/kg	–	–	–	20.5	kg/d	1 672
$MgSO_4$	0.868 €/kg	–	–	–	4.1	kg/d	427
Big bag	5 €/bag	bag/d	4	2 509	4.7	bag/d	2 795
Total				**16 385**			**45 256**
Fixed OPEX							
Labor cost for maintenance and repair	2% of CAPEX			4 832			17 154
Material cost for maintenance and repair	4% of CAPEX			9 664			34 308
Insurance, laboratory, and plant overhead	15% of Labor cost			725			2 573
Total				15 220			**54 035**
Total OPEX				**31 606**			**99 291**

and €857,704 for hydrolyzed production (Table 7). The cash flow analysis conducted on these investments yielded the unit CAPEX as 0.10 and 0.36 €/kg of feed ingredient (Table SI.10).

The OPEX, which may fluctuate annually based on market conditions, primarily consists of the cost items listed in Table 8. As shown, these costs include not only electricity, water, enzymes, and chemicals but also labor, materials for maintenance and repair, insurance, laboratory expenses, plant overhead, and quality control costs. Salaries can vary depending on factors such as the facility's geographic location, plant type, and operational hours. Consequently, labor costs were calculated as a percentage of CAPEX, similar to the costs for maintenance and repair materials, insurance, laboratory, and plant overhead.

Table 8 presents the OPEX costs for the options of hydrolyzed and non-hydrolyzed feed ingredient production for a plant with a capacity of 1 tonne of feed ingredient. As shown, the yearly OPEX for the non-hydrolyzed feed ingredient production is more than three times that for the hydrolyzed feed ingredient production. For both options, the fixed and variable OPEX items account for half of the total OPEX, with the highest cost being for materials used in maintenance and repair. In detail, the OPEX for hydrolyzed feed ingredient production is significantly higher due to increased requirements for maintenance, more frequent repairs, and higher consumption of electricity and chemicals. These higher operational costs are attributable to the specific characteristics of the processes employed for hydrolysis. In contrast, non-hydrolyzed OP-based feed ingredient production benefits from the absence of a hydrolysis process, which reduces the consumption of utilities and lowers maintenance needs, leading to its comparatively lower OPEX.

It is worth mentioning that the geographical location of the facility plays a crucial role in determining salary levels, as labor costs can vary widely based on local wage standards and the availability of skilled workers. The plant type and hours of operation also influence the total labor costs, with more complex or continuous operation plants requiring a larger, more specialized workforce. Understanding these cost components and their variations is essential for making informed decisions about the operational and financial strategies of the facility. By analyzing the detailed breakdown of OPEX, as shown in Table 8, stakeholders can better identify areas for potential cost savings and efficiency improvements.

After discussing the CAPEX and OPEX involved in the production of animal feed ingredient from OP, it is imperative to investigate the environmental costs associated with this process. While CAPEX and OPEX shed light on the financial investments and operational costs required, understanding the environmental costs provides a holistic view of the sustainability implications of such ventures. By analyzing the environmental costs associated with OP-based feed ingredient production, we aim to comprehend the broader environmental implications of this production process, identify opportunities for mitigating negative environmental effects, and underscore the importance of incorporating environmental considerations into the decision-making regarding animal feed ingredient production from OP. Figure 9(a) and (b) present the environmental costs associated with the production of 1 ton of hydrolyzed and non-hydrolyzed OP-based feed ingredient, respectively in comparison to the disposal of the waste OP (The details of environmental costs for hydrolyzed and non-hydrolyzed feed ingredient are provided in Table SI.9). As can be depicted, the environmental cost associated with both hydrolyzed and non-hydrolyzed feed ingredient production is much lower than those of OP composting and landfilling. However, the environmental cost of incinerating waste OP is lower than that of the hydrolyzed and non-hydrolyzed OP-based feed ingredient production across all impact indicators, marking about a 300% reduction for the hydrolyzed case and 200% reduction for the non-hydrolyzed case.

The valorization scenarios for both hydrolyzed and non-hydrolyzed OP-based feed ingredient production enable the creation of revenue through the production of valuable feed ingredients. As seen in Table 9, the net present value of the revenues from selling 1 kg of non-hydrolyzed and hydrolyzed feed ingredient are estimated as 0.28 and 0.44 €, respectively (Table SI.10).

The CAPEX, OPEX, environmental costs, and the revenues calculated are presented in Table 9. All the costs presented in this table including the unit costs presented are as present values (PVs). PV calculations were done with the following assumptions; the discount (interest) rate is 3%, the scrap value is 0% of the purchasing cost, and the life span of the project is 20 years. As can be depicted in Table 9, the PVs of OPEX and CAPEX for the non-hydrolyzed feed ingredient were calculated as 0.36 and 1.85 €/tonne of feed ingredient sold, respectively. The net total cost was found to be 0.09 €/kg and 1.40 €/kg, for the non-hydrolyzed and hydrolyzed feed ingredient, respectively. This suggests that the overall economic burden of producing and selling the non-hydrolyzed feed ingredient is relatively low, making the project financially viable. Both CAPEX and OPEX are manageable within the projected revenues, while also considering environmental costs.

Conclusions

This study employed LCA and LCC methodologies to investigate the environmental and economic sustainability of producing animal feed from waste OP, focusing on two variations: hydrolyzed and non-hydrolyzed feed ingredients. LCC data were derived from pilot-scale experiments

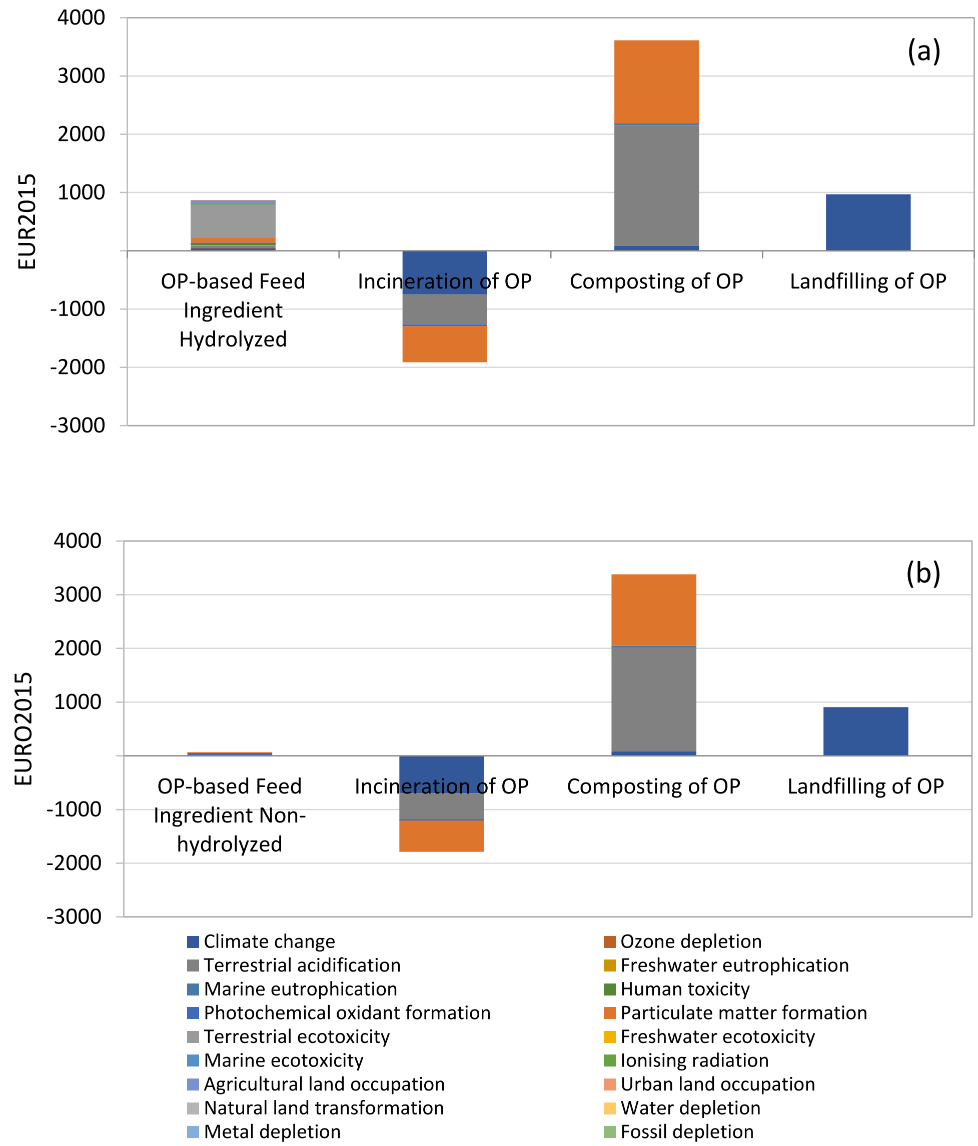


Fig. 9 Environmental costs for 1 tonne of (**a**) hydrolyzed, and (**b**) non-hydrolyzed OP-based feed ingredient

for feed ingredient production and existing literature for animal feed production. Environmental impacts were assessed using the ReCiPe 2016 (H) V1.06, measured per tonne of animal feed at both midpoint and endpoint levels. The results indicated that hydrolyzed or non-hydrolyzed OP-based feed ingredients contribute minimally to overall animal feed production impacts, with a slight 12% increase in human health impacts for the hydrolyzed variant. However, when focusing on the feed ingredient production stage, the saccharification-hydrolysis process used for the hydrolyzed variant significantly increases environmental impacts due to enzyme and electricity consumption, which account for approximately 50% and 35% of the total impacts, respectively. The smaller differences in impacts between hydrolyzed and unhydrolyzed OP-based animal feed production, compared to the feed ingredient production stage, are attributed to the limited presence of OP-based ingredients in the animal diet and the dominant impacts of other feed ingredients.

Sensitivity studies revealed that the environmental impacts were relatively stable, with variations of ± 3 to 12% based on factors of electricity mix type, transportation mode, and electricity consumption. However, transportation distance was found to cause a considerable increase in environmental impacts of feed ingredient production, particularly for non-hydolyzed variant. The Compared to conventional animal feed production and OP waste disposal methods (e.g. incineration, composting, and landfilling), waste valorization reduced environmental impacts, although it did not outperform incineration.

The LCC analysis, including NPV calculation, showed that producing non-hydrolyzed feed ingredient from waste OP is significantly more cost-effective than the hydrolyzed variant, with a net cost was 0.09 €/kg versus 1.40 €/kg for

Table 9 NPV calculations for the production of 1 ton of feed ingredient

Cost items	Non-hydrolyzed feed ingredient	Hydrolyzed feed ingredient
Revenues		
PV, €	666,854	1,066,966
€/kg of feed ingredient sold	0.28	0.44
CAPEX		
PV	241,593	857,704
€/kg of feed ingredient produced	0.10	0.36
OPEX		
PV, €	470,215	1,477,198
€/kg of feed ingredient produced	0.20	0.62
Environmental cost		
Cost, EUR2015	159,630	2,094,326
€/kg of feed ingredient produced	0.07	0.87
Total Cost (PV), €	871,438	4,429,228
Total Annual Cost (PV), €	43,572	221,461
Total Cost (PV), €/kg of feed ingredient produced	0.36	1.85
Net Total Cost as NPV, €	204,584	3,362,262
Cost-effectiveness (€/kg of feed ingredient produced)	**0.09**	**1.40**
Cost-effectiveness (€/kg of OP processed)	**0.01**	**0.15**

the hydrolyzed version. This indicates that the non-hydrolyzed feed ingredient is financially viable, with manageable CAPEX and OPEX.

In conclusion, the study underscores the significance of adopting a holistic approach that integrates both environmental and economic considerations in assessing the sustainability of waste valorization strategies, such as converting OPs into animal feed. While waste valorization offers promising environmental benefits, particularly in comparison to conventional waste disposal methods, economic viability is also crucial for its broader adaptation.

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Data Availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information file. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

Declaration of Generative AI in Scientific Writing The authors used ChatGPT/OpenAI during the preparation of this manuscript to assist with grammar and spelling corrections, as well as improving language clarity and readability. After using this tool/service, the authors thoroughly reviewed and edited the content as necessary, taking full responsibility for the final publication.

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