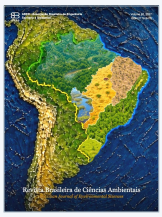
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Competitive advantage in biodiesel production: conversion of glycerol and phospholipid-rich gum into value-added streams

Vantagem competitiva na produção de biodiesel: conversão de glicerol e goma rica em fosfolipídios em correntes de valor agregado

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Abstract

The rapid expansion of biodiesel production has reinforced its relevance in low-carbon energy transitions while exposing a critical structural limitation associated with high production costs and narrow profit margins. Under these conditions, the effective utilization of by-products such as crude glycerol, phospholipid-rich gum, and soapstock emerges as a key factor influencing the overall performance and viability of biodiesel systems. This review repositions biodiesel by-products from residual liabilities to strategic resources by examining their conversion into value-added products, including biofertilizers and biogas, with particular emphasis on phosphorus recovery from degumming gum and carbon recovery from crude glycerol. These pathways offer opportunities to enhance resource efficiency and support integrated biorefinery configurations, although they also face key limitations related to process instability, feedstock variability, pretreatment requirements, and regulatory constraints that impact scalability and environmental performance. Overall, by-product valorization can play a central role in improving both the sustainability and the economic performance of biodiesel systems, supporting the transition toward more integrated and resilient biorefinery configurations.

Keywords biorefinery · by-product valorization · phosphorus recovery · biofertilizers · anaerobic digestion · circular economy

Resumo

A rápida expansão da produção de biodiesel tem reforçado sua relevância nas transições para matrizes energéticas de baixo carbono, ao mesmo tempo em que evidencia uma limitação estrutural crítica associada aos elevados custos de produção e às reduzidas margens de lucro. Nessas condições, o aproveitamento eficiente de subprodutos como o glicerol bruto, a goma rica em fosfolipídios proveniente da degomagem e a borra de neutralização (*soapstock*) surge como um fator-chave para o desempenho global e a viabilidade dos sistemas de produção de biodiesel. Esta revisão reposiciona os subprodutos do biodiesel, tradicionalmente considerados passivos residuais, como recursos estratégicos, ao examinar sua conversão em produtos de valor agregado, incluindo biofertilizantes e biogás, com ênfase especial na recuperação de fósforo da goma de degomagem e na recuperação de carbono do glicerol bruto. Essas rotas oferecem oportunidades para aumentar a eficiência no uso de recursos e favorecer a implementação de configurações integradas de biorrefinarias, ao mesmo tempo em que evidenciam limitações importantes relacionadas à instabilidade dos processos, à variabilidade das matérias-primas, aos requisitos de pré-tratamento e às restrições regulatórias que afetam a escalabilidade e o desempenho ambiental. Dessa forma, a valorização dos subprodutos pode desempenhar um papel central na melhoria da sustentabilidade e da competitividade econômica dos sistemas de produção de biodiesel, contribuindo para a transição em direção a configurações de biorrefinarias mais integradas, eficientes e resilientes.

Palavras-chave biorrefinaria · valorização de subprodutos · recuperação de fósforo · biofertilizantes · digestão anaeróbia · economia circular

1 Introduction

Global strategies to mitigate greenhouse gas emissions and strengthen energy security have accelerated the deployment of biofuels, positioning biodiesel as a central component of low-carbon transport systems (Mahate et al., 2023). Produced predominantly through the transesterification of vegetable oils or animal fats into fatty acid alkyl esters (FAAEs), biodiesel has gained recognition not only for its decarbonization potential but also for its socioeconomic relevance in agro-industrial regions (Mahate et al., 2023; Nogales-Delgado, 2025).

Biodiesel production has followed a sustained upward trajectory over the past decade (Mhetras and Gokhale, 2025). In Brazil, one of the world's leading producers, biodiesel output increased by 21% between 2023 and 2024, reaching 9.1 million m^3 (Correia et al., 2025). For every ten parts of biodiesel produced, approximately one part of crude glycerol is formed, while upstream oil pretreatment operations simultaneously generate substantial volumes of phospholipid-rich gum and soapstock, which concentrate residual catalysts, salts, metals, free fatty acids (FFA), and unreacted lipids.

Collectively, these streams represent a substantial industrial output characterized by high biochemical oxygen demand and chemical oxygen demand (COD), compositional variability, and potential environmental liability, which, when not effectively managed, may lead to soil and water contamination, regulatory non-compliance, and increased treatment costs (Barbusiński et al., 2021). However, biodiesel by-products are more than an environmental concern and are emerging as strategic elements within production systems. As biodiesel markets expand and profit margins remain constrained, the capacity to convert these residual streams into value-added products increasingly defines industrial competitiveness, directly influencing the economic viability of biodiesel production systems (Apostolakou et al., 2009; Omori et al., 2025).

Under these conditions, the economic structure of biodiesel production further reinforces the strategic role of by-product valorization. Production costs are largely driven by feedstock prices, which can account for up to 75–90% of total manufacturing costs (Apostolakou et al., 2009; Omori et al., 2025; Mehra and Goel, 2025), often making biodiesel 1.5 to 3 times more expensive than fossil diesel (Omori et al., 2025). This cost structure leaves limited room for profitability and increases sensitivity to operational inefficiencies. As a result, the competitive performance of biodiesel systems is increasingly shaped not only by fuel yield or process efficiency, but also by the ability to convert residual streams into higher-value products. Indeed, the valorization of by-products such as glycerol into value-added compounds has been shown to enhance overall process economics and improve system-level performance (Omori et al., 2025). Consequently, the capacity to extract value from by-products is not merely a sustainability strategy but a key factor influencing economic viability and long-term resilience in biodiesel production systems.

To identify relevant literature, a focused search was conducted using ScienceDirect, Scopus, and Google Scholar, with the primary search period covering studies published from 2015 to 2025, complemented by relevant publications from 2026 to capture the latest developments in biodiesel by-product valorization. Search strategies combined terms related to biodiesel production and by-products, including "crude glycerol," "phospholipid," "degumming gum," "soapstock," and "wastewater," with terms such as "valorization," "value-added products," "biorefinery," "conversion," "fermentation," "anaerobic digestion," "biofertilizer," "biogas," and "techno-economic analysis." For the assessment of economic reporting, additional combinations included "internal rate of return" OR "IRR," "net present value" OR "NPV," "payback period," "capital expenditure" OR "CAPEX," and "minimum selling price." The literature was screened for its relevance to the conversion, recovery, or utilization of by-products directly generated during biodiesel production, with particular emphasis on studies providing quantitative information on process performance, product generation, economic assessment, or potential process integration. Although the primary search focused on 2015–2025, selected earlier studies were retained when they provided foundational information or relevant process data necessary to contextualize the technologies discussed.

This review provides a structured and critical synthesis of the current state of biodiesel by-product valorization from a value-oriented perspective. It contextualizes the expansion of biodiesel production and the resulting increase in residual stream generation. It examines the biochemical and engineering foundations underlying the conversion of crude glycerol, phospholipid-rich gum, and soapstock into biofertilizers and biogas. It also discusses the principal operational bottlenecks, environmental trade-offs, and scalability challenges associated with these routes. By integrating technological insights with value-oriented process considerations, this work aims to clarify the conditions under which by-product valorization can contribute to more resource-efficient and resilient biodiesel systems.

2 Biodiesel by-products and challenges

The rapid expansion of biodiesel production, driven by climate mitigation policies and energy security goals, has unintentionally generated a parallel global environmental challenge: the large-scale production of chemically complex and highly polluting by-products. While fuel quality and conversion efficiency are tightly regulated and continuously optimized, the management of biodiesel-derived residues remains uneven across regions and production scales (Tomatis et al., 2024; Mehra and Goel, 2025; Omori et al., 2025). As a result, these by-products increasingly represent a global environmental management problem, particularly in water-scarce regions with limited regulatory capacity, where inadequate treatment or disposal can lead to severe impacts on aquatic ecosystems, soil quality, and wastewater infrastructure (Tomatis et al., 2024).

Biodiesel production has been extensively documented in the literature, with well-established technological routes encompassing feedstock pretreatment, transesterification, and downstream purification (Miotti et al., 2022; Mehra and Goel, 2025; Nogales-Delgado, 2025). While substantial efforts have been devoted to improving fuel

quality, reaction efficiency, and regulatory compliance, comparatively less attention has been paid to the cumulative environmental burden associated with the generation and management of by-products along the biodiesel production chain (Tomatis et al., 2024).

Among the upstream processing stages, oil degumming is a key node where waste generation and environmental risk are intrinsically shaped by process choice. Degumming can be carried out through alkaline, acidic, or enzymatic routes to remove phospholipids from the oil. For biodiesel marketed in Brazil, the standards of the National Agency of Petroleum, Natural Gas and Biofuels (ANP) set a maximum phosphorus content of 3 mg/kg (Table 1). These processes generate chemically and physically distinct residual streams with different environmental behaviors (Figure 1).

Alkaline degumming (Figure 1-a) promotes the formation of soapstock through saponification reactions between FFA and alkali, generating a highly alkaline, emulsified by-product rich in soaps, water, and entrained oil (Passos et al., 2019; Chew and Nyam, 2020). Soapstock exhibits a highly heterogeneous composition that depends on feedstock type, oil quality, and processing conditions. It is generally composed of water (approximately 45%, though variable), fatty acid salts (around 10%), neutral oil fractions (12%), residual phospholipids (9%), and a range of minor components (24%). It is further characterized by high alkalinity, foaming tendency, and elevated COD, which may constrain its effective valorization and downstream processing.

Acid degumming (Figure 1-b) converts non-hydratable phospholipids into insoluble forms, generating an acidic sludge commonly referred to as acid gum. This residue is typically enriched in intact phospholipids and inorganic salts and has residual acidity, resulting in a high organic load and limited immediate valorization pathways (Chew and Nyam, 2020). Enzymatic degumming (Figure 1-c) selectively hydrolyzes phospholipids through the catalytic action of phospholipases, generating lysophospholipids, FFA, and diacylglycerols that remain partially dispersed in an oil–water matrix known as lysogum (Passos et al., 2019; Khamies et al., 2024).

In contrast to conventional chemical degumming, which often leads to the co-removal of neutral oil with the hydrated gums, the enzymatic process promotes a more selective conversion of phospholipids while minimizing oil losses (Khamies et al., 2024). As a result, a greater fraction of the neutral oil is retained in the main phase, improving overall oil recovery and increasing the yield of conditioned oil available for subsequent transesterification. This enhanced oil retention not only contributes to higher biodiesel production efficiency but also reduces process inefficiencies associated with neutral oil entrainment in gum fractions (Passos et al., 2019).

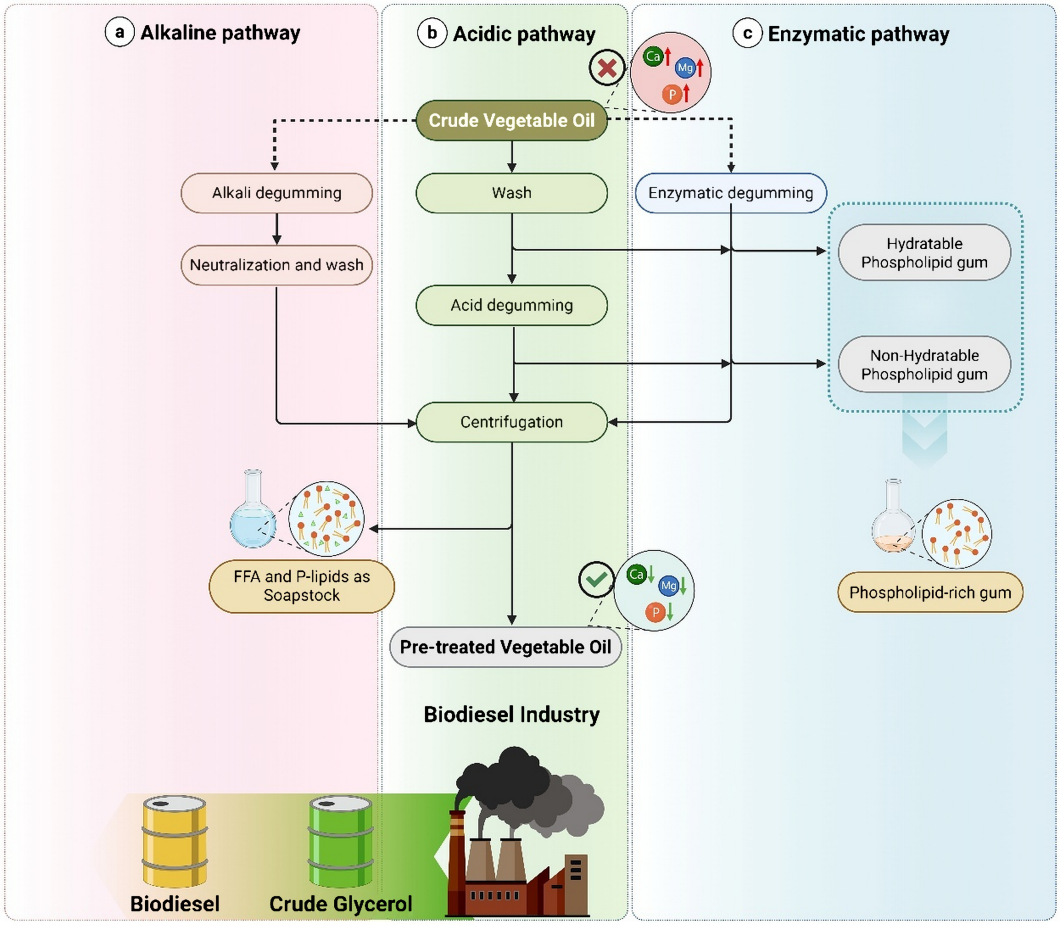


Figure 1. Degumming pathways in vegetable oil processing and the generation of phospholipid-rich streams

Table 1. Biodiesel quality specifications for commercialization in Brazil under ANP standards and corresponding analytical methods

CHARACTERISTIC	UNIT	LIMIT	METHOD		
			ABNT NBR	ASTM D	EN/ISO
Appearance	–	–	–	–	–
Density at 20°C	kg/m³	850 to 900	7148 / 14065	1298 / 4052	EN ISO 3675 / EN ISO 12185
Kinematic viscosity at 40°C	mm²/s	3.0 to 5.0	10441	445 / 7042	EN ISO 3104
Water content, max.	mg/kg	200.0	–	6304	EN ISO 12937
Cold soak filtration test (CSFT), max.	s	Report	–	7501	–
Flash point, min.	°C	100.0	14598	93	EN ISO 3679
Ester content, min.	% mass	96.5	15764	–	EN 14103
Sulfated ash, max.	% mass	0.020	6294	874	EN ISO 3987
Total sulfur, max.	mg/kg	10	15867	5453	EN ISO 20846 / EN ISO 20884
Sodium + Potassium, max.	mg/kg	2.5	15553	–	EN 14538
Calcium + Magnesium, max.	mg/kg	2.5	15553	–	EN 14538
Phosphorus, max.	mg/kg	3.0	15553	–	EN 16294
Copper strip corrosion, 3 h at 50°C, max.	–	1	14359	130	EN ISO 2160
Cold filter plugging point (CFPP), max.	°C		14747	6371	EN 116
Acid value, max.	mg KOH/g	0.50	14448	664	EN 14104
Free glycerol, max.	% mass	0.02	15908	6584	EN 14105
Total glycerol, max.	% mass	0.20	15908	6584	EN 14105
Monoacylglycerols, max.	% mass	0.50	15908	6584	EN 14105
Diacylglycerols, max.	% mass	0.20	15908	6584	EN 14105
Triacylglycerols, max.	% mass	0.20	15908	6584	EN 14105
Methanol and/or Ethanol, max.	% mass	0.20	15343	–	EN 14110
Oxidation stability at 110°C, min.	h	13	–	–	EN 14112 / EN 15751

Source: Compiled by the authors based on Brazil (2023, 2025).

These degumming-derived streams differ markedly in composition, reactivity, and environmental behavior (Dijkstra, 2013; Passos et al., 2019). Soapstock is dominated by saponified fatty acids and has high alkalinity and elevated COD, complicating conventional treatment strategies (Dijkstra, 2013; Passos et al., 2019). Acid degumming residues are generally more viscous and acidic, enriched in intact phospholipids and inorganic salts, whereas lyso-gum contains hydrolyzed phospholipid fragments with enhanced surface activity and higher biochemical accessibility. Although this latter property increases compatibility with biotechnological conversion routes, it may also complicate phase separation, storage stability, and downstream handling (Dijkstra, 2013).

Crude glycerol is the main by-product of biodiesel transesterification, equivalent to about 10% of the total biodiesel mass produced. In practical terms, approximately 10 kg of crude glycerol is generated for every 100 kg of biodiesel (Bansod et al., 2024). This stream is typically a brown, viscous liquid with a highly variable composition that depends on feedstock type, catalyst system, alcohol source, and purification strategy. It may contain substantial amounts of water, methanol, soaps, fatty acid methyl esters (FAME), glycerides, FFA, ash, residual catalysts, and inorganic elements such as calcium, magnesium, phosphorus, and sulfur (Bansod et al., 2024).

Without effective valorization strategies, these by-products risk compromising environmental performance and limiting economic viability, shifting the environmental burden from fossil carbon emissions to water pollution, nutrient losses, and increased treatment demands across global biofuel supply chains (Tomatis et al., 2024). Under these conditions, by-product valorization is more than a complementary sustainability strategy and becomes a central determinant of process performance and industrial competitiveness. This transition has the potential not only to mitigate environmental burdens but also to unlock additional revenue streams, directly reinforcing resource efficiency, circularity, and the long-term resilience of biodiesel production systems (Postaue et al., 2022; Tomatis et al., 2024).

3 Techno-economic analysis

Feedstock cost is widely recognized as the primary structural constraint on the economic viability of biodiesel production. Vegetable oils and fats account for 75–90% of total production costs (Aposto-

lakou et al., 2009; Mehra and Goel, 2025), exceeding 90% in systems reliant on edible oils (Vlysidis et al., 2011; Omori et al., 2025). In Brazil, soybean oil alone can account for up to 92% of operating costs, rendering profit margins highly sensitive to commodity price volatility and competition with the food sector (Omori et al., 2025).

This cost structure imposes a clear disadvantage relative to fossil diesel (Haas, 2005; Haas et al., 2006; Mehra and Goel, 2025), contributing to the economic infeasibility of small-scale plants (≤15 kt/year) and the closure of facilities in mature markets (Vlysidis et al., 2011; Sibal et al., 2026). Evidence from Apostolakou et al. (2009) and Vlysidis et al. (2011) shows that plants within this capacity range cannot remain viable on biodiesel revenues alone, reinforcing the need for additional revenue streams. Accordingly, production scales above 50 kt/year have been recommended to enhance economic robustness and reduce investment risks.

Under these constraints, maintaining competitiveness requires measures beyond process optimization, with by-product valorization emerging as a key strategy. Crude glycerol (≈10% of biodiesel output by mass), soapstock, and phospholipid-rich gum shift from residual streams to central components of biorefinery economics. Upgrading glycerol into value-added products such as hydrogen, electricity, or glycerol carbonate can increase NPV by more than 90% compared with non-valorizing systems (D'Angelo et al., 2018; Omori et al., 2025). Similarly, phosphorus recovery from soapstock (≈20.9%) enables low-cost fertilizer production, generating additional revenue while reducing wastewater treatment burdens (Juneja et al., 2022).

Collectively, these approaches enable value redistribution across the production chain, reducing reliance on biodiesel as the sole revenue stream and mitigating feedstock cost pressures (Selvakumari et al., 2026). For the comparative techno-economic assessment, studies were selected based on the availability of quantitative information that allowed the main characteristics and economic indicators of the valorization routes to be reported. Particular attention was given to the reporting of CAPEX, minimum selling price, IRR, NPV, and payback period, as described in the literature search and screening strategy presented in the Introduction. In this context, integrated biorefinery models aligned with circular economy principles are essential to ensure long-term economic resilience. Table 2 summarizes the techno-economic performance of selected valorization pathways, highlighting the variability associated with different processes and target products.

Glycerol-based platforms dominate current valorization strategies, encompassing thermochemical and biochemical routes that generate fuels, chemicals, and energy carriers with distinct economic performance. Thermochemical processes, particularly steam reforming, generally exhibit more robust indicators. For example, electricity generation combines a high IRR (i.e., the discount rate at which the NPV equals zero) of 23.20% with moderate CAPEX, indicating a favorable balance between technological maturity and market integration

Table 2. Techno-economic comparison of biodiesel by-product valorization pathways toward integrated biorefineries

Production method	Biodiesel by-product	New product	Capacity	Minimum selling price	CAPEX	IRR	NPV	Payback period	Reference
Steam reforming	Crude glycerol	Methanol	15,895 t/year [a]	846.00 USD/t	USD 43.3 million	17%	USD 74.2 million [b]	4.59 years [c]	(Kgwedi et al., 2023)
Fermentation	Crude glycerol	Succinic acid	430 t/year	4,311.00 €/t	€ 10.71 million	17.48%	€ 9.9 million [b]	5.50 years	(Vlysidis et al., 2011)
Steam reforming	Crude glycerol	Hydrogen	3,217.1 t/year	5.00 USD/kg	USD 26.9 million	13.40%	USD 12.4 million	12.01 years	(Omori et al., 2025)
Steam reforming	Crude glycerol	Electricity	10.95 GWh/year	0.20 USD/kWh	USD 9.62 million	23.20%	USD 15.7 million [d]	5.20 years	(Ziyai et al., 2019)
Anaerobic digestion	Crude glycerol	Biomethane	8,881 t/year	159.47 USD/MWh	USD 116.3 million	2.18%	USD 34.9 million	13.40 years	(Okolie et al., 2021)
Fermentation		Bioethanol	17,002 t/year	0.31 USD/L					
Fermentation	Crude glycerol	Malic acid	1,510 t/year	3,600 USD/t	USD 20.46 million	10.93%	USD 11.9 million [e]	6.71 years	(Selvakumari et al., 2026)
Precipitation	Soapstock	Natural fertilizer	0.43 kt/year [a]	386.70 USD/t	USD 91.3 million	–	–	–	(Juneja et al., 2022)
Precipitation	Wastewater stream	Natural fertilizer	0.51 kt/year [a]	386.70 USD/t	USD 91.45 million	–	–	–	(Juneja et al., 2022)
Esterification	Crude glycerol	Acetins	100,000 t/year	1,586 USD/t	USD 71 million	–	USD 235 million	1.7 years	(Pandit et al., 2023)

Note: Values are reported in the original currencies as presented in the referenced studies. (a) Assuming a standard operating year of 330 days; (b) NPV estimated over a project lifetime of 20 years; (c) Discounted payback period (DPBP); (d) Assuming an interest rate of 7% and a project lifetime of 25 years; (e) Assuming a project lifetime of 20 years and a discount rate of 10%. (–) Not reported.

(Ziyai et al., 2019). Similarly, methanol production shows a competitive IRR (17%) and a short payback period (4.59 years), suggesting greater economic predictability (Kgwedi et al., 2023). In contrast, hydrogen production, despite its strategic relevance, remains economically constrained, with lower IRR values and longer payback periods (Omori et al., 2025).

Biotechnological routes display greater variability. Products such as succinic and malic acids achieve moderate IRR values (≈10–17%), but their viability depends strongly on market prices and downstream processing costs (Vlysidis et al., 2011; Selvakumari et al., 2026). Although high-value chemicals can offset lower yields, this advantage is often counterbalanced by higher CAPEX and increased process complexity. Conversely, anaerobic digestion (AD) of glycerol to biomethane shows limited economic attractiveness, with an IRR of 2.18% and extended payback periods, indicating that energy valorization alone is insufficient to ensure competitiveness (Okolie et al., 2021).

A critical observation from the studies identified through the literature screening and summarized in Table 2 is the limited availability of comprehensive profitability assessments for soapstock and wastewater valorization pathways. Although these streams have been investigated for phosphorus recovery and fertilizer production, the studies identified do not consistently report profitability indicators such as IRR, NPV, and payback period. For example, Juneja et al. (2022) evaluated phosphorus recovery from both soapstock and wastewater using process simulation and techno-economic analysis, reporting capital and operating costs as well as additional revenues from phosphorus recovery, but not IRR, NPV, or payback period. This limited reporting restricts direct comparison with valorization pathways for which a complete set of profitability indicators is available. Therefore, rather than indicating that these pathways are intrinsically economically infeasible, the current evidence points to an incomplete techno-economic characterization and highlights the need for further profitability and scale-up assessments.

In light of these findings, strengthening the economic resilience of biodiesel systems requires a stronger focus on underexplored and strategically valuable by-products. While glycerol valorization is more extensively represented in the techno-economic literature, the techno-economic potential of phosphorus-containing residues remains insufficiently addressed, particularly given their dual role as environmental liabilities and strategic resources. Among these, soapstock and phospholipid-rich gum stand out as key intermediates linking waste management to value generation. Unlocking their potential requires not only process optimization but also integrated resource recovery frameworks that account for nutrient circularity and agricultural reintegration. The following section therefore examines phospholipid-rich gum as a platform for phosphorus recovery and its application in biofertilizer production, positioning these residues at the core of sustainable and competitive biodiesel biorefineries.

4 Unlocking value from soapstock and phospholipid-rich gum

Phosphorus management has emerged as a critical environmental and resource governance challenge on a global scale, driven by the finite nature of phosphate rock reserves, the geopolitical concentration of supply, and increasing nutrient losses across agro-industrial systems (Pratt et al., 2024). Within agricultural supply chains for biodiesel, substantial amounts of phosphorus are exported from soils during soybean harvest (Filippi et al., 2021). Concurrently, the expansion of biodiesel processing generates large volumes of residual streams, such as crude glycerol, which pose environmental challenges if not properly valorized (Tomatis et al., 2024; Omori et al., 2025). In this context, biofertilizers have gained attention as environmentally sound tools to reintegrate nutrients into productive agricultural cycles (Kumar et al., 2022).

The relevance of these residues becomes more evident when the phosphorus balance of soybean processing systems is considered. Defatted soybean meal contains approximately 500–600 mg of phosphorus per 100 g on a dry-weight basis (0.5–0.6%), as reported by Saio et al. (1967). For soybean seeds cultivated in Brazil, Filippi et al. (2021) reported an average phosphorus content of 550 mg per 100 g on a dry-weight basis for the 2015–2019 period. Industrial soybean processing also generates phosphorus-rich by-products. Valorizing these materials as fertilizer components offers a pathway to recover phosphorus and return it to agricultural soils, closing nutrient loops that are otherwise disrupted in linear production systems (Walsh et al., 2023). In principle, the phospholipid-bound phosphorus present in degumming gum could partially complement or substitute for mineral phosphorus fertilizers, provided that it is converted into plant-available forms (Ganem et al., 2025).

However, phosphorus bioavailability in soils is inherently complex. Organic phosphorus compounds such as phospholipids, inositol phosphates, and nucleic acids can account for 30–90% of total soil phosphorus, yet less than 1% is readily accessible to plants (Li et al., 2019). Phosphorus availability therefore depends on the degradation of fresh organic materials, which are rich in phospholipids and nucleic acids (Chavez-Ortiz et al., 2024). Thus, for phospholipid-rich gum to function effectively as a fertilizer component, its organic phosphorus fraction must be converted into inorganic phosphate forms that plants can absorb. A structured representation of this recovery pathway is presented in Figure 2.

This transformation is primarily mediated by soil microorganisms, which play a pivotal role in phosphorus cycling through the secretion of phosphatase enzymes capable of cleaving phosphate groups from organic molecules (Li et al., 2019). Under appropriate biological conditions, phospholipid-rich gum may therefore act as a slow-release phosphorus source, progressively supplying plant-available phosphate as microbial activity proceeds.

Isotopic tracing studies have shown that soil microorganisms can rapidly decompose phospholipids and even take up organic phosphorus compounds directly (Wasner et al., 2023). At the microbial level,

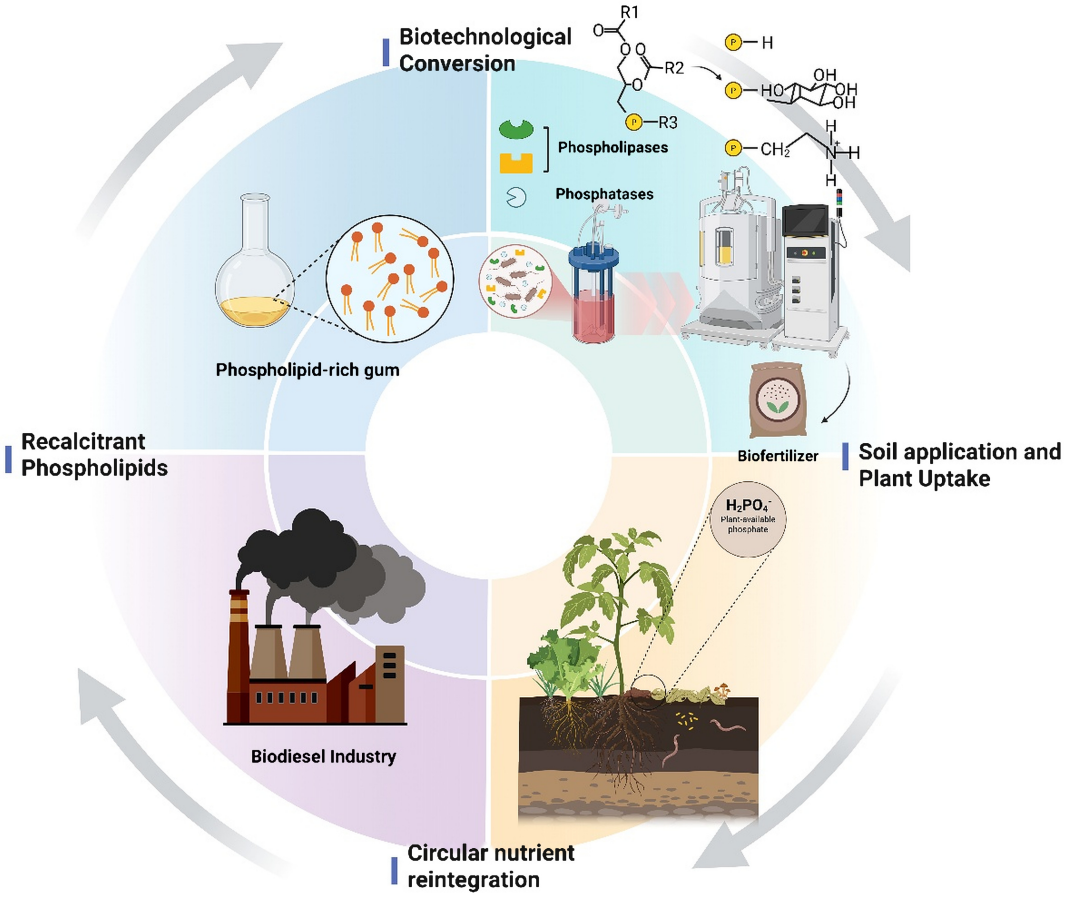


Figure 2. Circular phosphorus recovery from phospholipid-rich gum through biotechnological conversion into biofertilizers

controlled studies have demonstrated that specific soil microorganisms can directly metabolize phospholipid-bound phosphorus. Using lecithin as a model organophosphate, Li et al. (2019) showed that *Acinetobacter* sp. exhibited higher acid phosphatase activity than *Aspergillus niger* during incubation, while both microorganisms released comparable fractions of lecithin-bound phosphorus as soluble phosphate (16.5–17.9%), highlighting the complementary roles of bacterial and fungal pathways in mobilizing organic phosphorus pools.

At the system level, techno-economic and process modeling studies further support realistic recovery pathways. Simulations of soybean biodiesel plants revealed that soapstock and process wastewater can be chemically processed to recover a phosphorus precipitate suitable for use as a natural fertilizer (Juneja et al., 2022). The recovered phosphorus showed potential to partially replace commercial diammonium phosphate while simultaneously reducing phosphorus discharge to wastewater streams, reinforcing the combined environmental and economic benefits of valorization. Table 3 summarizes the main processing routes for soapstock and phospholipid-rich gum. Two contrasting maturity levels emerge. Soapstock splitting, most often performed with sulfuric acid under industrial conditions, yields an acid oil that can be converted into biodiesel meeting ASTM specifications at reduced production cost; however, it also generates a highly contaminated and saline acidic aqueous phase (Haas, 2005; Barbusiński et al., 2021). In contrast, phosphorus-oriented routes remain restricted to process simulations and laboratory-scale investigations (Li et al., 2019; Juneja et al., 2022). Phosphorus bound to phospholipids and phytate in lecithin cannot be recovered by chemical precipitation, which makes lecithin recovery as a co-product the most profitable alternative for this fraction (Juneja et al., 2022). Consequently, the valorization of phospholipid-rich gum as a phosphorus source still depends on validation with real degumming residues, complete techno-economic indicators, and integration within multiproduct biorefineries.

Nevertheless, the environmental viability of phosphorus recovery strategies depends on transparent system boundaries and comparison with alternative management pathways. Life cycle assessment (LCA) studies show that environmental outcomes depend on functional units, allocation procedures, and methodological assumptions, highlighting the need for harmonized evaluation frameworks (Lam et al., 2022). Integrated LCA should account for avoided mineral fertilizer production, reduced phosphorus discharge, energy use, and emissions during recovery and soil application (Lam et al., 2022; Pausta et al., 2024). Aligning phosphorus recovery with the Sustainable Development Goals (SDGs), particularly SDG 6, SDG 12, and SDG 14, requires governance frameworks ensuring that circular strategies deliver real environmental benefits rather than shifting impacts across systems (Egas et al., 2023).

Table 3. Valorization routes for soapstock and phospholipid-rich gum

By-product	Valorization / conversion route	Main target product	Key operational parameters / advantages	Technological readiness / limitations	Reference
Soapstock	Acid splitting with strong mineral acid	Acid oil (mixture of fatty acids and oil)	H_2SO_4 most often used; HCl under sulfate-discharge restrictions	Industrial scale; highly contaminated saline acidic wastewater	(Barbusiński et al., 2021)
Soapstock	Saponification and acidulation, followed by acid-catalyzed esterification	FAME (biodiesel)	>90% FFA acid oil; biodiesel met ASTM specifications; ≈USD 0.41 L^{-1}	Comparable engine performance; production cost estimated by process modeling	(Haas, 2005; Haas et al., 2006)
Soapstock and process wastewater	Chemical precipitation (NaOH, $CaCl_2$ at Ca:P 1:1; centrifugation)	Phosphorus precipitate sold as natural fertilizer (potential substitute for diammonium phosphate)	90% P recovery; cost USD 1.65–3.62 kg^{-1} P recovered	Process simulation only; IRR, NPV, and payback period not reported	(Juneja et al., 2022)
Lecithin gum	Separate co-product recovery from soybean meal	Lecithin (co-product); soybean meal with lower P content	54% P reduction; most profitable scenario	Process simulation only	(Juneja et al., 2022)
Lecithin (model organophosphate)	Microbial decomposition (*Acinetobacter* sp.; *Aspergillus niger*)	Soluble phosphate	16.5–17.9% of lecithin-P released as soluble P	Laboratory scale (5-day flask assays)	(Li et al., 2019)

5 Unlocking value from glycerol bioprocessing

Microbial conversion offers a versatile route for crude glycerol valorization, enabling its transformation into value-added chemicals, microbial lipids, and energy carriers. Depending on the microorganism, metabolic pathway, and process configuration, crude glycerol can serve as a carbon source for the production of compounds such as 1,3-propanediol (1,3-PDO), 3-hydroxypropionic acid (3-HP), single-cell oils, bioethanol, hydrogen, and biogas. These bioconversion routes differ substantially in substrate requirements, operating conditions, product characteristics, and downstream processing demands, as summarized in Table 4.

Beyond these representative products, the use of crude glycerol as a microbial feedstock has been explored across a broader range of bioproducts and fermentation platforms. The feasibility of these routes depends not only on the metabolic capacity of the selected microorganism, but also on the composition and quality of the crude glycerol, process control, and the requirements associated with product recovery and purification. Thus, although microbial conversion expands the range of products that can be obtained from crude glycerol, the economic and technological viability of each route is closely linked to the integration of biological performance with upstream and downstream processing requirements.

Among the energy-oriented pathways, AD plays a central role in waste-to-energy valorization by converting organic waste into biogas rich in methane and digestate rich in organic macro- and micronutrients with potential for land application, thereby creating additional value within production systems (Omori et al., 2025; Albuquerque et al., 2026). Beyond its technical function, AD contributes to improving resource efficiency, minimizing greenhouse gas emissions, reducing waste disposal costs, and generating complementary revenue streams. In this context, feedstock selection, blending strategies, and operational control become critical process variables that directly influence conversion efficiency, system stability, and the overall economic performance of biodiesel production systems (Nghiem et al., 2014).

Crude glycerol derived from biodiesel production poses a persistent waste challenge due to its extremely high COD, variable impurity profile, and limited disposal options (Nghiem et al., 2014). Inadequate handling or direct discharge of glycerol-rich streams can overload wastewater treatment plants, increase treatment costs, and lead to secondary pollution risks. As biodiesel production expands, the accumulation of glycerol has therefore shifted from a market issue to an environmental management concern, reinforcing the need for controlled valorization pathways within waste-to-energy systems (Nghiem et al., 2014).

One of the main limitations of AD systems within value-added frameworks is their reduced efficiency and stability under monodigestion regimes (Edwiges et al., 2018). Substrates such as waste activated sludge often suffer from excessive dilution, while carbohydrate-, protein-, or lipid-rich residues frequently have unbalanced C/N ratios that constrain microbial performance and energy recovery (Edwiges et al., 2018). Anaerobic co-digestion (ACoD) has therefore emerged as a key value-added pathway, improving nutrient balance, stabilizing digestion, and enhancing methane yields through the synergistic use of agricultural, urban, and industrial residues (Albuquerque et al., 2026), thereby increasing carbon recovery, strengthening system resilience, and contributing to the overall efficiency and economic performance of biodiesel production systems.

Crude glycerol has gained prominence as a strategic co-substrate due to its high carbon content (C/N ≈ 260:1), rapid biodegradability, and widespread availability (Omori et al., 2025). When co-digested with nitrogen-rich substrates such as animal manure, wastewater sludge, or microalgae, glycerol can correct nutrient imbalances, stim-

Table 4. Comparative overview of microbial routes for crude glycerol valorization

Target product	Microorganism / biocatalyst	Key operating parameters	Yield / titer	Main bottlenecks / challenges	Reference
Single-cell oil	*Rhodotorula toruloides* NRRL Y-27012	Carbon-to-nitrogen (C/N) ratio of 100; 90 g/L of crude glycerol	24.5 g/L of dry cell biomass; approx. 50% intracellular lipid content.	High energy and O_2 demand; costly cell disruption and solvent extraction	(Filippousi et al., 2022)
	Cutaneotrichosporon oleaginosum	Pretreated crude glycerol and corn stover; fed-batch culture, 30 g/L of glycerol; initial C/N of 30	80.7 g/L of biomass; 75.7% lipid content		(Liu et al., 2024)
1,3-PDO	*Escherichia coli* (engineered)	Glycerol-based media	Combined titer of 140.5 g/L	Osmotic stress; strict redox/pH control; energy-intensive diol separation	(Zhang et al., 2023)
1,3-PDO	*Lactobacillus reuteri* JH83	Pure and crude glycerol	93.2 g/L and 93 g/L		(Ju et al., 2021)
Bioethanol	*Saccharomyces* spp.	Purified glycerol	40.4 g/L; conversion efficiency of 0.49 g ethanol/g glycerol consumed	Low glycerol metabolic flux; product inhibition; energy-intensive distillation	(Rezk Khattab and Watanabe, 2021)
Biohydrogen	Microbial consortium GCL	40 g/L of crude glycerol; anaerobic	10 L of H_2/L medium	Incomplete conversion; volatile fatty acid (VFA) accumulation; low H_2 energy density	(Mehariya et al., 2023)
Biogas/biomethane	Anaerobic microbial consortium	1.2 m^3 biodigester; food-to-microorganism (F/M) ratio of 0.23 gCOD/gVS; crude glycerol	14.7 L CH_4/kg VS·d	Narrow operating window; acidification and VFA accumulation	(Mello et al., 2024)

ulate microbial activity, and substantially increase methane production (Devens et al., 2024). In this context, glycerol co-digestion emerges as a strategic valorization pathway that converts a low-value by-product into an energy-generating stream, reducing reliance on external disposal while strengthening the economic performance and competitive positioning of biodiesel production systems.

Empirical studies consistently report methane yield increases ranging from approximately 30% to over 150% following glycerol addition, depending on substrate combinations and operating conditions (Bułkowska et al., 2022). Such outcomes have contributed to the perception of glycerol as a high-value co-substrate within circular bioenergy narratives. However, these benefits must be interpreted critically alongside the operational constraints and process limitations that accompany glycerol integration, which may ultimately affect scalability and the consistency of value generation.

A further challenge lies in the scale mismatch between experimental evidence and operational reality. Most studies on glycerol co-digestion remain confined to short-term bench-scale reactors with working volumes between 0.2 and 2.0 L (Devens et al., 2024). In contrast, long-term pilot- and full-scale demonstrations, which are essential for informing regulatory frameworks and operational guidelines, remain scarce (Baba et al., 2013).

Available pilot- and large-scale studies highlight both the promise and the fragility of glycerol co-digestion. Nghiem et al. (2014) demonstrated that intermittent glycerol injection at low volumetric doses (0.63%) enhanced biogas production in a 50 L reactor co-digesting wastewater sludge, whereas higher doses (3%) compromised system stability. Baba et al. (2013) reported optimal methane yields at 0.10% (v/v) glycerol addition, followed by rapid acidification and yield decline at higher loadings. Similar trends were observed by Mello et al. (2024) in a 1.2 m^3 reactor, where increasing the glycerol concentration beyond 0.10% (v/v) resulted in a 41% reduction in daily methane yield. Collectively, these findings confirm that glycerol co-digestion operates within a narrow stability margin that remains difficult to reconcile with the robustness required for industrial waste-to-energy systems.

The critical gap lies not in the biochemical proof that crude glycerol can enhance methane yields but in the absence of structured environmental decision-support frameworks capable of guiding its safe and predictable integration into AD systems. While several studies demonstrate improved biogas production through glycerol co-digestion (Mehariya et al., 2023), the environmental performance of this strategy depends on operational boundaries, loading rates, and system resilience. Excessive organic loading may induce process instability, VFA accumulation, foaming, or deterioration of digestate quality, thereby transferring environmental burdens rather than mitigating them. To address this gap, a structured environmental decision-support framework for the ACoD of glycerol is presented in Figure 3. The framework includes controlled dosing strategies, real-time monitoring, adaptive microbial management, and regulatory guidance that explicitly accounts for environmental trade-offs.

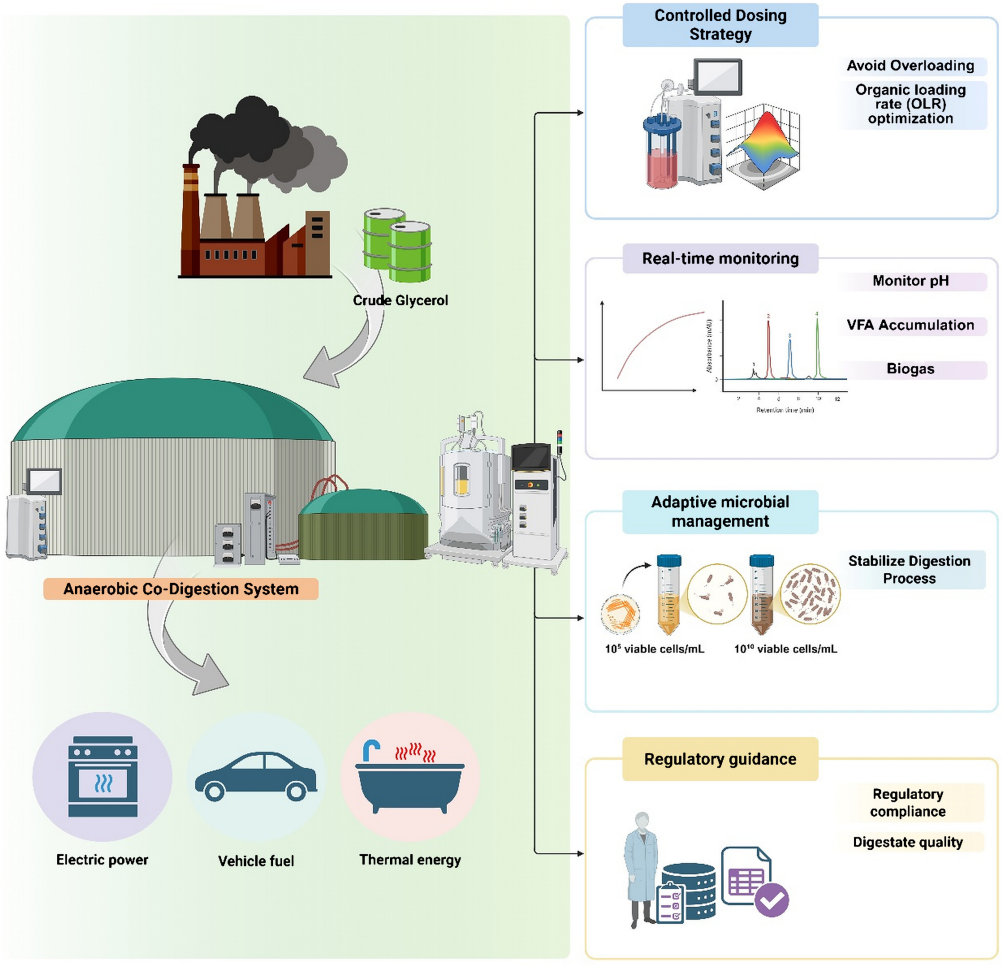


Figure 3. Anaerobic valorization of crude glycerol: operational strategies for stable biogas production and energy recovery

The strategic relevance of the ACoD of glycerol lies not in maximizing methane yield but in reducing environmental burdens across interconnected waste, energy, and nutrient management systems (Mello et al., 2024; Khatun et al., 2025). LCA provides a critical framework for evaluating these systems, as indicators focused solely on biogas production often overlook environmental hotspots and trade-offs across system boundaries (Lamolinara et al., 2022; Khatun et al., 2025). Comparative LCA approaches that account for avoided emissions from alternative glycerol disposal pathways demonstrate that the environmental benefits of co-digestion depend strongly on baseline waste management scenarios (Lam et al., 2022).

When evaluated within consistent and well-defined system boundaries, ACoD plays an important role in resource valorization and in improving the overall efficiency of biodiesel-based biorefineries. By converting glycerol and other residual streams into biogas, this approach enables energy recovery, reduces waste management burdens, and contributes to broader sustainability targets, particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). However, its effectiveness depends strongly on process integration, reactor stability, and controlled operating conditions to ensure efficient substrate conversion. Under optimized conditions, ACoD can enhance overall system performance rather than simply redistributing process limitations across the production chain (Vousoughi et al., 2026).

6 Conclusion

The sustainability of biodiesel systems will increasingly depend on their capacity to transform by-products into value-added resources rather than treat them as residual liabilities. Crude glycerol, phospholipid-rich gum, and soapstock are structurally embedded streams with substantial potential for conversion into high-value products, including biofertilizers and biogas. However, valorization should be understood not only as waste conversion but also as the strategic integration of by-products into economically and environmentally viable production chains. Accordingly, residue routing must be approached as a value-driven decision process, guided by criteria such as product yield, market relevance, nutrient recovery, carbon utilization efficiency, and process robustness. Feedstock variability further reinforces the need for flexible and adaptive valorization strategies capable of maintaining both product quality and process performance under fluctuating conditions.

Authors' contributions

Miotti Jr., R.H.: conceptualization; data curation; formal analysis; investigation; methodology; validation; writing – original draft; writing – review & editing. Cuba, E.E.V.: data curation; formal analysis; investigation; visualization; writing – original draft. Torres, D.Y.O.: data curation; formal analysis; investigation; writing – original draft. Duda, L.J.: data curation; formal analysis; investigation; visualization; writing – original draft. Oliveira, N.P.: data curation; formal analysis; investigation; visualization; writing – original draft. Edwiges, T.: data curation; formal analysis; investigation; visualization; writing – original draft; writing – review & editing. Woiciechowski, A.L.: formal analysis; supervision; funding acquisition. Soccol, C.R.: project administration; formal analysis; supervision; funding acquisition. Medeiros, A.B.P.: conceptualization; data curation; formal analysis; investigation; supervision; funding acquisition; validation; writing – original draft; writing – review & editing.

Conflicts of interest

The authors declare no conflict of interest.

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Declaration on the use of generative artificial intelligence

During the preparation of this work, the authors used ChatGPT to improve readability and language. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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