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Upcycling Almond Byproducts: A Technoeconomic and Environmental Assessment of Almond Hull Hydrolysate

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ABSTRACT

Almonds are a globally important food crop, and the processing of their kernels generates over 3 million metric tons of hulls annually—an abundant, sugar-rich byproduct that remains underutilized. This study presents the first integrated technoeconomic analysis (TEA) and life cycle-based sustainability assessment of almond hull hydrolysate (AHH) as a low-cost and environmentally favorable fermentation growth medium. Compositional analysis of AHH revealed high concentrations of fermentable sugars (glucose, fructose, sucrose, and galacturonic acid) with negligible fermentation inhibitors, eliminating the need for detoxification. Commercial-scale process simulations using SuperPro Designer estimated the minimum selling price (MSP) of AHH to range from \$0.092 to \$0.198/kg for the hydrochloric acid (HCl) process and from \$0.171 to \$0.279/kg for the citrate buffer (CB) process across internal rates of return (IRRs) from 5% to 25%. The HCl route consistently outperformed the CB process due to lower chemical costs and simplified operations. Cradle-to-gate LCA results further indicate that both AHH routes have substantially lower greenhouse gas emissions, fossil energy use, and water demand than conventional refined sugars such as glucose and sucrose. These findings demonstrate that valorizing almond hulls into fermentable sugars can reduce the environmental footprint and cost of microbial fermentation media. AHH thereby provides a scalable pathway to sustainable protein production, linking agricultural waste utilization with circular bioeconomy principles and supporting decarbonization of the food protein sector.

1 | Introduction

With the global population projected to reach 10 billion by 2050, demand for sustainable protein sources and biobased products is increasing, intensifying interest in alternative feedstocks that can support industrial microbial fermentation processes (Matassa et al. 2016; Smetana et al. 2015; United Nations, Department of Economic and Social Affairs, Population Division 2022). Agricultural residues such as molasses, citrus peel hydrolysate, and sugar beet pulp hydrolysate have long served as economical and effective substrates due to high levels of fermentable sugars (glucose, fructose, and sucrose) and pectin-derived sugars like galacturonic acid (John et al. 2007; Lin and Tanaka 2006; Matassa et al. 2016; Mussatto and Roberto 2004). Recent technoeconomic and process modeling studies validate the industrial feasibility of converting lignocellulosic biomass

Boon-Ling Yeo and Varun Gore are co-first authors.

(including sugarcane bagasse and apple pomace) into valuable sugars and bioproducts (Bravo-Venegas et al. 2023; Rebolledo-Leiva et al. 2024). Recent work has systematically compared the nutrient content and profiles of inhibitory compounds in lignocellulosic hydrolysates generated by different biorefinery strategies, offering key insights to guide substrate selection and process optimization for industrial microbial fermentation (Wang et al. 2024). Such analyses help explain why almond hull hydrolysate (AHH), when properly processed, can contain high levels of fermentable sugars with minimal inhibitors, enabling its use in fermentation media for production of diverse bioproducts.

Among plant-based crops, almonds (*Prunus dulcis*) have emerged as an important ingredient in dairy alternative products and as a promising feedstock for alternative protein production due to their favorable nutritional profile, sensory properties, and consumer acceptance (Cao et al. 2024, 2025; Suryamiharja et al. 2024). In addition to proteins, almonds are also rich in lipids, with oil contents typically ranging from 45% to 55% on a dry weight basis, primarily composed of monounsaturated fatty acids such as oleic acid, contributing to their nutritional value and broad utilization in food applications (Bolling et al. 2010; Yada et al. 2011). Almond kernels contain approximately 20%–25% protein by weight (Bolling et al. 2010). According to the USDA-NASS (2024) California Almond Objective Measurement Report, California produced approximately 2.80 billion pounds (1.27 million metric tons) of almond kernels, yielding an estimated 260,000–325,000 metric tons of protein (USDA-NASS 2024). Almond processing generates substantial quantities of byproducts, primarily hulls and shells (Huang and Lapsley 2019). Every kilogram of kernel yields roughly 0.6 kg of shell and 2.5 kg of hull (dry basis), resulting in approximately 3.18 million metric tons of hulls and 0.76 million metric tons of shells in California annually (Aktas et al. 2015; Holtman et al. 2015). Almond hulls are exceptionally high in carbohydrates, with sugar contents ranging from 31.8% to 42.2% on a dry basis, making them an attractive source of carbohydrates for use in fermentation media (Hall and Kononoff 2011; Thomas et al. 2019).

Despite being generated in large volumes, almond hulls are primarily used as cattle feed for dairies in California, with prices fluctuating between \$84 and \$187/MT (USDA 2026). Agro-industrial residues such as almond hulls, sugarcane bagasse, corn stover, cassava leaves, and fruit pomaces have garnered increasing attention as alternative carbon sources for microbial fermentation due to their low cost, regional availability, and high carbohydrate content (John et al. 2007; Lin and Tanaka 2006; Mussatto et al. 2012). Almond hulls represent a high-volume byproduct containing an estimated 1.34 million metric tons of fermentable sugars annually in California alone (DePeters et al. 2020; Holtman et al. 2015; Li and Zheng 2024). Several studies have evaluated AHH's potential as a fermentation substrate (Cao et al. 2024; Huang and Lapsley 2019; Li and Zheng 2024; Sitepu et al. 2023; Thomas et al. 2019). The almond industry is increasingly exploring upcycling strategies to convert hulls into higher-value bioproducts. When enzymatically or acid hydrolyzed, AHH yields a sugar-rich mixture (glucose, fructose, sucrose, and galacturonic acid) with minimal inhibitory byproducts, making it suitable for direct microbial fermentation without detoxification, lowering process complexity and cost (Li and Zheng 2024; Sitepu et al. 2023). AHH can therefore be used as a major media component in diverse fermentation platforms, including microbial lipid production, single-cell protein synthesis, bioethanol and lactic acid production, edible fungal biomass, and natural pigment synthesis (Cao et al. 2024; DePeters et al. 2020; Dias et al. 2025; Li and Zheng 2024; Thomas et al. 2019). Table 1 summarizes potential application areas, relevant microorganisms, end products, and supporting literature.

The feasibility of producing ethanol from lignocellulosic hydrolysates has been well established using conventional feedstocks such as corn stover. Schell et al. (2016) demonstrated an integrated process including dilute-acid pretreatment, enzymatic hydrolysis, and fermentation that achieved high solids conversion (approximately 80% conversion of cellulose and xylan). Their study emphasized rigorous accounting of oligomeric sugars during pretreatment and enzymatic hydrolysis, ensuring accurate yield calculations critical for technoeconomic analysis (TEA). Although such processes provide benchmarks for lignocellulose-to-ethanol conversion, studies specifically evaluating AHH have primarily focused on enzymatic hydrolysis optimization and sugar release. Recent investigations, such as those by Sitepu et al. (2023), have evaluated AHH as a substrate supporting microbial growth, including oleaginous yeasts, yet these remain largely at bench scale, focusing on sugar yield improvements without extensive exploration of AHH's broader utility across diverse microbial fermentation platforms.

Expanding beyond proof-of-concept, Dias et al. (2025) showed that olive mill waste hydrolysates can effectively support lipid synthesis in oleaginous yeasts such as *Yarrowia lipolytica*, underscoring the potential of agro-waste hydrolysates to sustain biomanufacturing. Similar approaches have been reported for citrus peel waste and apple pomace (Bravo-Venegas et al. 2023; González-García et al. 2018; Okoro et al. 2023; Rebolledo-Leiva et al. 2024). Yet comprehensive comparative studies on almond hulls remain limited. Notably, technoeconomic analyses of apple pomace hydrolysate suggested significant cost advantages for organic acid production relative to glucose-based media, although transparency in life-cycle assessment assumptions remains limited (Bravo-Venegas et al. 2023; Rebolledo-Leiva et al. 2024).

Despite these advances, no published study has conducted an integrated TEA and life cycle assessment (LCA) of AHH as a fermentation feedstock. Prior work has largely emphasized laboratory-scale hydrolysis optimization or single-product outputs without holistic assessment of industrial-scale economic feasibility, sustainability outcomes, or integration into circular bioeconomy frameworks. To address this gap, the present study provides the first integrated TEA and cradle-to-gate LCA of AHH production for use in microbial fermentation. Two hydrolysis pathways were evaluated and compared, including hydrochloric acid (HCl)-based hydrolysis and citrate buffer (CB)-based hydrolysis. Commercial-scale process simulations were developed in SuperPro Designer to estimate capital expenditures (CAPEXs), operating costs, minimum selling price (MSP), and profitability metrics for each pathway. The TEA outputs were subsequently integrated with cradle-to-gate LCA modeling to

TABLE 1 | Potential applications of almond hull hydrolysate (AHH) as a media component in fermentation.

Application area	Representative sugar/feedstock source	Target microorganism(s)	End products	References
Single-cell oils (SCOs)	Olive mill wastewater; olive tree pruning hydrolysates	*Yarrowia lipolytica*, *Cryptococcus curvatus*	Microbial lipids (biofuels, oleochemicals)	Dias et al. (2025), Papanikolaou and Aggelis (2011), Sitepu et al. (2014)
Single-cell protein (SCP)	Petroleum waste, starch, whey, sulfite waste liquor	*Candida utilis*, *Kluyveromyces marxianus*	Protein-rich biomass	Nasseri et al. (2011), Matassa et al. (2016)
Bioethanol	Crop residues; lignocellulosic hydrolysates	*Saccharomyces cerevisiae*, *Zymomonas mobilis*	Ethanol	Hahn-Hägerdal et al. (2006), Kim and Dale (2004)
Organic acids	Biomass hydrolysates; starchy and lignocellulosic feedstocks	*Lactobacillus* spp., *Aspergillus niger*	Lactic, citric, and succinic acids	John et al. (2007), Weusthuis et al. (2011)
Polyhydroxyalkanoates (PHAs)	Renewable feedstocks, waste streams, lignocellulosic biomass	*Cupriavidus necator*, *Ralstonia eutropha*	Bioplastics	Kourmentza et al. (2017), Chen (2009)
Xylitol/sugar alcohols	Dilute-acid lignocellulosic hydrolysates; sugarcane bagasse hemicellulose	*Candida tropicalis*, *Debaryomyces hansenii*	Xylitol	Mussatto and Roberto (2004), Prakash et al. (2011)
Natural pigments	Palm oil mill effluent; agro-industrial wastes	*Rhodotorula mucilaginosa*, *Rhodosporidium toruloides*	Carotenoids	Buzzini et al. (2007), Saenge et al. (2011)
Enzymes	Lignocellulosic biomass; agricultural residues	*Trichoderma reesei*, *Aspergillus* spp.	Cellulases, pectinases	Gusakov (2011), Cherry and Fidantsef (2003)
Specialty chemicals/esters	Fatty acid esters; branched-chain alcohol precursors	Engineered *Clostridium*, *E. coli*, *Bacillus subtilis*	*n*-butyl acetate, isopropanol, and acetoin	Atsumi et al. (2008), Feng et al. (2021), Lee et al. (2021)
Alternative protein	AHH	Filamentous fungi	Mycoprotein/protein-rich fungal biomass	Cao et al. (2024)

quantify environmental impacts associated with AHH production and benchmark them against conventional refined sugars such as sugar beet glucose and sugar cane sucrose. Together, the TEA and LCA frameworks explore the competitiveness, sustainability profile, and circular bioeconomy potential of almond hull valorization as a scalable pathway to enhance the overall protein and bioproduct output of almond production systems.

2 | Methodology

2.1 | Materials and Compositional Analysis of Almond Hulls

Almond (*P. dulcis*) hulls were harvested in 2023 and provided by The Wonderful Company (Shafter, California, USA). Hulls were air-dried at ambient temperature and stored in sealed containers until use. Batches were tracked based on year of use (pre-2024 and post-2024). Prior to compositional analysis, dried hulls were coarsely milled with an immersion blender for 5 min, followed by further size reduction using a Wiley mill to 40 mesh (< 0.425 mm particle size).

The oven-dry biomass composition (structural carbohydrates, acid-insoluble lignin, ash, extractives, and organic acids) was determined according to standard protocols for biomass feedstocks (Sluiter et al. 2012; Sluiter et al. 2005, 2012). Water and ethanol extractives were removed by successive Soxhlet extractions with nanopure water for 72 h, followed by 95% ethanol until the solvent ran clear. Extract-free hulls were air-dried before further use, and the masses of the water and ethanol extractives were found by weighing the remaining solids after drying in a rotary evaporator (Buchi Rotavapor R-200).

A separate warm water-extraction procedure was performed to determine soluble sugar content by mixing 20 mesh almond hulls with deionized water at 20% solids loading (w/w, wet basis) and incubating at 50°C with end-over-end rotation for five sequential 1 h extractions. Decanted supernatants were analyzed for soluble sugars, primarily sucrose, glucose, and fructose, by HPLC. Protein content of both untreated (30 mesh milled) and extractive-free hulls was quantified at the UC Davis Proteomics Core Facility following the amino acid and protein quantification method described by Sitepu et al. (2023).

2.2 | Production and Characterization of AHH

AHH was prepared by liquefaction of coarsely milled almond hulls in either (i) 0.1 M CB (pH 4.8) or (ii) deionized water acidified to pH 4.8 using concentrated HCl. Hydrolysis reactions were performed at a solid loading of 15% (w/w, wet basis). Enzymatic depolymerization was initiated by the addition of pectinase (*Pectinex Ultra Clear*, Novozymes, Lyngby, Denmark; Lot No. 0-32-71-1) at a dosage of 0.1 mg pectinase per gram of almond hulls on a wet basis. Incubations were carried out at 50°C for 72 h, with continuous agitation provided by a rotating bottle rack (end-over-end mixing). At the end of the incubation period, samples were centrifuged at 7500×*g* for 10 min to remove insoluble residues, and clarified supernatants were recovered as hydrolysates. Before analysis, supernatants were filtered through 0.22 μm syringe filters (nylon, 25 mm diameter; Biomed Scientific). Solubilized monosaccharides (glucose, xylose, arabinose, sucrose, galacturonic acid) and low-molecular-weight organic acids (acetic, citric, and lactic acids) were quantified by HPLC.

2.3 | Technoeconomic Assessment

2.3.1 | Process Simulations and Economics

Technoeconomic modeling was performed using SuperPro Designer Version 14 Build 1 (Intelligen Inc., Scotch Plains, NJ, USA). SuperPro Designer was employed for equipment specification and sizing, mass and energy balances, batch scheduling, and estimation of CAPEX, annual operating expenditure (OPEX), and cost of goods sold (COGS). Model inputs and assumptions were based on a combination of laboratory experimental results, process knowledge from the author's research, and published literature values, and default parameters provided by the SuperPro Designer database (see Table 2).

2.3.2 | Base Case Scenario

The base case scenario models a greenfield commercial facility processing 50,000 metric tons (MT, wet basis) of almond hulls annually. This processing capacity was selected as it represents ~1.5% of the total almond hull production in California and aligns with the throughput of a standard almond hulling and shelling facility, making it an industry-relevant scale. This corresponds to a projected output of 259 kMT AHH across 99 batches per year over 330 days. Almond hulls are assumed to contain 15% moisture (wet basis) at intake. The operational protocol follows the hydrolysis process described in Section 2.1, scaled according to empirical observations from laboratory-scale hydrolysis, where batch residence time is 81.58 h and process cycle time (time between the start of consecutive batches) is 79.83 h. The hydrolysis step is modeled as a 72-h batch operation, consistent with laboratory data.

The economic analysis compares two alternative AHH production scenarios. Both scenarios are assumed to use the same equipment size and process durations. They are distinguished by the buffer type used in the hydrolysis reaction: (i) 0.1 M CB and (ii) acidified deionized water (pH-adjusted to 4.8 with HCl), resulting in a 0.016 M HCl solution. These pH buffers were determined from bench-scale data conducted in the authors' lab. Key cost elements, including chemical usage, enzyme demand, cleaning cycles, utilities (i.e., steam, water, and power), and waste disposal, are itemized for each scenario. Table 3 summarizes major input quantities, unit costs, and process outputs for both buffer options. The production facility design specifies the use of ten 290,000-L stainless steel (SS304) mixing tanks (ASME-certified pressure vessels) to accommodate the large batch volumes, based on an operational buffer-to-dry-hull input mass ratio of 5:1. All vessels are assumed to be suitable for food-grade processing and equipped for cleaning by clean-in-place and sterilization by steam-in-place systems. A detailed process flow diagram is provided in Figure 1. Process durations, material and energy inputs, and

TABLE 2 | Economic analysis assumptions.

General facility parameters	Values
Base year	2025
Plant capacity (MT, wet basis, per year)	50,000 (almond hulls)
Construction period (months)	30
Start-up time (months)	4
Project lifetime (years)	25
Annual operating time (h)	7905
Annual operating time (days)	330 (35 days [~10%] for planned and unplanned downtime)
Depreciation method	Straight line method (10 years, years 3–12, with a salvage value of 5% of direct fixed capital)
Net present value discount rate (%)	7
Income tax rate (%)	40
Inflation rate (%)	0
Financing	100% equity

TABLE 3 | Summary of major input quantities, unit costs, and process outputs for both buffer options.

Category	Parameter	HCl process	CB process	Notes/units
Feedstock	Almond hulls processed	50,000 MT/year (w.b.)	50,000 MT/year (w.b.)	15% moisture
	Solids loading (hydrolysis)	15%	15%	(w/w, wet basis)
Buffer input	Buffer type	0.016 M HCl	0.1 M CB	pH 4.8 target
	Ratio buffer to biomass (mass)	5:1	5:1	kg/kg hull (d.w.)
	Annual buffer input mass	210,013,398	210,013,398	kg/year
	Buffer cost	0.001	0.1	$/kg
Enzyme input	Pectinase loading	0.1 mg/g AH (w.b.)	0.1 mg/g AH (w.b.)	Specify activity U/g
	Annual enzyme demand	5000	5000	kg/year
	Enzyme cost	15	15	$/kg
Operations	Batch cycle time	79.83 h	79.83 h	From lab trials
	Number of batches per year	99	99	Annual schedule
	Mixing tanks (capacity × #)	290,000 L × 10	290,000 L × 10	Stainless steel ASME
Utilities	Steam demand (SIP)	14,521	14,375	MT/year
	Electricity	2,027,925 kWh/year	2,020,165 kWh/year	Mixing, pumps, grinding
	Water usage	315,154.8	308,019.5	m^3/year
Outputs	AHH yield	259,505 MT/year	259,500 MT/year	Hydrolysate
	Sugar concentration in AHH	40.9 g/L	41.4 g/L	From HPLC
Economics	CAPEX	$76.5 million	$78.0 million	SuperPro estimate
	Annual OPEX	$23.1 million	$43.4 million	SuperPro estimate
	Cost of goods sold (COGS)	$0.09/kg	$0.17/kg	Unit production cost
	Minimum selling price (MSP) at 10% IRR	$0.11/kg	$0.19/kg	Selling before achieving 10% IRR

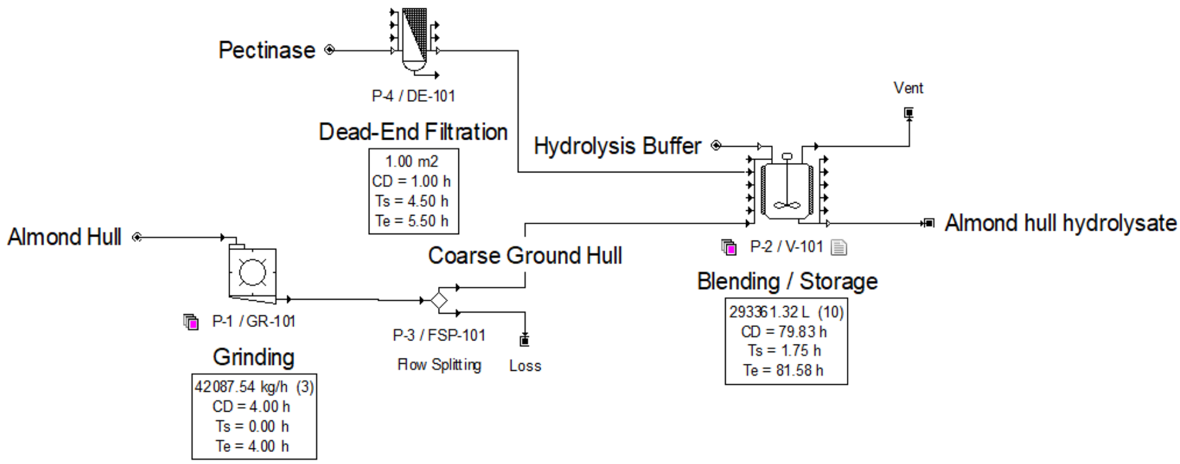

FIGURE 1 | Process flow diagram of the AHH production facility. Almond hulls are ground in equipment P-1; pectinase is sterile filtered in equipment P-4. Coarse ground hulls, pectinase, and hydrolysis buffer are transferred to the blending tank (P-2) for the hydrolysis reaction. CD, cycle duration; Te, end time; Ts, start time.

utilities consumption are derived from scaled laboratory protocols and SuperPro Designer default scaling equations. The SuperPro Designer base case models used in this work are publicly available at https://mcdonald-nandi.ech.ucdavis.edu/tools/techno-economics/. A free trial download of SuperPro Designer (https://www.intelligen.com/download/) can be used to view the models, run the simulations, and change process parameters/assumptions (although changes cannot be saved). All economic calculations were performed in 2025 USD. Equipment and installation costs are based on SuperPro Designer default factors.

2.3.3 | Economic Sensitivity Analysis

Sensitivity analyses were carried out to assess the effects of feedstock price and facility scale on the projected MSP of AHH. Almond hull prices have varied between $75 and $170/MT in recent years, with projections suggesting potential increases (Parsons 2022; USDA 2026). Since almond hull prices fluctuate due to harvest and environmental factors (EFs), it is important to evaluate how these variations affect the MSP of AHH. Almond hull prices were varied from $0 to $250/MT in the analysis. For this sensitivity analysis, the scale of production was held constant at 50,000 MT of almond hulls processed annually, and MSP was calculated at 10% IRR.

To identify an economically viable operating range, a sensitivity analysis was conducted on the scale of production. Facilities processing 2500, 5000, 10,000, and 25,000 MT of almond hull per year were simulated to evaluate the impact of scale on production cost. For this analysis, the almond hull purchase price was fixed at $150/MT, and MSP for AHH was again calculated at 10% IRR. Additional analyses varied IRR between 5% and 25% to determine the MSP for a facility processing 50,000 MT of almond hulls annually while holding the price of almond hulls constant at $150/MT (wet basis).

For this project, a 25-year total period (including the construction and start-up periods) with an annual tax rate of 40% is assumed. The IRR is defined as the discount rate at which the net present value (NPV) equals zero at the end of the project lifetime. The MSP is the product selling price at which the NPV equals zero at the end of the project's lifetime when discounted at the user-defined required rate of return.

2.4 | Process Mass Intensity (PMI) and Environment, Health, and Safety (EHS) Assessment

PMI is a widely used metric for assessing the material efficiency of a production process. It is defined as the total mass of all raw materials, water, and consumables required to produce 1 kg of the active product, expressed in kilograms of input per kilogram of product (Budzinski et al. 2019). PMI serves as an indicator of resource use efficiency and environmental impact, guiding efforts to optimize process sustainability.

In this study, PMI calculations account not only for raw materials and water used directly in production but also include the mass contributions of acids and bases employed for equipment cleaning. All cleaning solutions are assumed to be prepared in-house; therefore, the water used in their preparation is included within the total water consumption contributing to PMI.

This comprehensive accounting provides a thorough measure of the material inputs required per unit of AHH produced, enabling evaluation and comparison of process efficiency and sustainability between buffer scenarios or process designs.

The EHS assessment of the process was performed using the environmental evaluation method developed by Biwer and Heinzle (2004). This approach quantifies process inputs and outputs relative to the amount of product generated, expressed as the mass index (MI). The method evaluates potential impacts in key areas—natural resource depletion, air quality, water and soil quality, and hazards and toxicity to humans, plants, and animals. Each material used as an input or produced as an output is assigned an EF, which reflects its environmental significance. These factors are derived from 14 impact categories, with each compound classified in the ABC semi-qualitative system: A (high negative impact), B (moderate impact), or C (low or negligible impact). The environmental index (EI) of each component is then calculated by weighing its MI with its EF. The total process EI is obtained by averaging the EI values of all inputs and outputs, providing an overall indicator of the process's environmental relevance. The environmental impact of the almond hulls themselves was not included in this analysis.

2.5 | LCA

2.5.1 | Scope

This study employed a cradle-to-gate LCA approach, capturing environmental impacts from raw material acquisition through the production boundary, defined here as the AHH process. An attributional LCA methodology was applied. The assessment excluded downstream phases such as product use, maintenance, and end-of-life. Each component of the AHH system was analyzed in terms of raw material sourcing, upstream processing, and downstream conversion. A declared functional unit of 1 kg of AHH media (consisting of 500 g of AHH) was established to calculate life cycle inventories (LCIs) and enable comparison of environmental impacts with alternative production scenarios.

2.5.2 | Inventories

Inventory data for AHH were compiled from the Ecoinvent, Agribalyse, and Agrifootprint databases, accessed using the SimaPro software suite. Process inputs of water, steam, and electricity for both upstream hydrolysate production and downstream processing of AHH were derived from SuperPro Designer modeling outputs. Associated energy-related emissions were modeled using the Ecoinvent process for the North American Western Grid electricity mix. Since no published LCI was available for sodium citrate ($NaC_6H_7O_7$), a custom dataset was generated. This assumed production via partial neutralization of citric acid ($C_6H_8O_7$) with sodium bicarbonate ($NaHCO_3$) as per Formula 1. The molecular weight ratio of reactants to product was used to calculate the mass requirements of citric acid and sodium bicarbonate for 1 kg sodium citrate production. Input LCI flows were scaled accordingly and summed to construct the final dataset, including the direct release of CO_2 in the reaction as illustrated in Formula 1.

$$NaHCO_3 + C_6H_8O_7 \rightarrow NaC_6H_7O_7 + CO_2 + H_2O$$

Formula 1. *Production of sodium citrate by reaction of citric acid with sodium bicarbonate.*

Inventory values for almond hull production in California were taken from Marvinney and Kendall (2021), applying an economic allocation to separate hull-specific burdens from whole fruit production impacts using 2020 pricing data. This allocation was updated in the present analysis using a current almond hull market price of $150/MT. The fractional economic value of each almond fruit component (hull, shell, and kernel) was calculated by multiplying the value in USD of each yield component by its mass proportion at harvest. The inventory values reported by Marvinney and Kendall (2021) were multiplied by the resulting fraction of whole-fruit economic value assigned to each yield component to produce economically allocated inventory values.

A US national LCI dataset for almond production was taken from the EcoInvent database and subject to the same economic allocation calculations for hull-specific burden. The primary differences between these datasets were in treatment of assumed soil and biomass carbon storage, with the EcoInvent LCI including temporary carbon storage, and in treatment of ecotoxicity impacts, with the Marvinney and Kendall analysis taking a more regionally specific approach to calculation of pesticide-related field-level impacts. The EcoInvent almond product dataset also makes use of a different water footprinting methodology, which results in a significantly lower water use value as compared to the California-specific study.

2.5.3 | Scenario and Sensitivity Assessment

To evaluate allocation sensitivity, almond hull prices were systematically varied from $0 to $270/MT. At a price of zero, almond hulls were treated as a byproduct or waste stream with no allocated impacts. Under this scenario, a system expansion approach was used in which AHH displaces alternative sugar sources. This displacement was calculated as a credit to the system for avoided demand/production of that quantity of sugar replaced by AHH.

A variety of scenarios were assessed. Primarily, the CB process was compared with the HCl process. For each of these production scenarios, three modeling choices were examined: (1) Use of California-specific almond production LCI, (2) US generalized almond production LCI, and (3) treatment of almond hull as a byproduct of almond production in the case where the economic value of hull is set at 0. This scenario includes system expansion and the displacement of alternative sugar sources in media production—here, the mean of processed sucrose, raw beet sugar, and raw cane sugar was assumed. The displacement scenario inventory was thus calculated as hydrolysate media production with almond hull inventory flows allocated as 0, and mean sugar inventory flows subtracted.

2.5.4 | Impact Assessment

Impact characterization factors (CFs) from the ReCiPe model (Goedkoop et al. 2008) were used to convert inventory flows to a full suite of environmental impacts, excluding freshwater eutrophication for which CFs were not available. These CFs were extracted from SimaPro. The California-specific almond dataset from Marvinney and Kendall (2021) reported a more limited set of impacts, as follows: water use (m^3), fossil energy use (kg oil eq.), GWP100 H (kg CO_2eq.), fine particulate matter formation (kg $PM_{2.5}$eq.), ozone formation, terrestrial ecosystems (kg NO_xeq.), terrestrial acidification (kg SO_2eq.), freshwater eutrophication (kg P eq). This may result in underreporting of the

TABLE 4 | Almond hull hydrolysate composition for citrate buffer (CB) and hydrochloric acid (HCl).

Components	Citric acid buffer	Hydrochloric acid
Glucose	16.87 (0.12)	16.30 (0.22)
Xylose	0.95 (0.06)	1.03 (0.07)
Galactose	1.38 (0.09)	1.52 (0.10)
Arabinose	1.62 (0.09)	1.72 (0.13)
Sucrose	6.29 (0.08)	6.71 (0.25)
Fructose	58.96 (0.54)	60.84 (1.49)
Galacturonic acid[a]	10.63 (0.31)	15.15 (0.37)
Lactic acid	0.51 (0.01)	0.58 (0.12)
Formic acid	0.16 (0.00)	0.15 (0.00)
Acetic acid[a]	1.17 (0.02)	1.34 (0.02)
Levulinic acid	0.43 (0.01)	0.49 (0.01)
HMF[a]	0.05 (0.00)	0.09 (0.00)
Citrate[a]	0.28 (0.00)	0.07 (0.00)

Note: All values are g/L concentrations with standard deviations included within parentheses.
[a]Statistically significant differences in concentrations based upon evaluation using a two-sided Welch's *t*-test given a significance level of 0.05 for sets containing three replicates for each buffer.

impact categories not included in the California-specific LCI modeling scenarios.

3 | Results

3.1 | Almond Hull Feedstock Are Carbon-Rich

Separate almond hull batches were used to produce hydrolysate for yeast screening (Batch 1) and bioreactor fermentation (Batch 2), as summarized in Table S1. Both batches, originating from the same harvest, contained similar levels of ash and structural carbohydrates (galactan, arabinan, and mannan) alongside high concentrations of water-extractable sugars. Protein concentrations were low and consistent with typical almond hull composition from California and nonpareil varieties. High galactan and arabinan contents indicate substantial pectin, supporting the use of pectinase treatment for efficient liquefaction and sugar release. Warm-water extraction from Batch 2 revealed considerable amounts of water-accessible glucose and fructose, confirming the feedstock's suitability for fermentation (Li and Zheng 2024; Sitepu et al. 2023).

3.2 | Enzymatically Liquefied Almond Hulls Provide a Carbon-Rich Hydrolysate

Water-soluble sugars, mainly glucose, fructose, and sucrose, serve as the principal fermentation substrates in AHH. Pectinase treatment effectively liquefied the hulls, enhancing sugar solubilization and enabling high solids loading compared to other agricultural feedstocks (see Table 4). Both citric acid and HCl buffers yielded similar initial pH conditions (4.8), facilitating efficient enzymatic hydrolysis under identical temperature, duration, and mixing parameters, ultimately resulting in highly similar hydrolysate sugar profiles with minor differences in organic acid profiles. The abundance of galacturonan and acetyl after enzymatic treatment further corroborates pectin breakdown as a key mechanism driving liquefaction. Notably, the HCl buffer resulted in higher galacturonic acid, acetic acid, and HMF concentrations within the hydrolysates, suggestive that low buffer capacity during pectinase treatment results in higher organic acid production and an increase in sugar degradation.

3.3 | Growth of Microbial Cells in Produced Media

A previous study demonstrated that many yeast species were able to grow in the AHH produced under the CB process. This hydrolysate was not supplemented with nutrients such as vitamins, minerals, or cofactors. A study by Sitepu et al. (2023) demonstrated that selected yeasts grew effectively on AHH (see Figure 2) and enhanced their protein profile by increasing the amount and essential amino acid content. In particular, *Zygoascus hellenicus* UCDFST 11-671 and several related strains showed increased cell mass production and a higher protein content, with notable enrichment in essential amino acids such as lysine, valine, and tryptophan compared to the unfermented AHH. Nitrogen supplementation further boosted protein yield, achieving up to a threefold increase and reaching 6.3% of dry weight after 2 days of incubation.

3.4 | Technoeconomic Analysis

Table 5 summarizes the process economics for the two AHH production processes for the base case facility designs sized for processing 50,000 MT (wet basis) of almond hulls per year. The estimated CAPEX stands at $76.5 million for the HCl process and $78 million for the CB process. For the HCl process, this includes equipment purchase costs of $20.6 million; other direct costs—such as installation, piping, instrumentation, insulation, electrical facilities, buildings, yard improvements, and auxiliary facilities—amounting to $22.6 million; and indirect costs for engineering and construction of $19.5 million (Table 6). Additional expenses cover contractor fees and contingencies totaling $9.4 million and start-up and validation costs of $3.6 million. The slight difference in CAPEX is primarily attributable to the higher working capital requirement of the CB process of $2.66 million compared to $0.8 million for the HCl process due to its increased raw material costs.

Operational expenditure (OPEX) is estimated at $23.1 million per year for the HCl facility and $43.5 million per year for the CB facility. As shown in Figure 3, the largest components of OPEX are raw materials and facility-dependent expenses, including maintenance, insurance, local taxes, and factory overhead. The major cost contributors to the raw material costs are almond hulls and chemicals for buffer preparation. The cost disparity between the two processes is mainly driven by the higher expense associated with CB usage compared to HCl for pH control.

FIGURE 2 | Preliminary screening of diverse yeast strains on AHH citrate buffer agar for conversion of agricultural waste to high-value product, previously published (Sitepu et al. 2023). The ability of yeasts to grow well on this medium indicates their capacity to utilize the sugars for their growth and overcome possible inhibitors present. The best-performing strains were subsequently scaled up in shake flasks in liquid media to evaluate their ability to produce targeted high-value metabolites, such as protein and lipids.

3.4.1 | Economic Sensitivity Analysis

Sensitivity analyses were conducted to assess how feedstock cost, production scale, and IRR assumptions affect the MSP of AHH.

3.4.1.1 | Effect of Almond Hull Feedstock Price. MSP for a 10% IRR, 25-year project lifetime, increased with rising almond hull prices for both hydrolysis processes (Figure 4A). At a feedstock price of $0/MT, the MSPs were $0.08/kg for the HCl process and $0.16/kg for the CB process. When the almond hull price rose to $250/MT, the MSP increased to $0.13 and $0.21/kg for the HCl and CB processes, respectively. Across the evaluated price range, the CB process consistently exhibited higher MSPs than the HCl process. The nearly parallel trends indicate that the effect of almond hull cost on MSP is independent of the buffer type used in hydrolysis, since the conversion of almond hulls to sugars in AHH is similar for the two buffer types.

3.4.1.2 | Effect of Production Scale. Production scale exerted a pronounced influence on MSP (10% IRR, 25-year project life), particularly at smaller capacities (Figure 4B). MSP decreased from $0.174/kg (HCl) and $0.253/kg (CB) at 2.5 kMT/

TABLE 6 | CAPEX breakdown of the two processes.

CAPEX cost contributors	Cost		Unit
	HCl process	CB process	
Equipment purchasing cost	20.6	20.5	$ million
Other direct cost	22.6	22.5	$ million
Indirect cost	19.5	19.4	$ million
Contractor's fee and contingency	9.4	9.4	$ million
Start-up cost	3.6	3.6	$ million
Working capital	0.8	2.6	$ million

TABLE 5 | Executive summary of the process economics of the two processes.

Parameter	Cost		Unit
	HCl process	CB process	
CAPEX	76.5	78.0	$ million
OPEX	23.1	43.5	$ million/year
Annual production	259,505	259,518	MT/year
COGS	0.09	0.17	$/kg
COGS (without depreciation)	0.06	0.14	$/kg
MSP at breakeven	0.08	0.16	$/kg

Abbreviations: CAPEX, capital expenditure for the facility; COGS, cost of goods sold (i.e., the unit production cost); MSP, minimum selling price, defined as the selling price at which the project achieves a zero net present value (NPV), corresponding to an internal rate of return (IRR) of 10% over a 25-year project lifetime with a 40% tax rate; and OPEX, annual operating expenses.

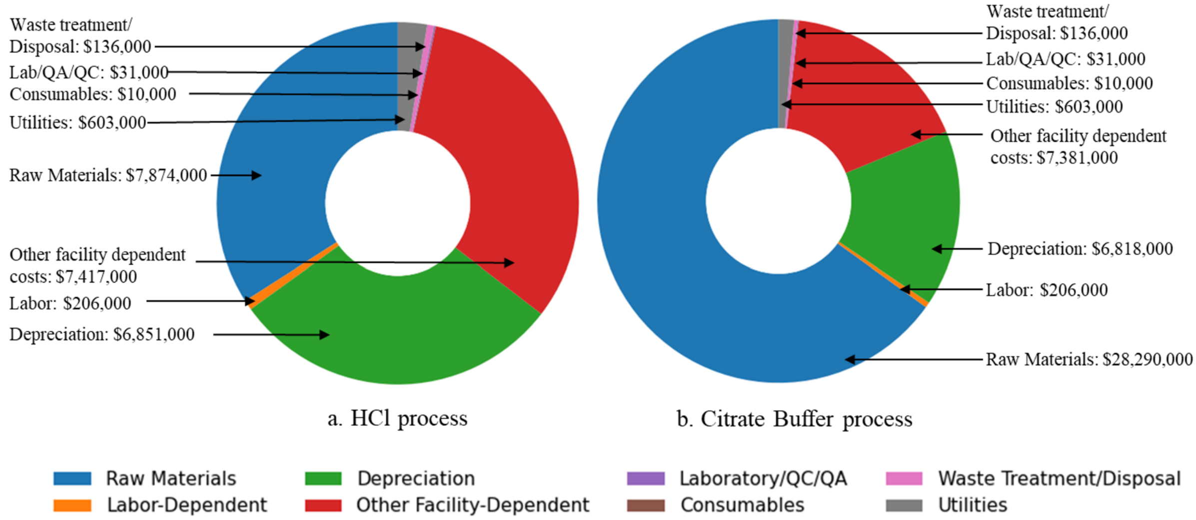

FIGURE 3 | (A) OPEX breakdown for HCl facility—Raw material cost: $7,874,000 (34.05%); Labor: $206,000 (0.89%); Depreciation: $6,851,000 (29.62%); Other facility-dependent costs: $7,417,000 (32.07%); Laboratory/QC/QA: $31,000 (0.13%); Consumables: $10,000 (0.04%); Waste treatment/disposal: $135,000 (0.59%); and Utilities: $603,000 (2.61%). (B) OPEX breakdown for CB facility—Raw material cost: $28,291,000 (65.08%); Labor: $206,000 (0.47%); Depreciation: $6,818,000 (15.69%); Other Facility-Dependent costs: $7,381,000 (16.98%); Laboratory/QC/QA: $31,000 (0.07%); Consumables: $10,000 (0.02%); Waste Treatment/Disposal: $135,000 (0.31%); and Utilities: $596,000 (1.37%).

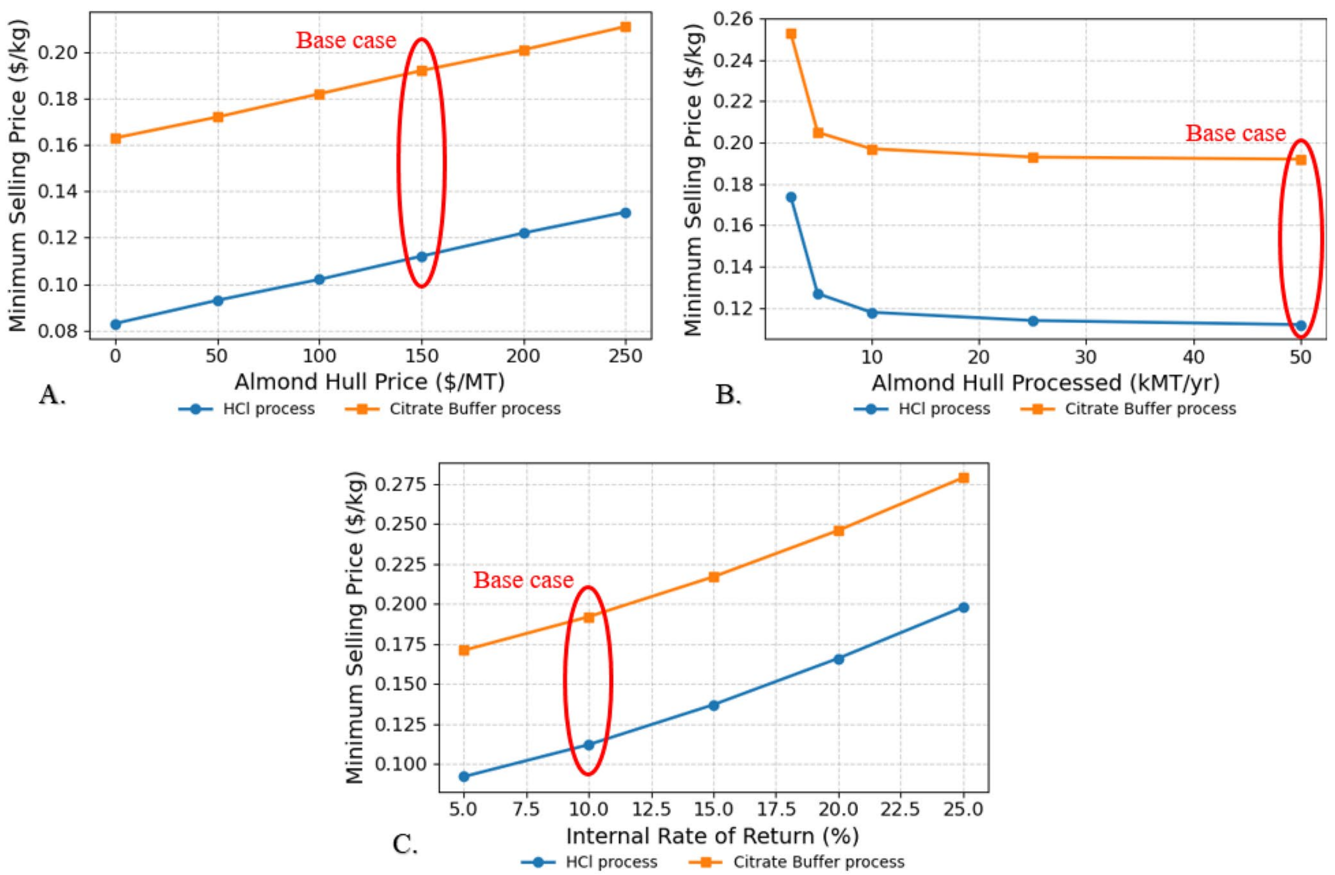

FIGURE 4 | (A) Sensitivity of AHH MSP at varying almond hull prices to achieve 10% IRR over a 25-year project life, at a 40% tax rate. (B) Sensitivity of AHH MSP at varying facility production scales to achieve 10% IRR over a 25-year project life, at a 40% tax rate, processing 50 kMT of almond hull/year. (C) Sensitivity of AHH MSP to achieve varying IRR at a 40% tax rate, processing 50 kMT of almond hull/year at a selling price of $150/MT over a 25-year project life span.

year to $0.118/kg (HCl) and $0.197/kg (CB) at 10 kMT/year. Beyond this point, further increases in production capacity yielded only marginal cost reductions, with MSPs approaching $0.112/kg (HCl) and $0.192/kg (CB) at 50 kMT/year. Across all evaluated scales, the HCl process consistently outperformed the CB process by approximately $0.06–$0.08/kg, underscoring

TABLE 7 | Profitability parameters for the two processes.

Profitability metric	Value	
	HCl process	CB process
COGS	\$0.09/kg	\$0.17/kg
NPV (at 7% discount rate)	\$386 million	\$264 million
IRR	45.5%	35.2%
Payback period	1.61 years	2.21 years

Note: These calculations assume a 25-year project lifespan, a 40% tax rate, 10-year straight-line depreciation for the purchased equipment, and an AHH selling price of \$0.35/kg.

its superior cost competitiveness. These results suggest that economies of scale are largely realized by around 10 kMT/year, beyond which additional economic gains are minimal. Consequently, firms may retain strategic value by delaying investment in very large-scale facilities (processing > 10 kMT almond hulls/year), preserving flexibility while maintaining near-optimal cost performance.

3.4.1.3 | Effect of Targeted IRR. The MSP required to achieve specified IRR was calculated for both the HCl and CB processes (Figure 4C). As expected, MSP increased with increasing target IRR for both processes, reflecting the need for higher selling prices to meet higher return requirements. Across all IRR levels, the CB process consistently exhibited a higher MSP than HCl because of higher capital and operating costs. For example, at a 10% IRR, the MSP for HCl was \$0.112/kg, whereas for CB it was \$0.192/kg. Across all IRR levels, the CB process consistently exhibited higher MSPs than HCl, with the cost gap remaining relatively constant at approximately \$0.08–0.09/kg. These results suggest that HCl is economically more favorable, as it can achieve a given IRR at a lower selling price, whereas CB may require higher market prices to meet equivalent return targets.

Table 7 summarizes profitability metrics used to compare the two AHH production processes. The NPV calculations use a discount rate of 7% and assume the real price remains constant over the life of the project. The profitability parameters NPV and IRR suggest that the HCl process is more profitable than the CB process. When the selling price of AHH is \$0.35/kg, the IRR of the two processes is 45.5% and 35.2%, respectively. These calculations confirm that both processes are gainful investments, as an IRR of 10% is usually considered good. Many investors have payback period goals of 5 years or less, and both processes have lower payback periods.

3.5 | PMI and EHS Assessment

Table 8 shows that 83% of the PMI is attributed to water, the majority of which originates from the hydrolysis buffer. The other raw materials used in buffer preparation and cleaning contribute only a small fraction of the total PMI. The PMI values were used as the MI in the environmental impact assessment. The EI was then calculated using the average method (Mv). From these values, the general effect index (GEI)—defined as the ratio of EI to MI—was determined. The GEI (Mv) ranges from 0 to 1, where lower values

TABLE 8 | Process mass intensity.

Material	HCl process usage (g/kg AHH)	CB process usage (g/kg AHH)
Almond hull	192.7	192.7
NaOH	0.387	0.387
Citric acid	0.186	2.9
Hydrochloric acid	1.076	n.a.
Sodium citrate	n.a	19.3
Pectinase	0.019	0.019
Water	1214.4	1186.9

indicate better overall environmental performance. For the HCl process, the GEI (Mv) is 0.0002, primarily due to the use of HCl for pH maintenance and NaOH during clean-in-place. For the CB process, the GEI (Mv) is 0.0001, attributed to NaOH used during clean-in-place. These results indicate that both proposed processes exhibit a very small overall environmental impact.

3.6 | LCA of AHH

3.6.1 | Life Cycle Impacts

The LCA of the AHH production process evaluated four scenarios, representing two hydrolysis process options (HCl and CB) and two almond hull life cycle inventory (LCI) datasets. The HCl process exhibited generally lower environmental impacts than the CB process, in some categories by nearly an order of magnitude (Figure 5). In the HCl process, electricity generation and citric acid production were the primary contributors to most impact categories, while pectinase enzyme production was the largest contributor to ecotoxicity in the California-specific LCI scenario (Figure 5A). The California-specific hull LCI dataset (Figure 5A) also resulted in higher water use and lower ecotoxicity associated with almond hull production than the generalized U.S. dataset (Figure 5B). These differences primarily reflect methodological distinctions between the two LCI datasets, with the California-specific dataset incorporating statewide compliance reporting on pest control practices, county-specific yield data, and a production land area-based allocation method.

In contrast, impacts associated with the CB process were dominated by sodium citrate, the principal chemical input for pH control (Figure 6). Similar to the HCl process, the California-specific hull LCI dataset (Figure 6A) resulted in higher water use and lower ecotoxicity associated with almond hull production than the generalized U.S. dataset (Figure 6B), owing to the same methodological differences between the two LCI datasets.

3.6.2 | LCA Sensitivity

Sensitivity analysis was used to help quantify uncertainty associated with almond hull impacts. Given the use of economic

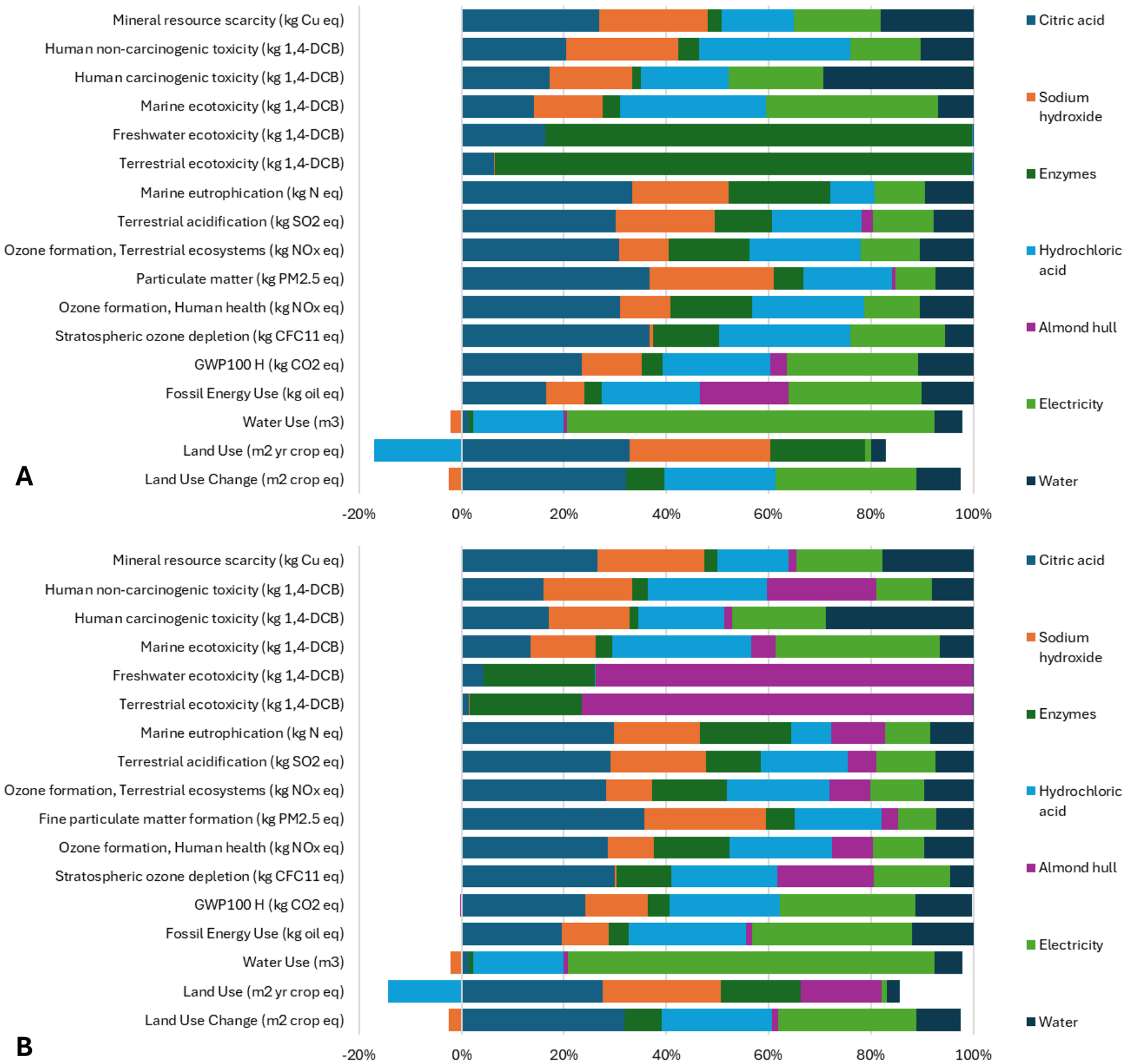

FIGURE 5 | Environmental impacts of almond hull hydrolysate (AHH) production using the hydrochloric acid (HCl) process with (A) California-specific (Marvinney and Kendall 2021) and (B) US generalized (Wernet et al. 2016) almond production life cycle inventory datasets.

allocation to assign impacts of the almond production system to hull as a coproduct, changes in hull price have the potential to create significant uncertainty and variability in the calculated environmental impacts of AHH production. Almond hull, historically considered a waste stream or byproduct of almond production, has in recent decades become an important feed source to the California dairy industry.

Thus, changes in the regional dairy production landscape driven by economic and regulatory factors, as well as the availability and price of other feed sources (corn, alfalfa, etc.), can drive variability in almond hull price and treatment in the calculation of footprints. Figure 7 illustrates the percent change in AHH production impact values as a function of hull price, with the magnitude of slope representing sensitivity. The sensitivity varies by impact depending on its respective intensity in the almond hull impact set—thus, the model is least sensitive to ozone formation as the least intense impact category in almond hull production, and most sensitive to freshwater eutrophication given the high intensity in this impact dimension associated with almond hull production.

Where the assumed value of almond hull drops to zero, it can be considered a waste stream with zero associated impacts as calculated by economic allocation. In this case, a system expansion approach may be adopted whereby alternate, substitutable products in appropriate proportion may be displaced and the impacts of their production thus avoided. Here, alternate sugars from US beet and sugarcane as well as a processed white sugar and an unspecified sugar source represented by the average of the three were examined (Figure 8). The magnitude of change associated with credits to the AHH production system for sugar displacement is determined by the magnitude of impacts associated with a given source and the quantity required in the AHH process. The greatest impact reductions were observed in ozone formation and cane sugar.

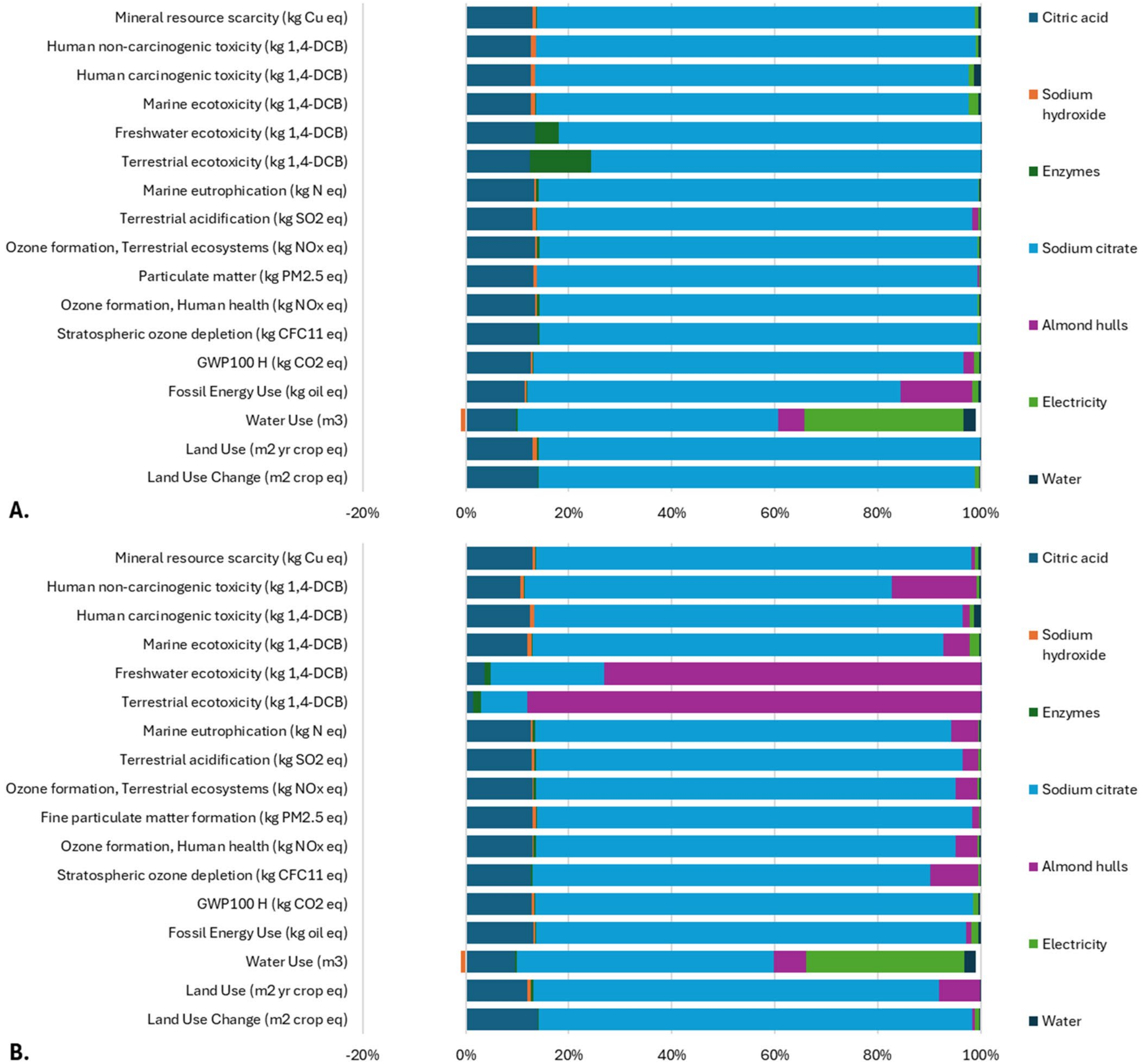

FIGURE 6 | Environmental impacts of almond hull hydrolysate (AHH) production using the citrate buffer (CB) process using (A) California-specific (Marvinney and Kendall 2021) and (B) US generalized (Ecoinvent 2024) almond production life cycle inventory datasets.

Relatively little effect of displacement was observed for water use impacts.

AHH-based media production was compared with a simulated media produced using alternative sugar sources. These simulated media compositions were compared with AHH production under both processes and the three modeling scenarios: California almond hull LCI, US almond hull LCI, and byproduct/displacement (Figure 8). With almond production impacts allocated to hull using a value of $150/MT, the AHH media produced from the CB process outperformed or were comparable with simulated alternatives in most environmental impact categories, with the exceptions of land-use change, mineral resource scarcity, freshwater ecotoxicity, particulate matter emission, and stratospheric ozone depletion. AHH produced via the HCl process consistently exhibited lower environmental impacts than both the simulated media and the CB process. Both the CB- and HCl-derived AHH processes modeled using a system expansion approach, including credits for displacement of conventional sugar production, demonstrated substantially lower environmental impacts, with reductions ranging from 2000% to 3000% across all evaluated impact categories.

4 | Discussion

4.1 | Technoeconomic Performance and Cost Drivers

This study presents the first integrated TEA-LCA of AHH as a fermentation feedstock. AHH demonstrates strong economic potential due to the abundance, local availability, and low

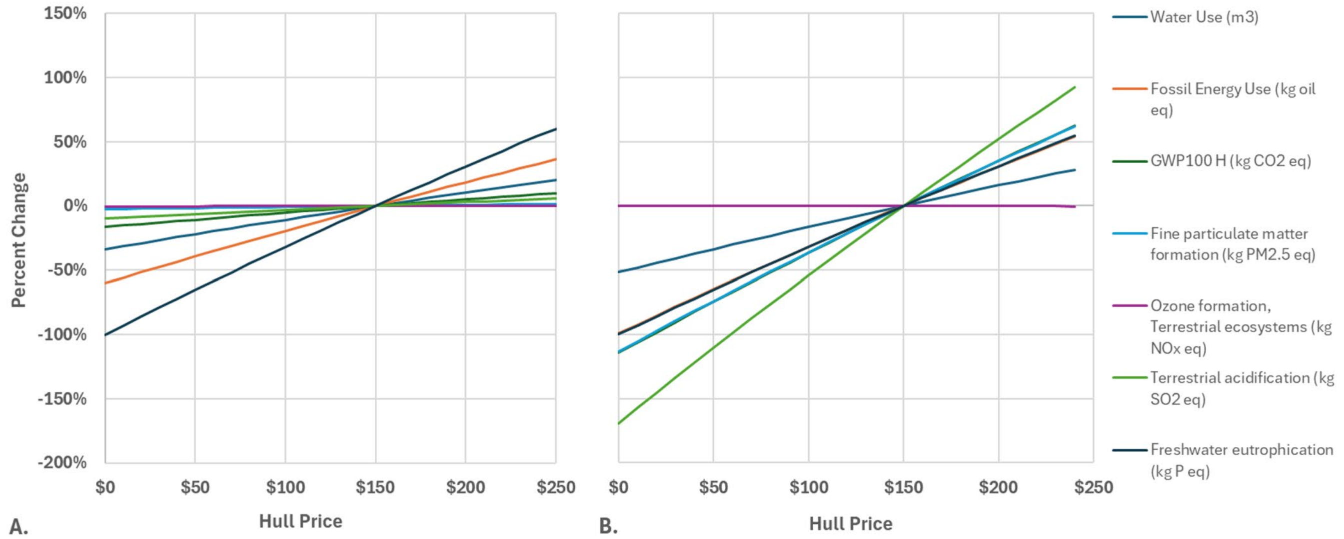

FIGURE 7 | Model output sensitivity to change in almond hull feedstock price in the range of \$0–\$250.00/MT (wet basis) for AHH media produced through (A) the CB process and (B) the HCl process. Environmental impact reductions greater than 100% are observed where impact values fall into the negative range (I.E., production processes produce environmental benefits).

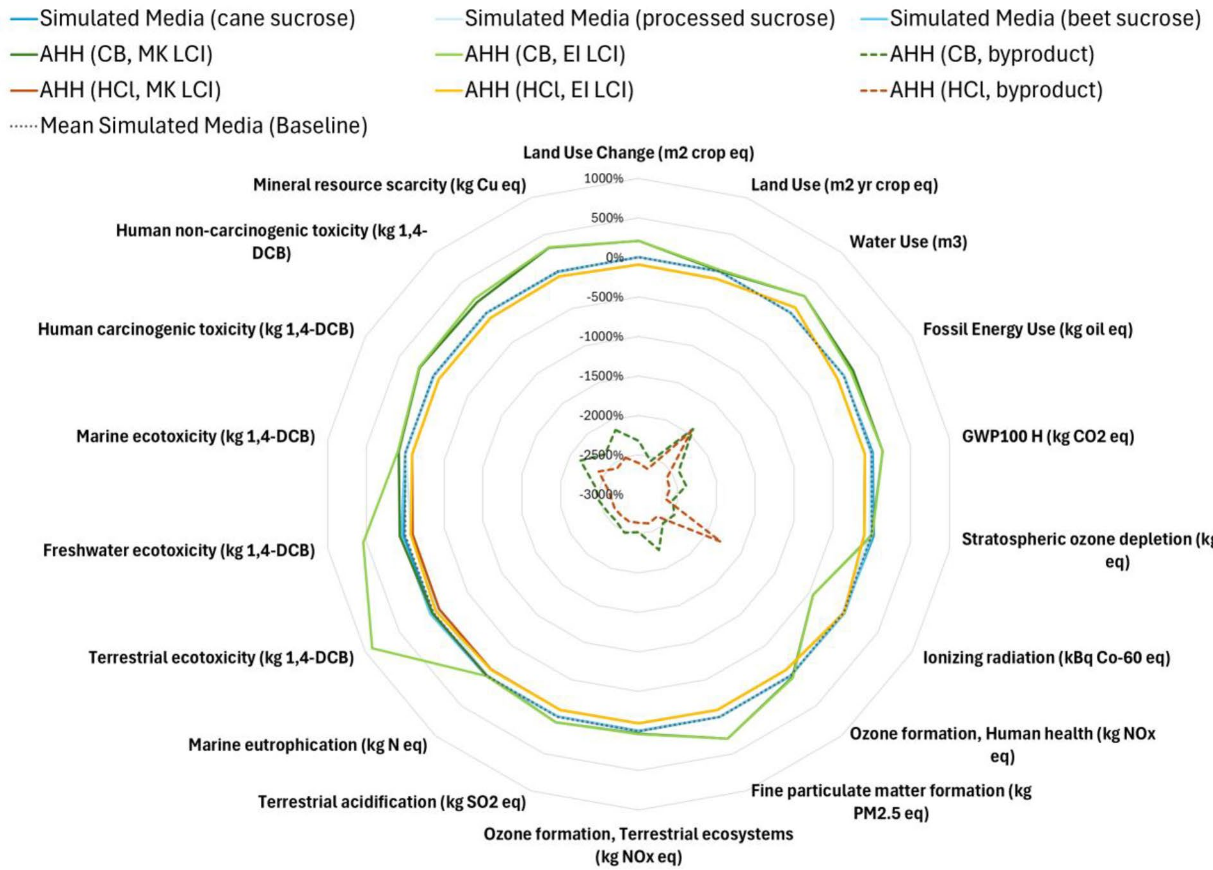

FIGURE 8 | Impact comparison between various production and modeling scenarios. In blue, simulated AHH media using fructose, glucose, and sucrose from various sources. In orange and green, media produced with AHH from the CB and HCl processes, respectively, using either California-specific (MK: Marvinney and Kendall 2021) or generalized US (EI: EcoInvent) almond production inventory flows allocated economically to hull, assuming a value of \$150/ton. Dotted lines represent the special case where hull is treated as a waste stream or byproduct of almond production (value = zero). In this case, a system expansion approach is adopted in which the use of AHH media production is assumed to displace the use of sucrose, glucose, and fructose in quantities found in AHH. Values are reported relative to the mean of all scenarios to view all impact categories on the same axis (dashed line).

market value of almond hulls compared to conventional sugar sources. As discussed in Section 3.2, AHH contains several components that enhance microbial growth. A synthetic medium replicating the composition of AHH, comprising 18.5 g DW/L glucose syrup, 16.5 g DW/L high-fructose corn syrup, 6 g DWL refined sugar, and 6 g/L galacturonic acid, would cost approximately $0.21/kg. In contrast, the COGS for the two AHH production processes are $0.09 and $0.17/kg. In addition to lower cost, the AHH provides all nutrients needed for yeast growth as shown in Figure 2, eliminating the need to supplement with vitamins, minerals, or cofactors. This finding highlights AHH as a cost-effective alternative to conventional fermentation media. Limiting factors for use of almond hulls to produce bioproducts include almond allergies, potential pesticide residues, and the hulls being stored in heaps on the ground at the processing facilities, which may limit use in the production of food ingredients.

For comparison, a lignocellulosic sugar production facility modeled by Ou et al. (2021) processes 547,500 MT DW biomass/year. It achieves an MSP of $0.45/kg at a 10% IRR, producing a 30 wt% glucose stream. The AHH process, with a sugar concentration of ~4 wt% (glucose, sucrose, and fructose), yields an MSP of $0.11/kg for the HCl process and 0.19/kg for the CB process at the same IRR. Although the process by Ou et al. (2021) appears more economical on a per-sugar basis, it excludes facility-dependent costs—which represent 61.7% of total operating costs for the HCl process and 32.7% for the CB process. When these are excluded for comparability, the HCl process is ~33% less expensive on a per-gram sugar basis, whereas the CB process is roughly twice as costly due to higher raw-material expenses. Overall, these results demonstrate that the proposed AHH process appears economically competitive with other waste-biomass sugar production processes.

Although both almond hull price and the internal rate of return (IRR) influence the MSP, neither can be readily optimized to reduce production costs. In contrast, production scale is a controllable parameter with a direct impact on process economics. Sensitivity analysis indicates that increasing facility throughput beyond 10,000 MT almond hulls per year results in only marginal reductions in MSP. This finding supports a stepwise scaling approach—initially constructing facilities at approximately 10,000 MT/year to capture the primary economies of scale, with the option to expand as market certainty and demand increase.

4.2 | PMI and EHS Implications

PMI analysis shows the process is water-intensive (≈83% of PMI; Table 8), largely because the hydrolysis step operates at a 5:1 buffer-to-biomass mass ratio. Despite high water use, the EHS scores are very low for both routes (GEI [Mv] ~10^{-4} to 10^{-3}), reflecting the benign nature and dilute use of most inputs. The slightly lower GEI (Mv) for CB is driven by the hazard classification scheme and does not account for energy burdens; in contrast, the LCA (Section 3.5) indicates the HCl route has lower cradle-to-gate impacts overall. Practically, closed-loop water reuse and CIP/SIP optimization could reduce PMI without affecting conversion.

4.3 | Environmental Performance, Allocation, and System Boundaries

The environmental performance of AHH as a sugar source for microbial fermentation compares favorably with that of alternative sugar sources as indicated above. This is primarily due to the status of hull as a relatively low-value agricultural coproduct as compared to the primary product of almond production—kernel—as well as in comparison with primary sugar crops like sugarcane and sugar beet. Using economic allocation to assign impacts to an agricultural coproduct reflects the balance of motivation driving the production system: almond orchards are planted to produce almond kernel, with valorization of coproducts like hull a distant second priority. This priority structure is reflected in the relative economic value of each coproduct, making economic allocation an appropriate choice for assigning impacts.

Almond hulls have been valued as a dairy feedstock in California for decades and so have a well-established market and consistent valuation. The scenario of a zero value and adoption of system expansion and displacement is included for methodological comparison but is not considered a best practice for coproduct treatment in the LCA model for almond hull. With the development of new coproduct use pathways like AHH, the economic value of almond hull and similar agricultural coproducts is more likely to increase in the foreseeable future than to drop to zero.

Even with the considerable water use demanded by almond production, the AHH media production processes both reduce water consumption compared to the alternative sugar sources examined here. Greenhouse gas emissions, eutrophication, and acidification impacts are also reduced. These represent some of the most well-characterized and prioritized impact categories, positioning AHH well from a sustainability standpoint.

The tradeoffs observed in ecotoxicity, ozone depletion, and particulate matter emission are generally a lower priority for sustainability efforts and occur only with the CB process. AHH from the HCl process appears to be an excellent option from an environmental performance standpoint (Figure 8). Other than the chemical inputs, which are required in fixed ratios, grid electricity is the primary contributor to most impacts in the HCl-derived AHH process (Figure 5). This raises the potential for adoption of on-site renewable energy to further improve the environmental performance of HCl-derived AHH production, given that changes in chemical inputs are less feasible.

Further work is needed to assess changes in environmental impacts with process scaling. At larger scales, production efficiency can be increased—potentially resulting in less energy and resource demand and an associated reduction in impacts. Increased net financial returns per unit of AHH product are possible at larger scales as well. If environmental impacts are expressed on a value-based functional unit rather than the mass-based unit adopted here, increases in economic efficiency can produce significant commensurate increases in environmental performance. Although such economic-based functional units are less commonly used in LCA, there is an argument to be made that such reporting reflects the primary motivations for production in a profit-driven system and thus can provide an important counterpoint to traditional mass or energy-based functional units.

5 | Conclusion

Using an LCA approach to evaluate the environmental performance of AHH production demonstrates that AHH is comparable to or less impactful than alternative cell culture media sugar sources derived from primary agricultural products rather than coproducts like almond hulls. Of the two pathways examined, the HCl process is less impactful in every category. Modeling choices can have a significant effect on impact estimates, but the overall conclusion that the HCl process outperforms alternative media formulations on environmental performance remains consistent over all of the modeling options tested.

1. *Economic viability*: At commercial scale (50 kMT/year), AHH can be produced at \$0.11–0.19/kg MSP (at 10% IRR), with the HCl route outperforming CB due to substantially lower OPEX (Table 5; Figure 3). Most economies of scale are realized by ~10 kMT/year (Figure 4B). MSP is most sensitive to IRR, then scale, then hull price (Figure 4A–C).
2. *Environmental advantage*: Cradle-to-gate impacts for AHH are lower than refined sugars, with the HCl route showing the lowest overall impacts across inventories and allocation choices (Figures 5–8). Electricity dominates several categories, highlighting on-site renewables and heat integration as high-leverage improvements.
3. *Operational insights*: PMI is dominated by water; closing water loops and right-sizing CIP/SIP can reduce PMI without compromising hygiene.
4. *Strategic fit*: AHH offers a scalable, circular pathway to reduce the cost and footprint of fermentation media sugars for sustainable proteins and bioproducts, especially when leveraging existing almond infrastructure.

For near-term deployment, we recommend HCl-based AHH produced at a production scale of ≥ 10 kMT of almond hulls per year and co-located with an almond hulling and shelling facility, with staged expansion and targeted renewable-utility decarbonization. This pathway can materially lower the cost and emissions of fermentation media across lipids, SCP, organic acids, and ethanol, advancing both sustainable protein sources and agro-residue upcycling goals. Additionally, AHH as a sugar-rich media component should be tested for a variety of industrial and food fermentation applications.

Author Contributions

Boon-Ling Yeo: formal analysis, funding acquisition, investigation, methodology, project administration, software, supervision, writing – original draft, writing – review and editing. **Varun Gore:** formal analysis, data curation, investigation, methodology, software, writing – original draft. **Alex Ogino Hitomi:** investigation, methodology, data curation, writing – original draft. **Karen A. McDonald:** conceptualization, investigation, resources, funding acquisition, project administration, supervision, writing – original draft, writing – review and editing. **Elias Marvinney:** software, data curation, methodology, writing – original draft. **Irnayuli Sitepu:** investigation, methodology, data curation, writing – original draft, writing – review and editing. **Tina Jeoh:** funding acquisition, resources, supervision, project administration, writing – review and editing. **Kyria Boundy-Mills:** funding acquisition, resources, supervision, project administration, writing – review and editing.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Process mass intensity (PMI) inventories for almond hull hydrolysate (AHH) media and simulated hydrolysate media, reported as input quantity per kg of product. (A) AHH media produced via the hydrochloric acid process. (B) AHH media produced via the citrate buffer process. (C) Simulated hydrolysate media formulated from pure sugars. **Table S2:** Impacts.