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Research Article

Assessing Environmental and Economic Sustainability: Valorizing Grape Stems for Animal Feed Production

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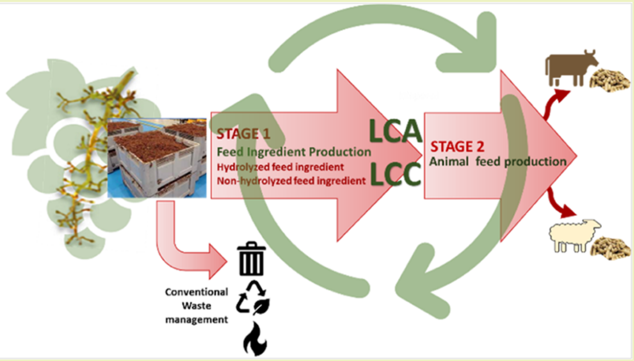

ABSTRACT: This study evaluated an innovative strategy for valorizing grape stems (GS) from the winery industry as an animal feed ingredient from both environmental life-cycle and economic perspectives. Two processes for GS-based feed ingredient production were compared: one using hydrolyzed GS and the other using nonhydrolyzed GS, alongside the conventional animal feed production process. Using primary pilot-scale data for GS-based feed ingredient production and secondary data for animal feed production, life-cycle assessments, and economic analyses were conducted. Results showed that hydrolyzing GS leads to 3.8 times higher impacts on human health compared to the nonhydrolyzed variant, primarily due to NaOH and electricity usage, although this difference becomes negligible at the animal feed production stage. Incorporating GS-based feed ingredients was found to reduce the environmental impacts of animal feeds, primarily due to reductions in other ingredients. Economically, producing nonhydrolyzed GS-based feed ingredient proved more feasible, with a net present value of €-106,766 for a plant with a capacity of 1000 kg/d. GS valorization scenarios yield lower environmental impacts than landfilling and composting, although not compared to incineration, which offers notable energy recovery potential. This study suggests adopting GS valorization in animal husbandry to support a circular economy, providing insights for stakeholders.

KEYWORDS: *LCA, LCC, grape stem byproduct, waste valorization, animal feed*

INTRODUCTION

Wine production is not just a cultural tradition but also a significant economic driver globally, contributing to the agricultural sector and trade. Over recent years, the industry has witnessed stability in production volumes, with the global output remaining at around 260 million hectoliters, according to data from the International Organisation of Vine and Wine.[1] Within the European Union, where winemaking has deep historical roots, production volumes have shown a notable increase, reaching approximately 244.1 million hectoliters in 2023.[2] However, alongside the growth of wine production comes the challenge of waste management, particularly concerning grape stems (GS). GS typically constitutes 5% (w/w) of the grape bunch's total weight,[3] varying based on the grape variety, bunch quality, health, and reach. This byproduct contains abundant phenolic compounds, cellulose, hemicellulose, and lignin and has the potential for reuse in the production of spirits, dietary fiber, vegetable protein concentrates, fertilizers, and animal feed.[4] However, the usual practice involves its disposal, typically through composting or composting in vineyards. This raises concerns about environmental sustainability and calls for innovative solutions to effectively manage agricultural waste.

In response to these challenges, the concept of waste valorization has emerged as a promising approach to address both environmental concerns and resource optimization. Rather than viewing GS as nothing more than waste, there is growing interest in extracting value from them through innovative processes. By implementing principles of the circular economy, efforts are underway to convert GS into useful resources, thereby reducing waste and promoting sustainability within the winemaking industry. The possible application of GS as animal feed is one area of particular interest in the valuation of GS. With the livestock sector increasingly focused on sustainability and cost-effectiveness, GS presents an attractive option as a feed ingredient. GSs, which are rich in nutrients and bioactive compounds,[5] can potentially enhance the nutritional profile of animal feed formulations.[6] Moreover, by repurposing GS as feed, we can not only reduce waste in winemaking but also contribute to the

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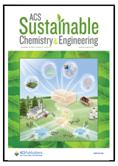


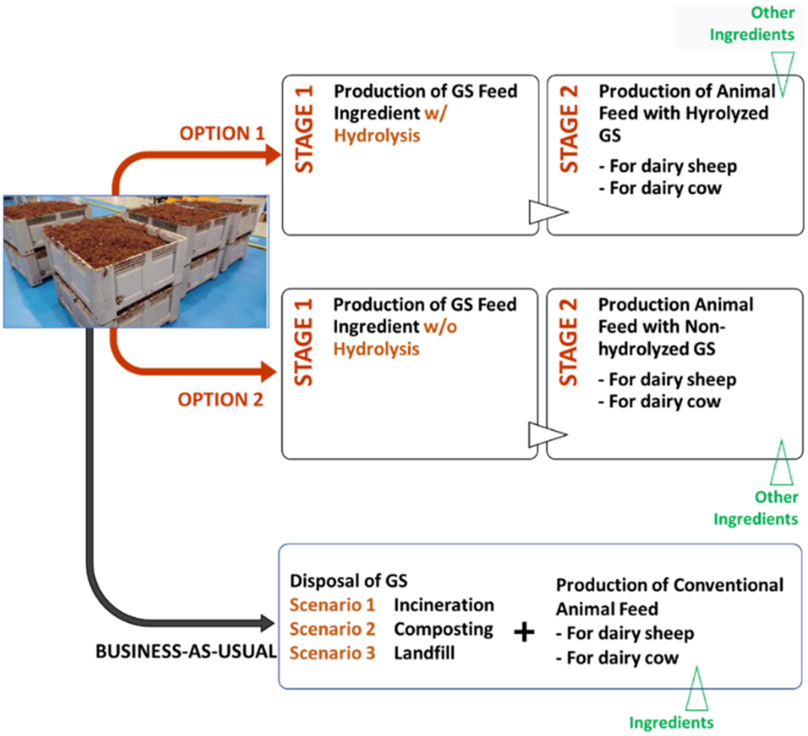


Figure 1. Approach in the LCA study for animal feed from GS.

development of a circular agricultural economy.[7] In this context, two innovative waste valorization processes have been recently developed in the NEEWFEED Project;[8] one involves hydrolysis of GS, the other without it, both converting GS into high-value secondary feed.[2] According to San Martin et al.,[2] hydrolysis with alkaline chemicals improves the in vitro digestibility of GS by breaking down its lignocellulosic bonds into smaller, more digestible fragments. This process also improves polyphenol concentrations and the antioxidant capacity of the ingredient, which finally implies an increase in the utilization of the nutrients of the ingredient by the animal. However, the environmental and economic implications of implementing these circular strategies, whether or not hydrolysis is involved, are still uncertain. It is crucial to ensure that new processes aimed at implementing circular strategies effectively minimize the adverse environmental and economic impacts.[9] Additionally, it is important to evaluate whether the benefits of hydrolysis justify the process considering the economic and environmental impacts of the additional process steps required for its implementation. This assessment will help determine if the overall benefits outweigh the economic and environmental costs, ensuring that the process is both economically and environmentally viable.

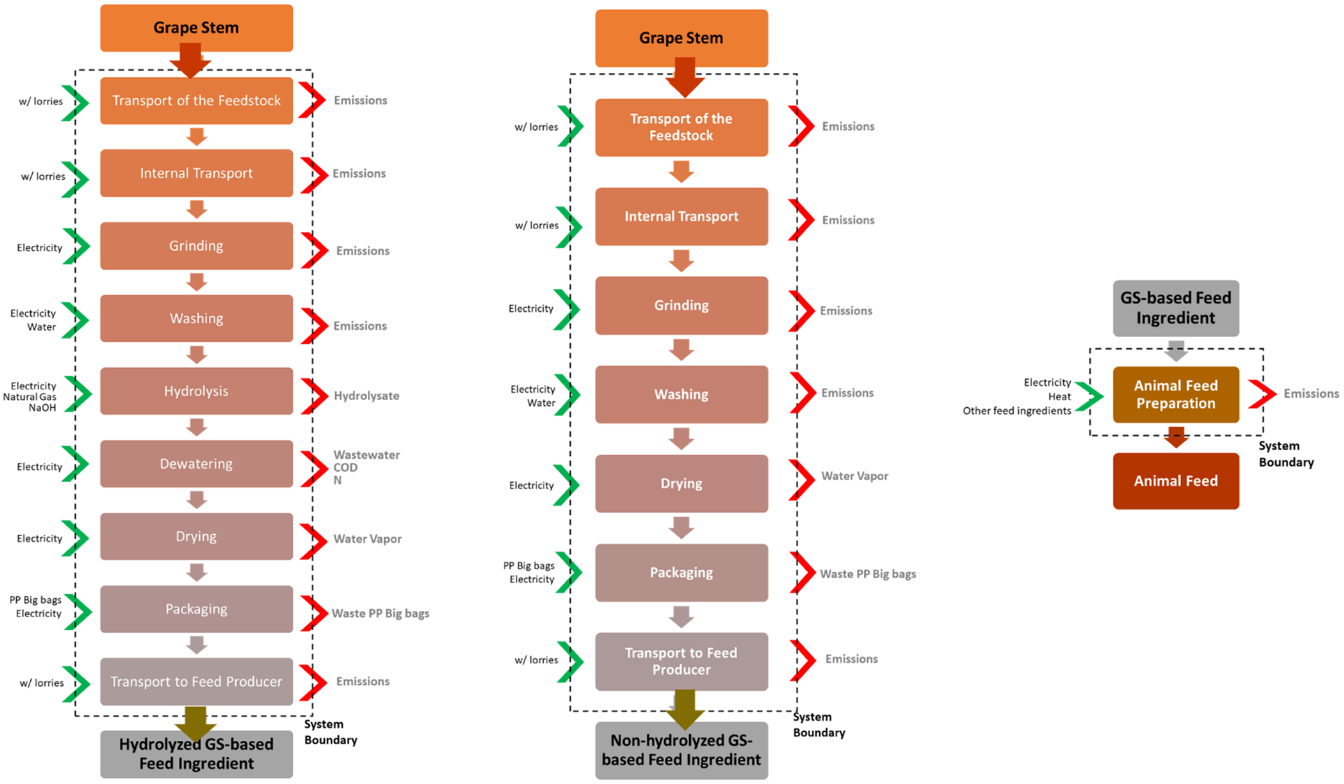
This study aims to examine the environmental impact of producing animal feed from GS with (hydrolyzed GS-based feed ingredient) and without alkali hydrolysis (nonhydrolyzed GS-based feed ingredient) and assess whether this approach is both economically viable and environmentally sound, using consequential life-cycle assessment (LCA) and life-cycle costing (LCC) methodologies. Consequential LCA is used to rigorously assess the environmental impact of valorizing GS as opposed to its disposal. The cradle-to-gate LCA modeling aims to pinpoint key stages and parameters contributing to environmental impacts, while the LCC analysis aims to provide a comprehensive understanding of the economic feasibility of these processes.

The scope of the LCA encompasses the production of GS-based animal feed ingredients and the subsequent manufacturing of feed for dairy cows and sheep. Additionally, comparisons are made with conventional animal feed production for both dairy cows and sheep as well as various GS disposal methods such as incineration, composting, and landfilling. This dual analysis evaluates the sustainability of valorization strategies from both environmental and economic perspectives within the framework of a circular economy. Data sources include pilot-scale experiments for GS-based feed ingredient production and the literature on animal feed production and GS disposal. The LCC study assesses capital expenditures (CAPEX), operational expenditures (OPEX), environmental costs associated with GS-based feed ingredient production, and projected revenues from feed ingredient and byproduct sales. Notably, it does not consider animal feed production costs due to inadequate cost data for other feed ingredients used in dairy cow and sheep diets. Ultimately, this research aims to provide valuable insights into the development of sustainable feed production practices in the livestock industry, advancing principles of the circular economy.

■ MATERIALS AND METHODS

LCA. The environmental impact assessment methodology adhered to the standard LCA procedure outlined in international guidelines (ISO 14040[10] and ISO 14044[11]) using SimaPro software (9.3.0.3). This standard approach involves four steps: defining goals and boundaries, collecting data on resource use and emissions to develop an inventory, and evaluating and interpreting the impacts.

Goal and Scope Definition. The LCA functional unit (FU) is defined as 1000 kg of animal feed. This aligns with the capacity of equipment used for processing GS into feed ingredients, which is typically rated in tons per hour or day. This approach ensures that the assessment is relevant to industry standards.



(a) (b) (c)

Figure 2. Process flowchart for the production of (a) hydrolyzed GS-based feed ingredient, (b) nonhydrolyzed GS-based feed ingredient, and (c) animal feed (dotted lines represent system boundaries).

Two waste valorization options, each containing two stages, were examined: in the first stage, the production of hydrolyzed and nonhydrolyzed GS-based feed ingredients, and in the second stage, the production of animal feed for dairy sheep and dairy cows utilizing the produced GS-based feed ingredient. Additionally, for comparison with the current situation, three business-as-usual scenarios were created and analyzed where the GS waste is disposed of instead of valorized, and conventional animal feeds for both dairy sheep and dairy cows are produced (Figure 1).

The system boundary encompasses the “cradle-to-gate” stages for both the animal feed ingredient and animal feed production, starting from the transport of GS to the plant, as well as all of the associated inputs and outputs. It is important to note that upstream processes related to grape and wine production, which generate waste GS, are excluded from the assessment. This exclusion, which aligns with the requirements of a consequential LCA, aims to focus on evaluating the benefits and trade-offs of converting waste GS into secondary feed compared to business-as-usual scenarios. By concentrating on the valorization of waste GS, we streamlined the assessment to address the specific impacts of this process. This approach enables a more focused and manageable analysis, ensuring that the LCA aligns with its intended goals and provides clear insights into the environmental implications of waste GS valorization.

Process flow diagrams as well as system boundaries for converting waste GS into hydrolyzed (Option 1) and nonhydrolyzed (Option 2) GS-based feed ingredient are illustrated in Figure 2a,2b, respectively. Figure 2c presents the system boundary for the production of animal feed. As shown, the production process for both hydrolyzed and nonhydrolyzed GS feed ingredients begins with grinding and washing. Washing is essential to reduce the sugar content of GS, which can cause problems during the drying phase due to sugar melting at high temperatures. This sugar content arises from residual grapes that were not removed during destemming. For the hydrolyzed GS-based feed ingredient, washing is followed by hydrolysis to enhance digestibility. GS is high in lignin, which restricts microbial enzymatic access to cellulose and hemicellulose, potentially affecting digestibility. In the NEWFEED Project, alkaline hydrolysis was tested and found to enhance the fiber digestibility. This process uses NaOH to break down lignin molecules, producing fragments and a neutral liquid known as a hydrolysate or effluent. The subsequent step for both hydrolyzed and nonhydrolyzed GS is drying, which reduces moisture content to prevent microbial deterioration and ensure sufficient shelf life to be incorporated into feed for animal consumption.[2]

Inventory Analysis. Table 1 details the resources used to produce the GS-based feed ingredient as well as the relevant emissions. As shown, it breaks down the process from bringing GS to the plant, processing them into the GS-based feed ingredient, and finally packaging and transporting the finished product to the animal feed production facility. Most of the inventory data comes directly from the pilot study performed for the production of both hydrolyzed and nonhydrolyzed feed ingredients, except for the packaging and final transport. For those last steps, common industry practices were used to estimate the resource needs.

The feed ingredients used in developing the relevant LCA models for Stage 2 are listed in Table 2. For all feed ingredients other than GS-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 were 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 Tables S1 and S2, available in the Supporting Information. To ensure consistency and ease of comparison, priority was given to units based on “market” units rather than those involving processing at a plant, as found in the databases. “Market” units include both the production of the ingredient at the plant and its transportation to the animal feed production facility. The feed preparation process covers all steps in animal feed production, such as crushing, blending, pelletizing,

Table 1. Inventory Data for the Production of the GS-Based Feed Ingredient (Stage 1) (for FU of "One Ton of Animal Feed Produced")

activity #	activity	Option 1 hydrolyzed GS-based feed ingredient production		Option 2 nonhydrolyzed GS-based feed ingredient production	
1	transportation to the plant in a lorry 32 t EURO6 * 100 km				
		GS	357 kg	GS	295.2 kg
2	internal transportation in a lorry 3.5–7.5 t EURO6 * 0.5 km				
		GS	357 kg	GS	295.2 kg
3	grinding (Comitrol 3640°)				
	inputs	GS	357 kg	GS	295.2 kg
		electricity	4.06 kWh	electricity	3.36 kWh
	outputs	ground GS	357 kg	ground GS	295.2 kg
		solids in the ground GS	110.7 kg	*solids in the ground GS*	91.5 kg
4	washing (ISHER Model UPF-200)				
	inputs	ground GS	357 kg	ground GS	295.2 kg
		tap water	357 L	tap water	295.2 L
		electricity	0.61 kWh	electricity	0.5 kWh
	outputs	washed GS	439 kg	washed GS	363 kg
		liquor	279 L	liquor	230 L
5	hydrolysis (Inoxtorres Ø2.3 × 3 m (13 m^3))				
	inputs	washed GS	439 kg		
		tap water	549 L		
		electricity	2.2 kWh		
		NaOH (0.5%) 1:1.25 ratio	3.29 kg		
	outputs	hydrolyzed GS	992 kg		
6	dewatering (Filter Centrifuge - FINISHER Model UPF-200)				
	inputs	hydrolyzed GS	992 kg		
		electricity	0.61 kWh		
	outputs	dewatered hydrolyzed GS	321 kg		
		liquor (wastewater)	671 kg		
7	drying (Flash Dryer - RINA JET - S-2824)				
	inputs	dewatered hydrolyzed GS	321 kg	washed GS	363 kg
		electricity	22.8 kWh	biomass energy	18.8 kWh
	outputs	dried hydrolyzed GS	100 kg	dried GS	100 kg
		solids in dried hydrolyzed GS	90 kg	*solids in dried GS*	90 kg
		dry matter content	90%	*dry matter content*	90%
		water evaporated	221 kg	water evaporated	263 kg
8	packaging				
	inputs	dried hydrolyzed GS feed ingredient	100 kg	dried GS feed ingredient	100 kg
		electricity	0.016 kWh		0.016 kWh
		number of big bags used	2	number of big bags used	2
		mass of big bags used	0.47 kg	mass of big bags used	0.47 kg
		big bag carry capacity	50 kg/bag	big bag carry capacity	50 kg/bag
		vig bag empty weight	0.233 kg/bag	big bag empty weight	0.233 kg/bag
	outputs	GS feed ingredient packed	100 kg	GS feed ingredient packed	100 kg
		waste big bags (10%)	0.05 kg	waste big bags (10%)	0.05 kg
	big bag production (for 100 big bags) (adopted from Ruban)[12]				
	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	3.2619×10^{-5} kg	CH_4	3.2619×10^{-5} kg
		NO_2	0.0041 kg	NO_2	0.0041 kg

Table 1. continued

activity #	activity	Option 1 hydrolyzed GS-based feed ingredient production		Option 2 nonhydrolyzed GS-based feed ingredient production	
		soot	0.0005 kg	soot	0.0005 kg
		NO	1.5657×10^{-5} kg	NO	1.5657×10^{-5} kg
		CO_2	0.40944 kg	CO_2	0.40944 kg
		benzo(a)pyrene	3.9143×10^{-6} kg	benzo(a)pyrene	3.9143×10^{-6} kg
		SO_2	0.0005 kg	SO_2	0.0005 kg
10	transport to feed producer				
	inputs	GS feed ingredient packed	100 kg	GS feed ingredient packed	100 kg
		distance	100 km	distance	100 km
	outputs	GS feed ingredient packed	100 kg	GS feed ingredient packed	100 kg

Table 2. Inventory Data for the Production of Dairy Cow and Sheep Feed (Stage 2) (for FU of "1000 kg of Animal Feed Produced")

		animal feed production with GS-based feed ingredient		conventional animal feed production	
	item	hydrolyzed	nonhydrolyzed	dairy sheep feed	dairy cow feed
		Dairy Cow Feed Preparation			
inputs	maize	370 kg	370 kg		342 kg
	soybean meal	287 kg	287 kg		251 kg
	palm kernel meal	80 kg	80 kg		150 kg
	wheat middlings	40 kg	40 kg		144 kg
	rapeseed meal	30 kg	30 kg		20 kg
	sunflower meal	10 kg	10 kg		11 kg
	fat salts	29 kg	29 kg		29 kg
	molasses	20 kg	20 kg		20 kg
	calcium carbonate	17 kg	17 kg		17 kg
	sodium bicarbonate	11 kg	11 kg		11 kg
	sodium chloride	2 kg	2 kg		2 kg
	vitamin & minerals	3 kg	3 kg		3 kg
	GS-based feed ingredient	100 kg	100 kg		0 kg
	heat	315 MJ	315 MJ		315 MJ
	electricity	135 MJ	135 MJ		135 MJ
output	packed animal feed	1000 kg	1000 kg		1000 kg
		Dairy Sheep Feed Preparation			
inputs	barley grain	190 kg	190 kg	50 kg	
	oats	240 kg	240 kg	530 kg	
	maize	150 kg	150 kg	100 kg	
	distiller dried grain	50 kg	50 kg	0 kg	
	rapeseed meal	160 kg	160 kg	210 kg	
	rapeseed oil	50 kg	50 kg	50 kg	
	molasses	30 kg	30 kg	30 kg	
	vitamin & minerals	30 kg	30 kg	30 kg	
	GS-based feed ingredient	100 kg	100 kg	0 kg	
	heat	314.9 MJ	314.9 MJ	314.9 MJ	
	electricity	135.1 MJ	135.1 MJ	135.1 MJ	
output	packed animal feed	1000 kg	1000 kg	1000 kg	

cooling and packaging, and therefore, all of the impacts associated with all inputs and outputs.

Assumptions made throughout the LCA study, along with their respective sources (where applicable), are presented in Table 3.

Impact Assessment. The impact assessment method is ReCiPe 2016 (H) (V1.06). This method employs a combined midpoint/end-point approach, linking impacts on 17 midpoint impact categories to three damage categories, which encompass all stages of assessment: characterization, damage assessment, normalization, weighting, and single score.[13] Table S3 in the Supporting Information lists the specific midpoint impact categories considered, while the end-point categories encompass human health, ecosystems and resources. The approach followed in converting normalized impact scores to single scores and the weighting factors used are given in S1 and Table S4, respectively.

Interpretation. In the interpretation stage of LCA, which marks the conclusive phase of the assessment process, the collected impact data undergo rigorous analysis and evaluation to derive meaningful conclusions regarding the environment. This step involves converting the life-cycle impacts obtained from the previous stages into a set of indicators that represent various impact categories. These indicators are then normalized and aggregated to facilitate the comparison and synthesis of results. Adhering to ISO 14040 standards, normalized and singular scores are utilized in assessing the results. This phase encompasses the following steps: (i) selection of impact categories, category indicators, and characterization models, (ii) classification, and (iii) characterization. To analyze the results, both single score and

Table 3. Assumptions Considered and Their Sources[a]

process/unit	assumption	source
	Stage 1	
cultivation of grape	cradle-to-gate impacts of grape cultivation are excluded as GS is a waste but not cultivated on purpose to produce animal feed ingredient	
transport of the feedstock to the plant	transport, freight, lorry >32 tonne, euro6 {RER} | market for transport, Conseq, S	Ecoinvent 3
	distance: 100 km	
unloading and intermediate storage of the feedstock in the plant	negligible impact	
internal transport	transport, freight, lorry 3.5−7.5 tonne, euro3 {RER} | market for transport, Conseq, S	Ecoinvent 3
	distance: 0.5 km	
grinding, washing, hydrolysis, dewatering, packaging	electricity, medium voltage {RER} | market group for Conseq, S	Ecoinvent 3
grinding	no loss of feedstock during grinding	
washing	tap water is used (tap water {Europe without Switzerland} | market for | Conseq, S)	Ecoinvent 3
	liquor from the process will be used for bioethanol production; hence considered an avoided product. The bioethanol production yield is 10.12 g of bioethanol/L of liquor	
dewatering	liquor from the dewatering process will be sent to the wastewater treatment plant	
drying	the bag filters of the drying equipment ensure that all dusts are recovered	
packaging	a big bag's 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	Ruban[12]
	electricity used during filling: 0.008 kWh/bag	FlowMatic 08 (n.d)
	10% big bag waste	
transport to animal feed producer	transport, freight, lorry >32 metric tonne, euro6 {RER} | market for transport, Conseq, S	Ecoinvent 3
	distance: 100 km	
	Stage 2	
electricity	adopted from animal feed processing (i.e., for 0.93 kg feed 0.293 MJ electricity mix). This consumption includes electricity use for packaging as well	Agri-footprint 5
heat	adopted from animal feed processing (i.e., for 0.94 kg feed 0.127 MJ heat from residential heating system)	Agri-footprint 5
	Current Disposal Practice for Feedstocks	
end of life for feedstocks	− waste treatment, composting of food waste, EU27	Ecoinvent 3
	− waste treatment, incineration of waste, food, EU27	
	− waste treatment, landfill of waste, food, EU27	
end of life for feedstocks	the transportation distance from the place where GS waste is generated to the waste treatment point is 100 km and the transportation is by a lorry	

[a] RER: Regional Environmental Reference; European area.

midpoint results were used. Table S3 provides midpoint-to-end-point factors and normalization factors for end-point impact categories, as well as weighting factors for converting end-point impacts into a single score.

Sensitivity Analysis. A sensitivity analysis was conducted to understand how various input parameters of electricity mix type, transport type, electricity consumption, and transportation distance affect LCA outcomes (Table 4). By analyzing how adjustments in these parameters can impact the overall results of LCA, we gained insights into their impact on results. Additionally, we explored the sensitivity of the total impacts to the most influential parameters affecting the environmental impacts of GS-based feed ingredient production. For each parameter, alongside its default value, one or two alternative options were defined to quantify inherent uncertainties.

Table 4. Base and Alternative Scenarios Considered for Sensitivity Analysis of the Environmental Impacts of Hydrolyzed GS-Based Feed Ingredient Production

parameter	base scenario	scenarios
electricity mix type	European Electricity Mix (RER)	European Electricity Grid Mix (GRIDM)
transport type for transporting the feedstock to the plant	freight transport in a lorry of the size class >32 tonne	freight transport in European train
electricity consumption	30.3 kWh/FU	10% increase
		10% decrease
transportation distance for transporting the feedstock to the plant	100 km	150 km
		1000 km
most influencing parameter	3.29 kg of NaOH/FU	10% increase
		10% decrease

LCC. A comprehensive LCC analysis was conducted for both hydrolyzed and nonhydrolyzed GS-based feed ingredients to evaluate the economic viability of the proposed value chain and provide valuable insights into its feasibility and potential adoption within the livestock sector. The analysis primarily focused on determining the net present value (NPV) of the cost of the GS-based feed ingredient production, a critical financial metric used to gauge the financial profitability and long-term viability of investment projects.[14] The analysis considered both CAPEX and OPEX as cost items, while revenue from selling the feed ingredient product to animal feed producers and the liquor generated from the washing steps of production of both hydrolyzed and nonhydrolyzed GS for bioethanol production were included as revenues. Additionally, an environmental cost analysis was performed to complement the financial assessment. This aspect of the evaluation quantifies environmental impacts in monetary terms, encompassing both the costs associated with environmental damage and the benefits of environmental restorative actions, such as climate change mitigation and nutrient recovery initiatives.

The NPV, encompassing the environmental costs, was calculated using the formula

Table 5. Midpoint Characterization Results for the Production of GS-Based Feed Ingredient

midpoint impact category	symbol	unit	nonhydrolyzed GS-based feed ingredient	hydrolyzed GS-based feed ingredient
global warming	GW	kg CO_2 eq	7.38	14.90
stratospheric ozone depletion	SOD	kg CFC11 eq	-2.41×10^{-05}	-2.67×10^{-05}
ionizing radiation	IR	kBq Co-60 eq	0.76	1.01
ozone formation, human health	OF-HH	kg NOx eq	0.228	0.275
fine particulate matter formation	FPF	kg PM2.5 eq	0.00499	0.0397
ozone formation, terrestrial ecosystems	OF- TE	kg NOx eq	0.359	0.423
terrestrial acidification	TA	kg SO_2 eq	−0.0051	0.0462
freshwater eutrophication	FE	kg P eq	0.00622	0.0205
marine eutrophication	ME	kg N eq	−0.00582	−0.00272
terrestrial ecotoxicity	TE	kg 1,4-DCP	87.7	151.0
freshwater ecotoxicity	FET	kg 1,4-DCP	0.254	0.880
marine ecotoxicity	MET	kg 1,4-DCP	0.375	1.220
human carcinogenic toxicity	HCT	kg 1,4-DCP	0.205	0.883
human noncarcinogenic toxicity	HNCT	kg 1,4-DCP	4.0	23.6
land use	LU	m^2 a crop eq	−0.63	1.39
mineral resource scarcity	MRS	kg Cu eq	0.0069	0.0243
fossil resource scarcity	FRS	kg oil eq	1.99	3.48
water consumption	WC	m^3	0.1790	−0.0744

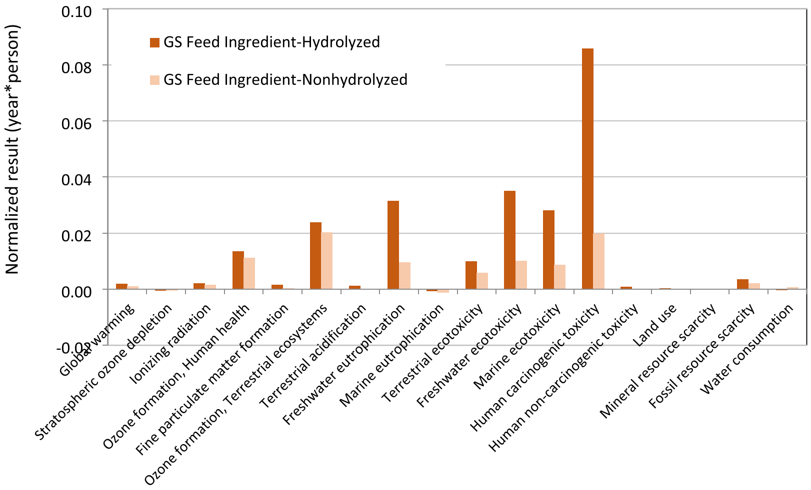


Figure 3. Normalized impacts of the hydrolyzed GS-based feed ingredient and nonhydrolyzed GS-based feed ingredient.

$$\mathrm{NPV} = \sum_{t=0}^{n} \left(\frac{\mathrm{CAPEX} + \mathrm{OPEX} - \mathrm{revenues}}{(1+r)^n} + \mathrm{environmental\ cost} \right) \tag{1}$$

where

n: life span of the plant

r: discount rate

A discount rate of 3% was utilized to discount all future cash flows of an investment, thereby determining its NPV. The operational life span of the feed ingredient production system from GS was set at 20 years.

Estimating CAPEX involves a comprehensive assessment of both direct and indirect cost components, each calculated as a percentage of the total CAPEX, as detailed in S2 and Table S5 in the Supporting Information. Direct costs encompass expenses related to equipment procurement, installation, instrumentation, piping, and electrical equipment. The costs of purchased equipment were sourced from equipment suppliers (Table S6). Since the data for purchased equipment costs pertained to higher capacities, a scaling factor was applied to adjust for the transition from these production capacities to the production capacity of 1000 kg/day of feed ingredient, by applying the "0.6 Rule", which originates from the relationship between equipment cost and capacity increase.[15]

$$\frac{\cos t_2}{\cos t_1} = \left(\frac{\mathrm{size}_2}{\mathrm{size}_1} \right)^m \tag{2}$$

where m is the scaling factor.

Tribe & Alpine[15] explained that m may vary depending on the technology nature and ranges between 0.5 and 1. In this study, to comprehensively represent the entire plant, a value of 0.8 was adopted.[16] Additional CAPEX considerations such as land procurement, architectural planning, and building construction were not factored into the CAPEX calculations as these are highly case-dependent.[17]

The approach utilized to calculate the OPEX involves utilizing unit prices (Table S7) for variable costs, while fixed costs are determined as a specific percentage of CAPEX (Table S8). For the calculation of variable OPEX, annual production of GS-based feed ingredient totaling 90,000 kg/year with 90 operational days per year was assumed. Conversely, fixed OPEX, which denotes expenditures such as labor, repair and maintenance, and laboratory expenses, is assigned based on the specified percentages. OPEX during the construction year is regarded as zero.

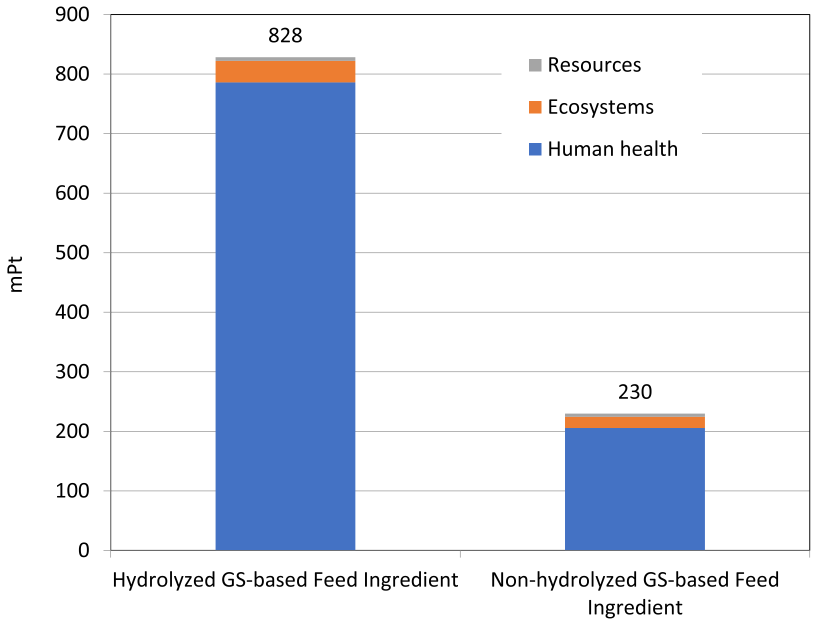


Figure 4. Comparison of hydrolyzed and nonhydrolyzed GS-based feed ingredients as single scores.

Revenues are calculated based on sales from both the feed ingredient product to animal feed producers and the liquor obtained during the washing of GS to bioethanol producers (Table S9).

The environmental costs are calculated based on environmental prices for the social cost or pollution, expressed in €/kg pollutant using SimaPro (9.3.0.3) software. These prices cover both the economic loss of well-being that occurs when one additional kilogram of the pollutant finds its way into the environment and the cost of measures to mitigate it.[18] To calculate the environmental cost, the method of Environmental Prices V1.02/European Environmental Prices (2015) was used. This method expresses environmental impacts in monetary units, based on midpoint-level environmental prices, meaning that the values of environmental themes are used as a weighting set. The absolute values of the midpoint impacts are multiplied by their respective environmental unit price, based on EU28 emissions in 2015. Table S10 presents the midpoint impact categories and their respective environmental unit prices.

RESULTS AND DISCUSSION

Life-Cycle Impacts of the GS-Based Feed Ingredient Production. The midpoint environmental impacts of producing 100 kg of GS-based feed ingredient, which is used for producing 1000 kg of animal feed (FU), are presented in Table 5 for hydrolyzed and nonhydrolyzed variants. In Figure 3, these impacts are represented as normalized values. It is evident that there is a significant increase in the environmental impact with the hydrolysis of GS, particularly noticeable in the human carcinogenic toxicity (HCT) and freshwater ecotoxicity (FET) categories. Specifically, in HCT, the impact increases from 0.205 to 0.883 kg 1,4-DCP, and in FET, it increases from 0.254 to 0.880 kg 1,4-DCP when GS is hydrolyzed (Table 5).

On the other hand, the impact on water consumption (WC) shows a reverse trend. As illustrated in Table 5, the impact decreases from 0.1790 to −0.0744 m^3 when GS is hydrolyzed. This reduction is primarily due to the higher volume of water lost to evaporation during the drying process for nonhydrolyzed GS as compared to the hydrolyzed variant (318 and 221 m^3, respectively) as shown in Table 1. Additionally, although more tap water (549 m^3 more) is used during the hydrolysis process for hydrolyzed GS, wastewater is discharged after dewatering (671 m^3) (Table 1), thus returning to the environment.

A contribution analysis conducted on these two impact categories showed that the utilization of NaOH in the hydrolysis process is the most influential parameter, with a share of about 87% in total impacts exerted on the HCT category (Figure S1 in the Supporting Information). The significant impact of NaOH on the HCT category is attributed to the release of various harmful compounds including heavy metals and organochlorine compounds into the environment from the caustic soda industry, posing serious health risks to humans.[19] The second-highest contributor is electricity used in the hydrolysis process. Indeed, electricity use not only contributes to the HCT category but also many of the midpoint impact categories.[19]

In the case of nonhydrolyzed GS, although the highest environmental impacts are lower than those of hydrolyzed GS, they are observed primarily in ozone formation in the OF-TE and HCT categories (Figure S1). Specifically, the impact in the OF-TE category is 0.423 kg NO_x eq, while in the HCT category, it is 0.205 kg 1,4-DCP (Table 5). The most influential parameter was identified as electricity (obtained from biomass), contributing 25 and 78% to the impacts in the HCT and OF-TE categories, respectively (Figure S2a,b).

Figure 4 provides a comparison of the single score end-point impacts for hydrolyzed and nonhydrolyzed GS-based ingredient production options (The unit mPt denotes one-millionth of the annual environmental impact caused by the average European person). Evaluating end-point impacts is crucial as it interprets the midpoint environmental flows in terms of overall significance.[20] This figure reveals a significant increase in the magnitude of human health impacts when waste GS is hydrolyzed. Specifically, the human health impacts associated with hydrolyzed GS-based feed ingredient are 3.8 times greater than those of the nonhydrolyzed variant. Furthermore, ecosystem impacts are 1.9 times higher for the hydrolyzed ingredient, whereas impacts on resources remain nearly unchanged. As indicated above, the drastic increase in the

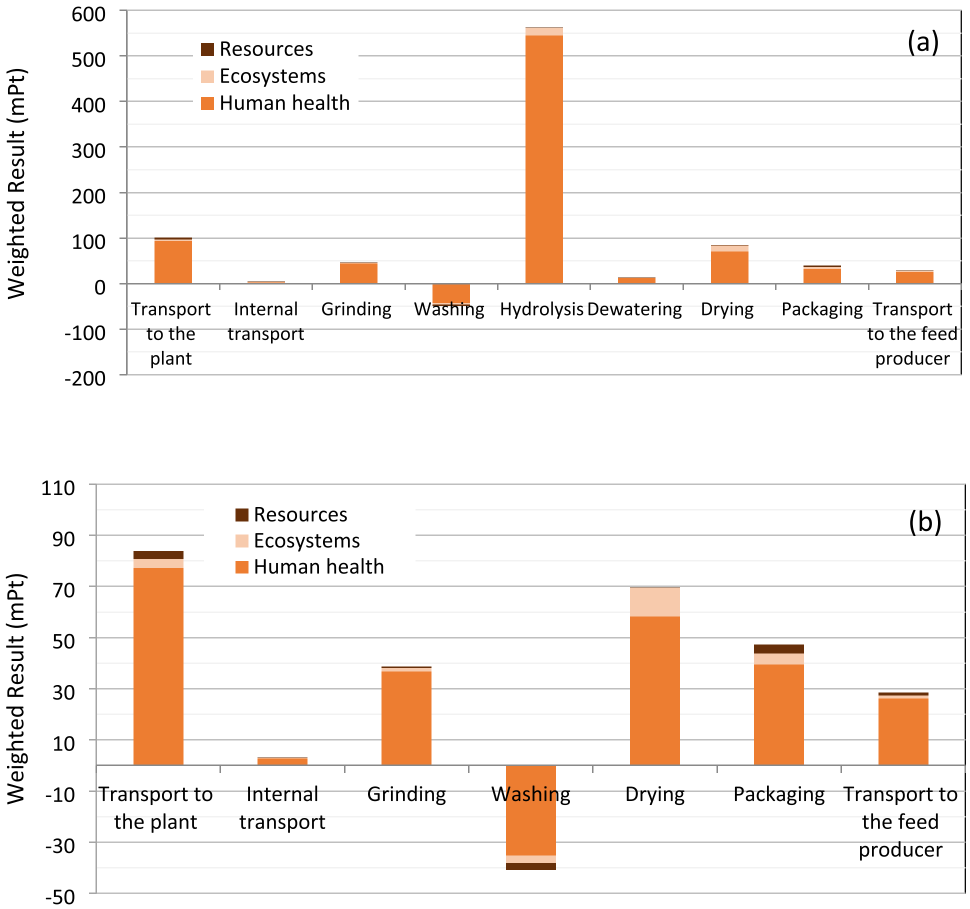


Figure 5. Process contribution to the single score impacts of 1000 kg of (a) hydrolyzed and (b) nonhydrolyzed GS-based feed ingredient production.

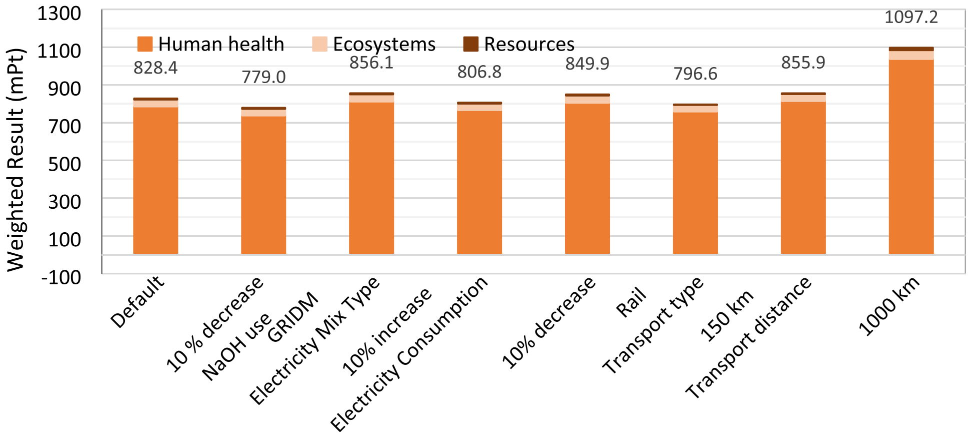


Figure 6. Sensitivity analysis for hydrolyzed GS-based feed ingredient production (default: NaOH use, 3.29 kg/FU; electricity mix type, RER; electricity consumption, 30.3 kWh/FU; transport type, lorry; transport distance, 100 km).

human health impacts of the hydrolysis of GS is due to the use of NaOH in the process.

Figure 5 presents the contributions of different process steps to the end-point impacts. As depicted, for the production of hydrolyzed feed ingredient, the most significant impact is in the human health category, scoring 545.2 mPt, attributed to the hydrolysis process and the associated use of NaOH. Aromaa et al.[21] noted that the production of caustic soda has a considerable human health and environmental effects on nearly all impact categories, with particularly high impacts in the HTP category. Hong et al.[19] highlighted that the electricity and diesel consumption involved in caustic soda production significantly contribute to these impacts, mainly due to the energy-intensive electrolysis process and chlorinated emissions (Takasuga et al.).[22] The second-highest contributor is the transportation of GS to the plant with a 93.7 mPt single score. In contrast, for the production of nonhydrolyzed feed ingredient, transportation to the plant emerges as the primary cause of environmental impact, particularly affecting human health with a score of 77.4 mPt. Chapa et al.[23] indicated that

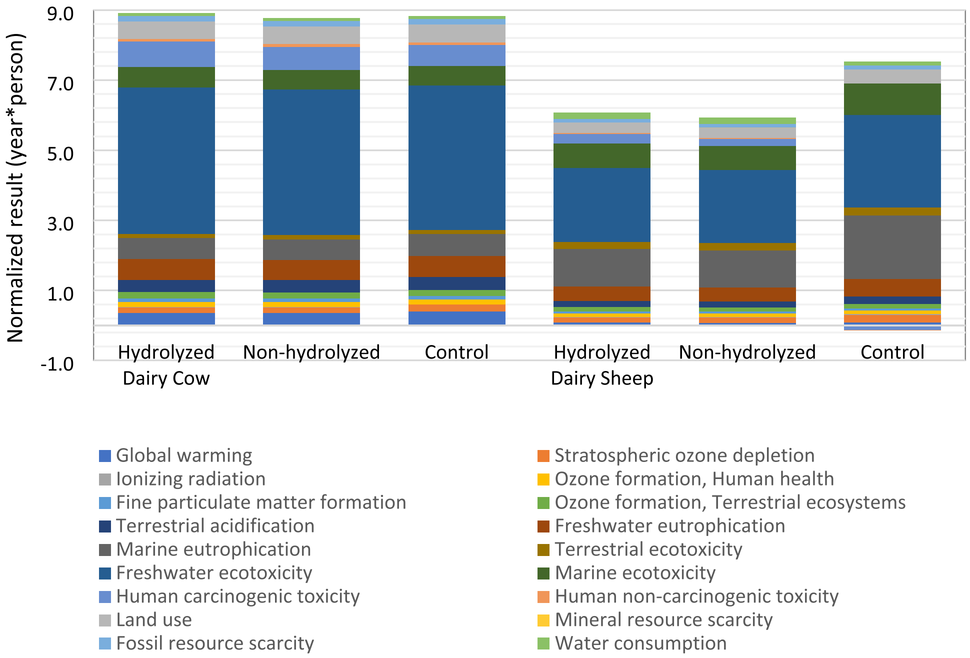


Figure 7. Normalized midpoint impacts of dairy cow and dairy sheep meals.

the human health impacts from transportation mainly stem from emissions of respiratory organics and inorganics.[23] The second largest contributor to the impacts of the nonhydrolyzed feed ingredient production is the drying process, accounting for 58.3 mPt due to electricity consumption.

On the other hand, the washing step positively influences environmental impacts, with a more pronounced effect observed in the hydrolyzed variant. For human health, the single score of the hydrolyzed variant is −42.8 mPt, which is approximately 1.2 times higher than the −35.4 mPt value of the nonhydrolyzed case. This positive contribution is attributed to the use of liquor from the washing process for bioethanol production, which is considered to be an avoided product. Consequently, the greater amount of liquor produced during the washing of the hydrolyzed ingredient results in a more significant positive contribution.

A sensitivity analysis was conducted to evaluate the reliability of the LCA results for the hydrolyzed GS-based feed ingredient, emphasizing the influence of the primary data and key assumptions. This evaluation was particularly deemed necessary considering the higher impacts observed with the hydrolyzed variant. Sensitivity analyses are seen as crucial in LCA studies to ensure robustness.[24,25] Factors, such as NaOH consumption, transportation distance, electricity mix type, and electricity consumption, as well as the transport type, were systematically varied. Figure 6 illustrates the outcomes, detailing their impacts on single scores. The analysis revealed significant findings: a 10% reduction in the amount of NaOH used led to a 6% decrease in the total impacts. Shifting from RER to GRIDM increased the single-score impacts by 3.3%. Variations of ±10% in electricity consumption resulted in an ±2.6% deviation in impacts. Using rail transport instead of lorry transport reduced end-point impacts by 3.8%. Importantly, increasing transportation distance from 100 to 1000 km escalated single score impacts by 32.4%. These results underscore the high sensitivity of impacts to the transportation distance. Our finding regarding the sensitivity of environmental impacts to the transportation distance for the waste to be processed is consistent with Siddique et al.,[26] who emphasized the importance of strategically locating food waste valorization facilities to minimize transit distances from food waste sources. While increasing transportation distances may be necessary for larger plants to achieve economies of scale, it can lead to higher logistical costs and greater environmental impacts, which may offset some of the benefits of scaling. Therefore, determining the optimal plant size involves balancing the advantages of scaling with the logistical challenges associated with transportation distances. For decision-makers, this balance is crucial in ensuring that the benefits of scaling are not undermined by increased logistical costs and environmental impacts. Making informed choices about plant size and location can help optimize overall sustainability and cost-effectiveness, aligning operational goals with environmental and economic considerations.

Life-Cycle Impacts of the GS Animal Feed Production. At the core of understanding, the environmental impact of developed GS-based feed ingredient production lies the crucial question of its contribution to overall environmental effects. Specifically, our aim is to determine the extent to which GS-based feed ingredients influence the environmental impact of animal feed production. To address this inquiry, we focused on evaluating the production processes of two essential animal feeds: those designed for dairy sheep and dairy cows. The characterization results on the midpoint level are presented in Table S11. From this table, it is clear that the environmental impacts associated with both dairy sheep and dairy cow feed with GS-based feed ingredients are lower than those without GS-based feed ingredient for most of the impact categories. Figure 7 provides a detailed comparison of the normalized midpoint environmental impacts of dairy sheep and dairy cow feed production, benchmarked against conventional variants. In dairy cow production, the feed containing the hydrolyzed GS-based feed ingredient shows a slight 5% increase in environmental impacts compared to nonhydrolyzed and conventional variants. Conversely, for dairy sheep feed, the inclusion of both hydrolyzed and nonhydrolyzed GS-based

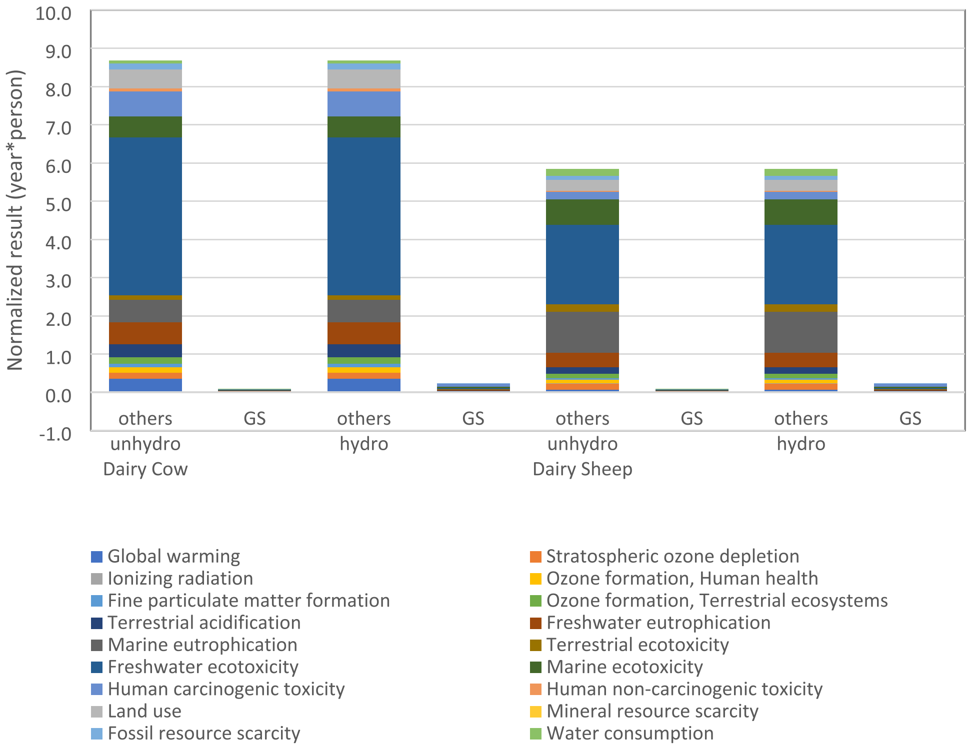


Figure 8. Impact contribution of GS-based feed ingredient to hydrolyzed and nonhydrolyzed GS-based feed production.

feed ingredient results in a significant decrease of about 20% in environmental impacts relative to conventional dairy sheep feed. This reduction is primarily due to reduced usage of rapeseed meal and oats when the GS-based feed ingredient is incorporated (Table 2). However, when it comes to the single score end-point impacts, these differences become much less pronounced (Figure S3). These results underscore the importance of adjusting animal feed composition when integrating GS-based feed ingredients into formulations.

Additionally, for both nonhydrolyzed and hydrolyzed GS-based feed ingredients and conventional animal feed, FET emerges as the most significant impact category, followed by HCT for the dairy cow feed and ME for the dairy sheep feed (Figure 7). The impacts on the FET category were found to originate mainly from the use of herbicides/fungicides/insecticides in the cultivation of other ingredients (results not shown).

Moreover, the figure demonstrates that the environmental impacts related to dairy sheep feed are significantly lower compared with those associated with dairy cow feed. This difference arises from the distinct composition of other ingredients used in formulating these two types of animal feeds, despite their GS-based ingredient contents being the same (Table 2).

Figure 8 further illustrates the limited environmental impact of GS-based feed ingredients in both animal feeds, attributed to their small presence within the feeds compared to the dominant environmental impacts caused by other ingredients.

Figure 9 depicts the contributions of feed ingredients and other inputs to the end-point environmental impacts of dairy sheep and dairy cow feed, distinguishing between hydrolyzed and nonhydrolyzed GS-based feed ingredients. It is evident that, for both dairy cow and dairy sheep meals, the primary impacts occur in the human health impact category, while the impacts on resources category are negligible. It is observed that feed ingredients other than GS-based ones significantly contribute to all end-point impact categories, whereas electricity and heat usage make comparatively minor contributions. The figure clearly demonstrates the minimal impact of GS-based feed ingredient in dairy cow and sheep feed across the end-point impact categories. For the dairy cow feed with hydrolyzed GS, significant impacts stem from fat, soybean, and maize, with GS itself contributing insignificantly (Figure 9a). The contribution of nonhydrolyzed GS-based feed ingredient is even lower. Similarly, for dairy sheep feed (Figure 9b), while the overall weighted impacts are lower compared to dairy cow feed, significant contributions originate from other ingredients such as rapeseed expeller, maize and barley grain in dairy sheep feed. These findings align with those of Ibáñez-Forés et al.[27] who reported higher environmental impact contributions from certain ingredients compared to the valorized ingredients from rice straw and citrus pruning waste used in animal feed.

Since the contribution of GS-based feed ingredients to the environmental impacts of dairy cow and dairy sheep feed was negligible, the sensitivity of these impacts to parameters related to GS-based feed ingredients was also negligible (Figure S4). As seen from Figure S4a,b, the results were sensitive only by ±0.1 to 0.6% for dairy sheep and ±0.1 to 0.2% for dairy cow feed, respectively. This finding is understandable considering the presence of GS-based ingredients within the animal diet at a small fraction (10% by weight) (Table 2) as well as the dominancy of the impacts caused by the other ingredients (Figure 8).

Life-Cycle Impacts of Business-As-Usual Scenarios. In assessing the environmental impacts of valorizing GS as animal feed versus traditional practices, we compared the impacts of conventional animal feed production and three most frequently used business-as-usual disposal scenarios for GS: landfilling,[28] composting[29] and incineration.[30] This comprehensive compar-

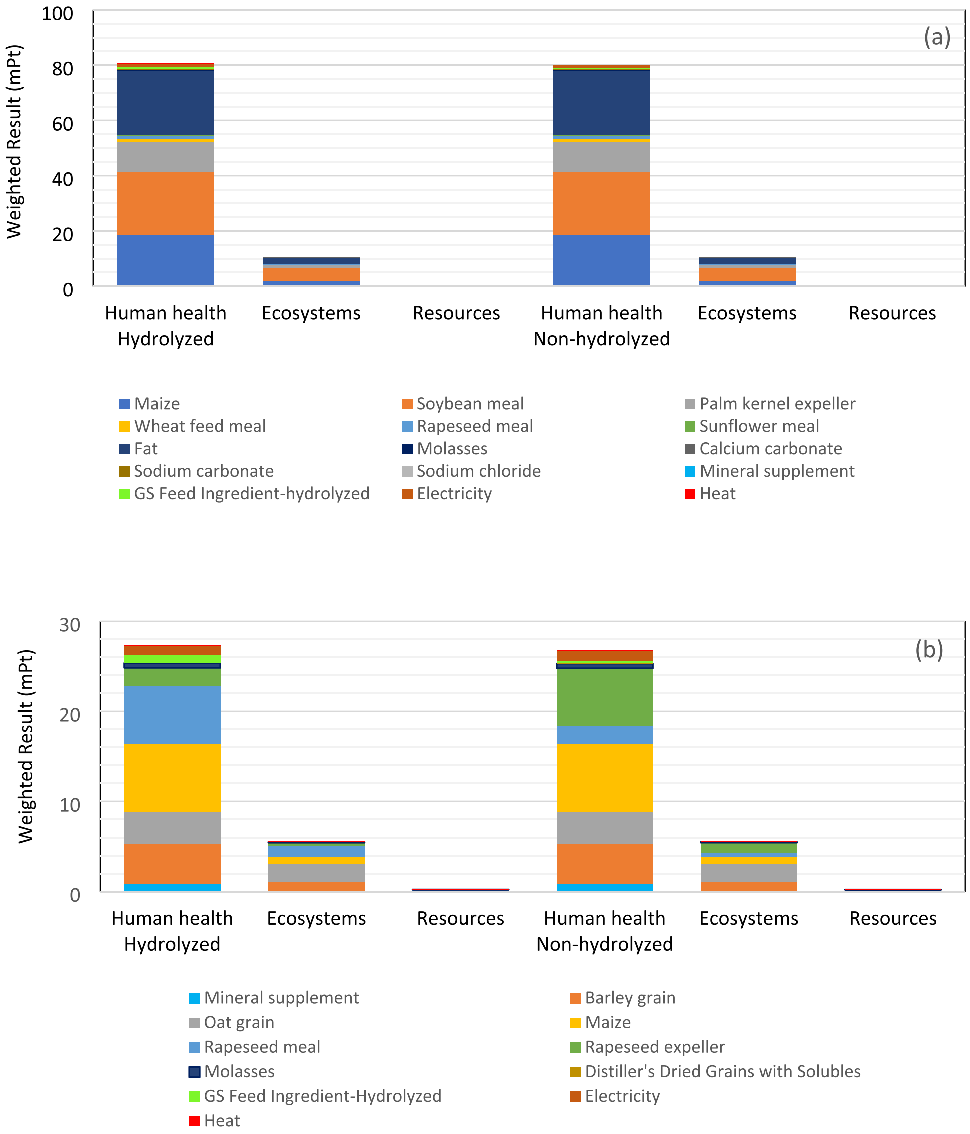


Figure 9. Impact contributions of animal feed ingredients to weighted impacts (a) dairy cow and (b) dairy sheep production.

ison highlights how valorizing GS as animal feed fares against established disposal practices in terms of environmental impact. We evaluated these disposal methods based on the quantity of GS required to produce 1000 kg of dairy cow or dairy sheep feed and compared these impacts with those of hydrolyzed and nonhydrolyzed GS-based dairy cow and dairy sheep feed of the same quantity.

Our LCA simulations indicate that valorizing GS as both dairy cow and dairy sheep feed results in reduced environmental impacts compared with business-as-usual scenarios involving landfilling and composting. The results are presented in Figure 10. As shown, all of the business-as-usual scenarios have significant impacts on the human health impact category. Specifically, the human health impacts associated with composting and landfilling are both higher than those of hydrolyzed or nonhydrolyzed GS-based feed production. Both landfilling and composting have single scores of over 110 Pt for dairy sheep and over 50 Pt for dairy cow feed production, while the corresponding scores for both hydrolyzed and nonhydrolyzed GS-based animal feeds are over 90 and 30. In contrast, incineration shows lower environmental impacts than animal feed production, primarily due to energy recovery. As shown in Figure 10, the impacts associated with the incineration of GS required to produce 1000 kg of dairy cow or dairy sheep feed are significantly lower than those of producing 1000 kg of dairy cow or dairy sheep feed. When GS is incinerated, it generates energy that can be harnessed for electricity or heat, offsetting some of the environmental impacts associated with conventional feed production. This energy recovery reduces the demand for energy from fossil fuels, which in turn lowers greenhouse gas emissions and decreases the overall carbon footprint. Expanding on this comparison, valorizing GS as animal feed not only reduces the volume of waste to be disposed of but also potentially lowers environmental impacts. This approach aligns with circular economy principles by converting waste into a valuable resource. Furthermore, by reducing the reliance on conventional feed production, which often involves intensive agricultural practices and associated environmental impacts, the overall environmental impact can be reduced.

Nevertheless, the choice between valorization and disposal methods should consider regional contexts and technological feasibility. While incineration with energy recovery shows promise in reducing impacts and contributing to renewable

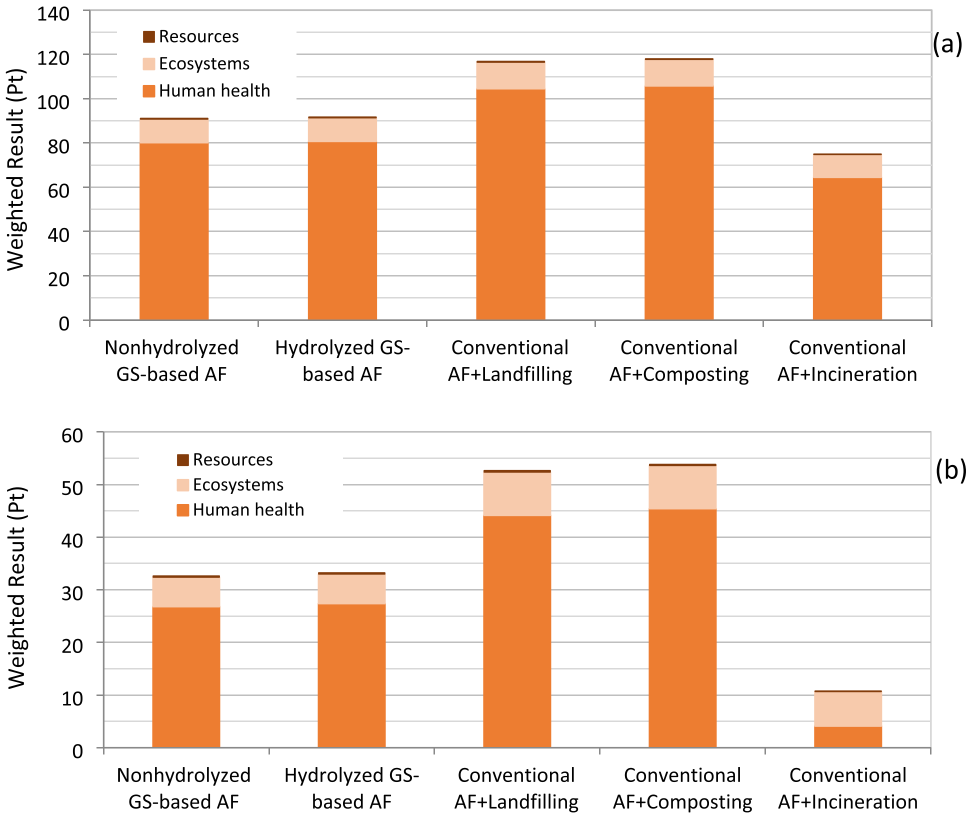


Figure 10. Comparison with the business-as-usual scenarios as single scores for 1000 tons of (a) dairy sheep and (b) dairy cow feed (AF: animal feed).

energy generation, it may require significant infrastructure investment and careful management of emissions and residues. In contrast, composting GS waste could contribute positively to soil fertility and organic matter content, albeit with potential challenges related to nutrient management and odor control. Moreover, the economic viability of each approach, including costs associated with collection, processing, and market demand for GS-based animal feed, plays a crucial role in decision-making.

Life-Cycle Costing for the GS-Based Feed Ingredient Production. In decision-making scenarios that involve LCA, it is crucial to assess the economic feasibility of the relevant products or processes. However, economic considerations often extend beyond the traditional LCA framework, necessitating a careful balance between economic factors and life-cycle performance. Therefore, an economic assessment was conducted to compare the costs and benefits of the GS waste valorization options, with the aim of identifying the optimal approach. The economic assessment of GS waste valorization scenarios mainly centered on evaluating CAPEX, OPEX, and the revenue from selling the resulting animal feed ingredient. Environmental costs were estimated to provide a comprehensive assessment of the sustainability implications associated with this valorization strategy. This assessment aimed to understand the broader environmental impacts of the production processes and identify opportunities to mitigate potential negative impacts. Cost and revenue estimates were based on a full-scale facility with a daily production capacity of 1000 kg of GS-based feed ingredient.

Table 6. Costs and Revenues for a GS-Based Feed Ingredient Production Plant with a Capacity of 1000 kg/d

cost item	nonhydrolyzed GS-based feed ingredient	hydrolyzed GS-based feed ingredient
	CAPEX, €	
direct	149,432	198,833
indirect	7865	10,465
total	157,295	209,297
	OPEX, €/year	
variable	8772	11,518
fixed	9910	13,186
total	18,681	24,704
	Revenues, €/year	
bioethanol	8280	10,044
GS-based feed ingredient	27,000	27,000
total	35,280	37,044
environmental cost, € 2015/1000 kg	49.8	10.1

Table 6 summarizes the CAPEX, OPEX, revenues, and environmental costs estimated for the GS-based feed ingredient production in a plant of 1000 kg/d capacity (the details for the calculation of CAPEX, OPEX, environmental costs, and revenues are provided in S2–S5, respectively). As seen, the CAPEX is 1.3 times higher for the hydrolyzed GS case than for the nonhydrolyzed case. Similarly, the OPEX for the hydrolyzed GS-based feed ingredient production is 1.32 times higher than for the nonhydrolyzed variant. As seen from Table 6, the resulting environmental cost for 1000 kg of feed ingredient is found to be about five times higher for the hydrolyzed GS-based feed ingredient than for the nonhydrolyzed variant. Revenues that originate from selling both the feed ingredient produced and the liquor from GS washing for bioethanol production are slightly higher for the hydrolyzed GS-based feed ingredient.

In Table 7, all costs and unit expenses are presented as present values (PV). The calculations were based on a 3% discount rate, 0% scrap value considered relative to the acquisition cost, and a project lifespan of 20 years. Specifically, the total costs amounted to 0.25 and 0.37 €/kg for the nonhydrolyzed and hydrolyzed feed ingredient produced, respectively. The net cost for producing the nonhydrolyzed GS-based feed ingredient production was determined to be −0.059 €/kg, denoting a negative value indicative of financial feasibility or a profitable value chain. In contrast, for the hydrolyzed variant, the net cost was calculated as 0.043 €/kg of feed ingredient produced. These findings underscore the economic viability of both production approaches, with the nonhydrolyzed feed ingredient demonstrating potential profitability even after accounting for all present value costs.

Table 7. Net Costs and Cost-Effectiveness for a GS-Based Feed Ingredient Production Plant with a Capacity of 1000 kg/d (Project Life Span: 20 Years)

cost items	nonhydrolyzed GS-based feed ingredient	hydrolyzed GS-based feed ingredient
	CAPEX	
PV	157,295	209,297
€/kg of feed ingredient produced	0.09	0.12
	OPEX	
PV, €	277,932	367,536
€/kg of feed ingredient produced	0.15	0.20
	Revenues	
present value (PV), €	560,157	588,165
€/kg of feed ingredient	0.31	0.33
	Environmental Cost	
cost, EUR2015	18,164	89,569
€/kg of feed ingredient produced	0.01	0.05
total cost (PV), €	453,391	666,402
total annual cost (PV), €	22,670	33,320
total cost (PV), €/kg of feed ingredient produced	0.25	0.37
net total cost (NPV), €	−106,766	78,237
cost-effectiveness (€/kg of feed ingredient produced)	−0.059	0.043
cost-effectiveness (€/kg of GS processed)	−0.020	0.012

A further comparison of these findings with the costs of conventional disposal options indicates that valorizing GS as an animal feed ingredient is more economically feasible than disposing of it by conventional methods (Table S12). The details of LCC calculations for the conventional disposal options are provided in Section S6.

■ CONCLUSIONS

The results from a cradle-to-gate LCA study demonstrate that the innovative strategy developed to valorize GS into a high-value animal feed ingredient has higher potential environmental impacts when GS is hydrolyzed. Hydrolyzing GS causes an increase in impacts due to the use of NaOH and electricity during the process. However, these impacts become insignificant when it comes to the animal feed production for both dairy cow and dairy sheep, since the presence of GS-based feed ingredient within the animal feed at a small fraction as well as the dominance of the impacts caused by the other ingredients. The predominant environmental impacts associated with animal feeds are due to other feed ingredients, such as fat, soybean and maize for the dairy cow feed and rapeseed expeller, maize and barley grain for the dairy sheep feed, rather than those derived from GS.

A sensitivity study showed that environmental impacts are not sensitive to the parameters of NaOH and electricity but to the transportation distance for the GS-based animal feed ingredient. However, this sensitivity disappears in the stage of animal feed production.

When compared to business-as-usual scenarios, GS valorization results in lower environmental impacts than landfilling and composting. However, it does not match the performance of incineration, which benefits from remarkable energy recovery. Despite this, GS valorization presents a more sustainable alternative to traditional waste disposal methods, aligning with the goals of reducing environmental impacts and promoting circular economy principles.

Based on the findings, it is recommended that producers of GS-based animal feed focus on minimizing environmental impacts by optimizing the production stage of GS-based feed ingredients and reducing transportation distances, which significantly contribute to the human health impacts. Implementing ecofriendly practices throughout the supply chain, such as strategically locating GS-based feed ingredient production facilities near animal feed production plants and using renewable energy sources, can help mitigate environmental impacts. By adopting these measures, animal feed producers can further mitigate environmental impacts and reduce operational costs.

To maximize the benefits of GS valorization, it is essential to enhance production processes and explore ways to improve the energy efficiency. Although incineration currently provides better energy recovery, continued research and technological advancements in GS valorization could enhance its sustainability and competitiveness.

The significance of these results extends to the broader community by contributing to more sustainable waste management practices and reducing the environmental footprint associated with agricultural byproducts. By enhancement of the sustainability of GS valorization, communities can benefit from improved environmental health, reduced pollution, and lower overall waste management costs. Additionally, advancing GS valorization technologies aligns with circular economy principles, promoting resource efficiency, and supporting long-term ecological balance. As such, these findings offer valuable insights for policymakers, industry stakeholders, and communities striving to adopt more sustainable practices and foster a greener economy.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.4c06005.

> Detailed description and data on the following topics: database units used in LCA, weighting factors used for converting impacts to a single score, midpoint LCA results, OPEX, CAPEX, revenues and environmental costs, life-cycle costing for disposal options, and

sensitivity analysis for animal feeds with hydrolyzed GS-based feed ingredient (PDF)

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Notes

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