

Review

Soy Molasses: A Sustainable Resource for Industrial Biotechnology

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Abstract: Soy molasses, a byproduct of soy protein concentrate production, offers potential as a substrate for biotechnological applications due to its rich composition of carbohydrates, proteins, lipids, and bioactive compounds. Despite this, it remains underutilized, often relegated to low-value applications such as animal feed or waste, largely due to variability in its composition, the presence of microbial inhibitors, and limited industrial awareness of its potential. This review explores the biotechnological strategies for valorizing soy molasses, focusing on its chemical and physical properties, potential applications, and the challenges associated with its use. Its high carbohydrate content supports its utilization in producing biofuels, organic acids, and polyhydroxyalkanoates (PHA), addressing the global demand for sustainable energy and materials while costing approximately 20% of the value of conventional carbohydrate sources. Additionally, bioactive compounds have extended applications to nutraceuticals and cosmetics, while proteins and lipids enable enzyme and biosurfactant production. However, challenges such as variability in composition, the presence of inhibitory compounds, and scalability issues require innovative approaches, including pre-treatment methods and strain engineering. By integrating soy molasses into a circular bioeconomy framework, industries can reduce waste, lower their carbon footprint, valorize agro-industrial residues, and generate economic value. This review underscores the untapped potential of soy molasses as a versatile, sustainable resource, while highlighting the need for continued advancements to transform it into a key player in industrial biotechnology.

Keywords: waste valorization; agro-industry byproduct; biorefinery; microbial fermentation; sustainable feedstock



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1. Introduction

One of the most important strategies for combating environmental degradation has been recognized in the circular economy driven by biorefinery innovations. These systems help address specific environmental pressures such as excessive agro-industrial waste generation, greenhouse gas (GHG) emissions, and the carbon footprint associated with conventional production processes by converting biomass into valuable bio-based products.

A biorefinery is a facility or system that employs a variety of technologies to convert biomass materials (feedstocks) into their individual components, like carbohydrates, acids, proteins, and triglycerides. These components can then be transformed into marketable products, chemicals, and biofuels, which maximize profitability and contribute to a sustainable, waste-minimizing economy [1,2]. This concept is central to the bioeconomy, which aims to utilize resources efficiently and sustainably, making it a key activity in reversing environmental degradation and supporting a circular economy [3].

According to the USDA Foreign Agricultural Service, Brazil is the global leader in soybean production, significantly influencing the world's supply. In 2023/2024, Brazil produced approximately 153 million metric tons of soybeans, accounting for about 39% of global production [4]. Soybeans have many uses in Brazil. The grain can be processed domestically through crushing, which yields meal and oil for both local consumption and international trade. Soybean oil plays a key role in the food and pharmaceutical sectors, as well as in biodiesel production. Notably, more than 80% of Brazil's biodiesel is derived from soybean oil, highlighting its critical importance in the country's renewable energy efforts [4,5].

The byproducts generated from the processing of soybeans into refined soybean oil, soy protein concentrate (SPC, a high-protein product obtained by removing soluble carbohydrates from defatted soy meal), and soy protein isolate (SPI, an even more purified form with over 90% protein content) hold significant potential for further utilization. This approach aims to maximize resource efficiency by transforming all residues into valuable products, enhancing the functionality of a soybean-based biorefinery [6]. Soy molasses, a byproduct derived during SPC production, represents a significant underutilized resource with immense biotechnological potential. This viscous liquid contains high concentrations of carbohydrates, proteins, lipids, and bioactive compounds, making it a valuable substrate for various industrial applications. However, much of this byproduct is either discarded or used in low-value applications such as animal feed, leading to environmental concerns and economic inefficiencies [7,8].

The valorization of agro-industrial byproducts, such as soy molasses, aligns with the principles of circular bioeconomy and sustainability. By converting this waste into high-value products, industries can reduce environmental impact while generating additional revenue streams. In particular, soy molasses is rich in raffinose family oligosaccharides (RFOs) such as raffinose and stachyose, which exhibit prebiotic properties and have applications in the food and nutraceutical industries [9,10]. Furthermore, its high carbohydrate content makes it an excellent candidate for biofuel production, including bioethanol and biogas, contributing to renewable energy solutions and reducing the investment required in the process, since it costs around 20% of the value of conventional carbohydrate sources [10–12].

The biotechnological potential of soy molasses extends beyond energy production. It has been successfully utilized in the cultivation of microorganisms *Mucor circinelloides*, *Aspergillus niger*, *Propionibacterium acidipropionici* and *Aureobasidium pullulans* for the production of organic acids, such as lactic, malic, gluconic, and propionic acids, which have applications in food preservation and bioplastics production [7,13–15]. Additionally, soy molasses serves as a substrate for producing polyhydroxyalkanoates (PHA) from diazotrophic bacteria, biodegradable plastics that address the growing demand for sustainable alternatives to petroleum-based polymers [11,16]. Its protein and lipid content also supports microbial production of biosurfactants and enzymes, enhancing its industrial versatility [13].

Despite its advantages, the utilization of soy molasses faces several challenges. Variability in its composition due to differences in soybean varieties and processing methods

requires standardized pre-treatment and bioprocess optimization. Additionally, the presence of inhibitory compounds such as phenolics and saponins can hinder microbial activity, requiring detoxification steps to improve fermentability [17–21]. However, pre-treatment stages are common in the context of biorefineries, with various methods for detoxification and decolorization for fermentation enhancement, like acidic, basic, enzymatic, and physicochemical hydrolysis to release fermentable sugars [14,17,22], and anaerobic–aerobic digestion, which reduces waste and produces an energy resource in the form of biogas [18,23].

Although various studies have explored the utilization of agro-industrial byproducts, there is a noticeable lack of comprehensive reviews dedicated specifically to soy molasses and its diverse biotechnological applications. Much of the existing literature focuses on narrow uses—such as bioethanol production or animal nutrition—without addressing the full potential of soy molasses within an integrated circular bioeconomy framework. In addition, critical aspects such as process scalability, pre-treatment techniques, and emerging applications like nanomaterials, biosurfactants, and bioplastics remain underexplored in previous reviews. This work seeks to bridge these gaps by presenting an up-to-date and multidisciplinary synthesis that highlights both the opportunities and the challenges in transforming soy molasses into a strategic resource for sustainable industrial development.

2. Soybean Processing and Byproducts

Soybean seeds are composed primarily of proteins (40–50%), fiber (3–6%), fat (18–21%), carbohydrates (30–35%), ash (3–6%), and total solids (88–92%) on a dry mass basis [24–26]. Hexane-based solvent extraction is the most widely used method to extract oil from soybean seeds, involving three main steps: preparation of the seeds, oil extraction, and removal of the solvent from both the oil and the meal [27,28]. In the manufacturing of soy-based products, large amounts of byproducts are generated, namely soybean hulls, okara, soybean meal, and soy molasses (Figure 1).

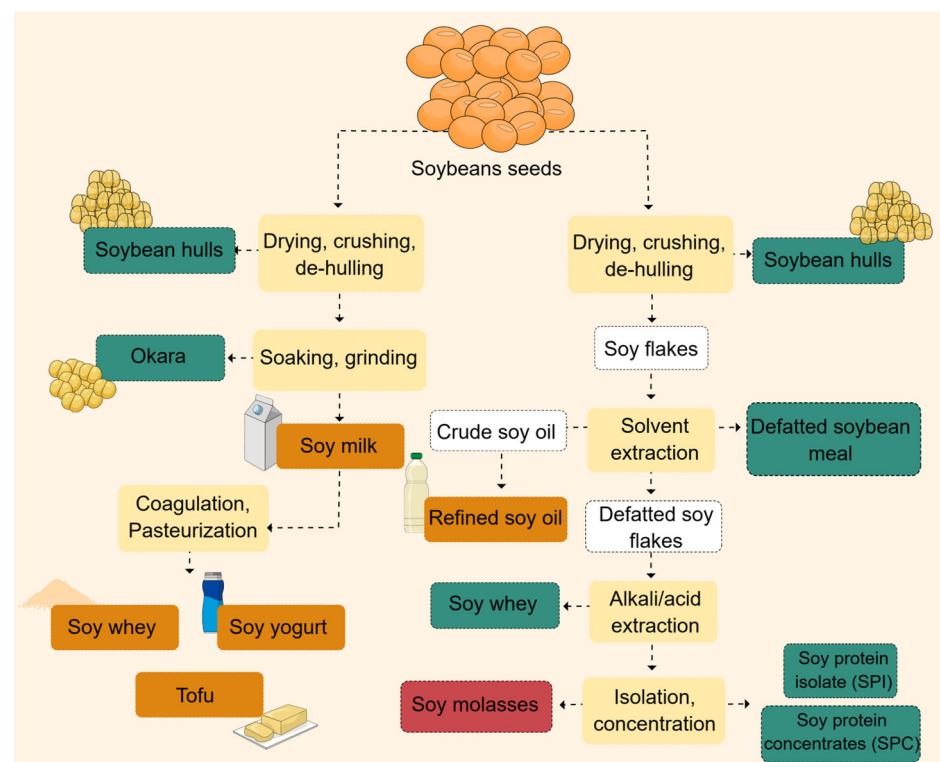


Figure 1. Overview of typical processing for the production of soy-based foods and their byproducts.

The soybean oil extraction process starts with hull removal, creating soybean flakes, followed by hexane extraction. The oil/solvent mixture (miscella) is processed to recover the crude oil, which is refined into edible oil. The solvent is recovered by evaporation or distillation. The defatted flakes are dried, ground, and marketed as soybean meal and serve as a major protein source in livestock feed. Further processing of defatted meal can produce SPC, SPI, and soy molasses [6,12]. Additionally, soybean curd residue, or okara, is a nutrient-rich byproduct from soy milk and tofu production. It is obtained from grinding and filtering soaked soybeans into a soy beverage [29,30]. Okara contains 40–60% fiber, 20–30% protein, and 10–20% fat on a dry basis, but also includes anti-nutritional factors like trypsin inhibitors and saponins, which limit its suitability for human consumption [29,31–34].

Approximately 85% of global soybean production is processed by crushing to produce defatted soybean meal and oil. Approximately 5 kg of soybeans is used to produce 1 L of soy oil, with the remaining 75–80% generated as a byproduct [12,35]. As shown in Figure 1, many byproducts from soybean processing are repurposed for creating animal feed, SPC, SPI, and soy molasses.

SPC, with a protein content of 65–72%, is made by removing soluble carbohydrates from defatted meal through acid leaching, aqueous ethanol extraction, or moist heat water leaching [36,37]. Most SPC is produced via alcohol extraction, which leaves soy molasses as a byproduct [12,38]. SPI, with over 90% protein, is created by extracting proteins from defatted meal using mild alkali, followed by precipitation at the isoelectric point [39].

Soy molasses is a viscous, brown syrup with around 25% moisture and a bittersweet taste, produced during the alcohol extraction process in the manufacturing of SPC [14,40,41]. The composition of soy molasses varies depending on factors like soybean variety, growing conditions, and year. Despite these variations, its main components are carbohydrates, including oligosaccharides (stachyose and raffinose), disaccharides (such as sucrose), and smaller amounts of monosaccharides (fructose and glucose), which together make up about 57% of the dry weight or 30% *w/v* [14,41]. Soy molasses also contains proteins, lipids, minerals, and phytochemicals like isoflavones and saponins, which may have health benefits [40,42]. In the industrial process, around 232 kg of soy molasses is generated for every ton of soybean meal produced [18].

The high oligosaccharide content in soy molasses limits its use in non-ruminant animal feed due to digestibility issues. However, many published studies have explored alternative uses of soy molasses, such as its use as a carbon source in microbial cultivation. This includes applications in producing malic acid [14], lipases [43], butanol [44,45], and bioethanol [42,46], offering potential value beyond feed supplementation. This diversification of uses contributes to minimizing waste and enhancing the value chain of soybean byproducts [47].

The presence of inhibitory compounds in soy molasses, such as phenolics, can require detoxification to enable their valorization. This treatment can be mediated by the cultivation of edible fungi in soy molasses, such as *Morchella rotunda*, *Morchella vulgaris*, and *Morchella conica*, reaching up to 56.6% of phenolic reduction. In addition, to increase the availability of fermentable sugars, acid and enzymatic hydrolysis processes can be applied to soy molasses, with documented increases of 7.6% in fermentation yields in ethanol production processes after applying enzymatic hydrolysis with commercial enzymes [38,48].

3. Characterization of Soy Molasses

The chemical composition of soy molasses plays a pivotal role in determining its suitability for various biotechnological applications. Table 1 presents a comparative overview of the chemical composition of major soy processing byproducts, highlighting the unique profile of soy molasses. Primarily, it consists of carbohydrates, including sucrose, raffinose,

and stachyose, which account for 50–60% of its dry weight. These carbohydrates make soy molasses an ideal substrate for processes such as bioethanol production and organic acid fermentation [7,14]. Raffinose family oligosaccharides (RFOs), which constitute a significant fraction of these carbohydrates, also exhibit prebiotic properties, contributing to the potential use of soy molasses in the development of functional foods [8,9].

Table 1. Comparative Composition of Soy Processing Byproducts.

Component	Soy Molasses	Okara	Soy Hulls	References
Carbohydrates (% dry wt)	50–60	10–15	30–40	[7,9]
Protein (% dry wt)	6–8	25–30	10–15	[49,50]
Lipids (% dry wt)	5–8	10–15	1–2	[10,13]
Fiber (% dry wt)	5–10	55	55–60	[8,19]
Bioactives	High	Moderate	Low	[11,17]

Additionally, soy molasses comprises 6–8% proteins rich in essential amino acids, and 5–8% lipids, predominantly unsaturated fatty acids like linoleic and oleic acids [13,14]. These components enhance its potential for enzyme and biosurfactant production, supporting its use in various industrial processes [10,13]. These compounds may act as biostimulants or precursors for sustainable agriculture [51,52]. For instance, soy molasses has been successfully used for *Bacillus* species cultivation, aiming at plant growth promotion [53].

Moreover, the presence of bioactive compounds, such as soyasaponins, isoflavones, and phenolic acids, adds functional value to soy molasses, with applications extending to the nutraceutical, cosmetic, and pharmaceutical industries. These compounds exhibit antioxidant, anti-inflammatory, and antimicrobial properties [17,54,55]. In contrast, the composition and functional properties of soy molasses differ significantly from other soy processing byproducts, such as okara and soy hulls. While okara is protein- and fiber-rich, and soy hulls are primarily composed of insoluble fiber, soy molasses is distinguished by its high soluble sugar content and bioactive compounds [55]. Physical properties such as viscosity, density, and water activity are influenced by processing methods and moisture content, directly impacting storage and transport. For instance, high viscosity and density may pose pumpability challenges during handling and processing, while elevated water activity can reduce shelf-life and increase susceptibility to microbial contamination. Addressing these constraints has led to the exploration of novel solutions such as thermal pre-treatment, enzymatic liquefaction, or formulation with stabilizers, and these adaptations may also enable applications in bioadhesives, thickening agents, and other value-added products [11,19,56,57].

4. Biotechnological Strategies for Soy Molasses Valorization

Soy molasses, a nutrient-rich byproduct of SPC production, offers immense potential for biotechnological valorization. Its abundant carbohydrates, proteins, lipids, and bioactive compounds serve as a versatile substrate for producing high-value products. This section examines the main biotechnological strategies for soy molasses utilization, their mechanisms, applications, and associated challenges. A wide range of products can be obtained using soy molasses as a fermentation medium, including proteins, lipids, functional saccharides, and fuels (Table 2).

Table 2. Comparative Analysis of Soy Molasses Valorization Strategies.

Strategy	Main Product(s)	Applications	Advantages	Challenges	References
Organic Acid Production	Propionic acid, lactic acid	Food preservation, bioplastics	Cost-effective substrate	Requires pre-treatment for RFO hydrolysis	[7,8,56]
Bacterial Cellulose	Bacterial cellulose	Medical devices, food packaging	High-value biopolymer	Scaling up and quality consistency	[13,14,58]
Bioethanol and Biogas	Ethanol, biogas	Renewable energy	Renewable and abundant feedstock	Phenolic inhibitors, detoxification required	[7,15,59]
Functional Oligosaccharides	Raffinose, stachyose	Prebiotics, functional foods	High market demand	Optimization for industrial scalability	[9,19,55]
Enzymes and Biosurfactants	Proteases, sophorolipids	Bioremediation, cosmetics, pharmaceuticals	Low toxicity, environmental benefits	Strain engineering for yield improvement	[15,19,60]
Nanomaterials	Graphene oxide, carbon dots	Electronics, bioimaging, drug delivery	High-value, innovative applications	High production costs	[8,54,58]
Biofloc Systems	Improved water quality	Aquaculture	Enhances sustainability of aquaculture systems	Limited adoption in large-scale farming	[10,12,61]
Bioplastics (PHA)	Polyhydroxyalkanoates	Biodegradable plastics	Sustainable, renewable	High costs of production	[13,15,55]

4.1. Organic Acid Production

The production of organic acids such as propionic, lactic, and acetic acids from soy molasses is well documented due to their industrial relevance. For instance, *Propionibacterium acidipropionici* efficiently converts raffinose and stachyose into propionic acid, achieving yields of up to 0.42 g/g [7,8]. Similarly, lactic acid production using *Lactobacillus* strains has been optimized with soy molasses as a carbon source, facilitating biodegradable polymer production [10,56].

Moreover, the co-production of acetic and succinic acids has been reported in mixed-culture fermentations, which enhances the economic feasibility of integrated biorefinery systems. The implementation of membrane separation or in situ product recovery techniques during fermentation further increases productivity and facilitates downstream processing, highlighting the relevance of soy molasses as a versatile and efficient substrate for organic acid biosynthesis [10,56]. To improve these processes, enzymatic hydrolysis of RFOs has been employed, increasing sugar accessibility for fermentation [9,19]. Integrated systems combining acid recovery with fermentation have enhanced yields while reducing costs [49,61].

4.2. Bacterial Cellulose Production

Bacterial cellulose (BC), known for its biocompatibility and high mechanical strength, can be synthesized using soy molasses. *Gluconacetobacter xylinus* has demonstrated high BC yields when cultivated on soy molasses compared to synthetic media [13,14,58,61,62].

Similarly, the modified SCOBY consortium of *Medusomyces gisevii* demonstrated a 58% increase in BC production when utilizing soy molasses as a carbon source; this improvement highlights the potential of soy molasses as an effective and economical substrate for BC production [9].

BC applications range from wound dressings to biodegradable food packaging, emphasizing its market potential [17,57]. Despite these advances, challenges such as maintaining consistent quality and scaling production persist [11,63].

4.3. Bioethanol and Biogas Production

Soy molasses is an excellent medium for microbial fermentation in biofuel production. Bioethanol provides a sustainable alternative to fossil fuels, along with biodiesel, biobutanol, biomethane, and biohydrogen. Various microorganisms, including bacteria, yeast, and fungi, are capable of fermenting sugar-rich substrates to produce bioethanol. Some of these microorganisms are *Pichia stipitis*, *Saccharomyces cerevisiae*, *Hanseniaspora uvarum*, and *Kluyveromyces marxianu* [38,46,57,64]. *Saccharomyces cerevisiae* effectively ferments sucrose and glucose into ethanol, achieving yields comparable to traditional substrates like molasses from sugarcane [7,15,38,65]. Furthermore, an established industrial process for ethanol production from soy molasses using *S. cerevisiae* has been documented in both laboratory and industrial scales. On the laboratory scale, the process achieves a productivity of 8.08 g/L.h, while the industrial yield reaches 162.7 L of absolute ethanol per ton of dry molasses [42]. However, since *S. cerevisiae* lacks the enzyme α -1,6-galactosidase, around 47% of the sugars in soy molasses cannot be fermented. Therefore, it is necessary to hydrolyze sugars like raffinose and stachyose before fermentation can occur [46]. Using *S. cerevisiae* with α -galactosidase-treated molasses significantly improved ethanol yield [21,38].

Biogas production through anaerobic digestion has also demonstrated high methane yields, leveraging the lipid and carbohydrate content of soy molasses [12,18,23,56,59]. However, inhibitors such as phenolics and saponins require pre-treatment for optimal energy recovery [16,19,60]. This demonstrates the potential of soy molasses as a valuable feedstock for efficient biofuel production.

4.4. Functional Oligosaccharides

Soy molasses contains significant concentrations of functional oligosaccharides, such as raffinose and stachyose, which exhibit prebiotic properties by stimulating beneficial gut microbiota [9,10,19]. Transforming soy molasses into functional soy oligosaccharides (FSO) represents a sustainable approach to maximizing the potential of agricultural residues. Through targeted biological processes, microorganisms selectively utilize specific carbon sources, allowing for the removal of sucrose while preserving important oligosaccharides like stachyose and raffinose [19].

Innovative methods like the biological purification process, using microorganisms such as *Wickerhamomyces anomalus*, have demonstrated the ability to selectively remove sucrose from soy molasses while retaining key oligosaccharides like raffinose and stachyose [7,8,10,66], while Wang et al. (2019) [57] produced other oligosaccharides by using an engineered *Yarrowia lipolytica* strain to hydrolyze the raffinose-family oligosaccharides in soy molasses into sucrose. The resulting soy molasses hydrolysate, rich in sucrose, was used to produce isomaltulose. Functional oligosaccharides have applications in functional foods, beverages, and nutraceuticals, but scalability and production costs remain areas for improvement [13,18,67,68].

4.5. Enzyme and Biosurfactant Production

The protein and bioactive compound content of soy molasses supports the production of industrial enzymes and biosurfactants. For instance, proteases and cellulases have been

produced using soy molasses as a substrate, with applications in the detergent and textile industries [17,19,63]. Process optimization and strain engineering are critical for enhancing yields and reducing production costs [14,60].

Biosurfactants are categorized based on their chemical structure and microbial origin into various groups: glycolipids, lipopeptides, phospholipids, fatty acids, neutral lipids, and polymeric biosurfactants [69]. Sophorolipids and rhamnolipids are glycolipids that have been synthesized for use in bioremediation and cosmetics [15,50]. Commonly used biosurfactants for soil remediation include rhamnolipids, fructose lipids, sophorolipids, and lipopeptides such as surfactin and polymyxin. Notably, rhamnolipid biosurfactants, primarily produced by *Pseudomonas aeruginosa*, have been extensively studied for their potential in removing pesticides from contaminated soil [50,70]. Other biosurfactant applications include detergent formulations [71,72], medical applications in films to prevent microorganism adhesion in interfaces [73,74], and to prevent oral infections [75,76]. Although biosurfactants have potential applications across various industries, their commercial-scale production has not yet been fully implemented due to low yields and high production costs.

4.6. Nanomaterial Synthesis

Soy molasses has been investigated as a promising precursor for the synthesis of nanomaterials, particularly carbon dots (CDs) and graphene oxide, owing to its high content of carbohydrates and bioactive compounds. These components provide carbon-rich structures and functional groups that are favorable for nanomaterial formation. Notably, the presence of diverse organic molecules in soy molasses may eliminate the need for additional surface functionalization steps during synthesis, simplifying the process and reducing costs. CDs derived from soy molasses have demonstrated desirable optical properties, including fluorescence emission, which are suitable for applications such as bioimaging and drug delivery. Additionally, CDs have gained significant attention due to their tunable size and unique optical properties. They are zero-dimensional nanomaterials, part of the graphene family, with a structure similar to graphene oxide but differing in size [77,78]. These materials are valuable for bioimaging, drug delivery, and electronics [8,57,58].

The most applied methods for the synthesis of CDs from different biomass derivatives acting as carbon sources are acid and hydrothermal oxidation, microwave-assisted, ultrasound-assisted, and electrochemical methods. Soy molasses-derived nanomaterials combine cost-effectiveness with sustainability, also ruling out the need for surface functionalization steps, since the different molecules present in this precursor can fulfil this role, though further studies are needed to optimize these processes and analyze the impact of soy molasses as a carbon source on the final composition of CDs [54,79].

4.7. Bioplastics and Polyhydroxyalkanoates (PHA)

Soy waste has proven to be an excellent bio-based source for packaging material. Polyhydroxyalkanoates (PHA) of medium length, a type of biodegradable and biocompatible polymer with great elastomeric and adhesive properties, can be synthesized from soy molasses and other waste carbohydrates by microbial fermentation. Strains like *Cupriavidus necator* and *Pseudomonas corrugata* utilize the sugars in soy molasses to produce intracellular PHA with high efficiency, and the mass of polymer can account for up to 17% of the dry mass of cells [9,10,13].

It has also been described that *Bacillus* species are able to produce bioplastics with high yields from soy molasses oligosaccharides. These have been reported to accumulate up to 90% of PHA utilizing raffinose; therefore, these microorganisms are candidates for the green and low-cost industrial production of PHAs [80]. Biodegradable polymers derived from sustainable and low-cost raw materials are emerging as a key solution, benefiting a scenario

of greater exploration and research into the use of residues such as soy molasses. These applications support sustainable alternatives to petroleum-based plastics used in fields like medicine, fibers, and agriculture and horticulture, aligning with global environmental goals [15,18].

5. Benefits and Challenges

The valorization of soy molasses through biotechnological processes offers significant environmental, economic, and social benefits. However, its implementation is not without challenges, as it requires addressing technical, economic, and scalability issues. This section examines the key advantages and obstacles associated with soy molasses utilization, supported by the recent literature. Table 3 shows an overview of the main benefits and challenges in soy molasses valorization.

Table 3. Comparative Analysis of Benefits and Challenges in Soy Molasses Valorization.

Category	Benefits	Challenges	References
Environmental	Waste reduction, lower GHG emissions, support for circular bioeconomy	Limited adoption of biotechnological processes in waste management	[7,58,59]
Economic	Higher-value products (e.g., prebiotics, bioplastics), reduced feedstock costs	High initial investment in infrastructure, process costs	[8,9,65]
Technical	High nutrient content for diverse applications	Variability in composition, inhibitory compounds, need for pre-treatment	[7,20,79]
Market	Rising demand for sustainable and functional products	Regulatory hurdles, consumer awareness and acceptance	[18,55,65]
Scalability	Potential for large-scale production of biofuels and biomaterials	Need for large-scale fermentation and purification systems, cost of enzyme treatments	[13,14,17]

5.1. Environmental Benefits

One of the most notable benefits of soy molasses valorization is its potential to mitigate environmental impact. Soy molasses, often discarded or underutilized, contributes to waste management challenges and environmental degradation. By converting this byproduct into high-value products, the burden on waste disposal systems is reduced, contributing to a circular bioeconomy [7,58].

Moreover, the use of soy molasses as a carbon source in biotechnological processes such as bioethanol and biogas production reduces reliance on fossil fuels, decreasing greenhouse gas emissions [10,59]. For instance, anaerobic digestion of soy molasses not only generates renewable energy but also produces nutrient-rich digestate, which can be used as biofertilizer, closing the nutrient loop [18].

Additionally, the production of biodegradable materials like polyhydroxyalkanoates (PHA) and bacterial cellulose from soy molasses aligns with global sustainability goals by reducing plastic pollution and supporting environmentally friendly alternatives [10,13].

5.2. Economic Benefits

From an economic perspective, valorizing soy molasses transforms a low-value byproduct into high-value commodities, enhancing the profitability of the soy industry [8,19]. For example, the production of prebiotics like raffinose and stachyose caters

to the growing demand for functional foods, a market projected to expand significantly in the coming years [9,65]. Additionally, incorporating soy molasses into bioprocesses also reduces costs by replacing traditional substrates, which are often expensive and less sustainable [14,49]. For instance, using soy molasses in biofloc systems for aquaculture has demonstrated cost savings in feed and water quality management [12,61].

The techno-economic feasibility of valorizing agro-industrial byproducts is well illustrated by several real-world cases. A pilot-scale project in China successfully produced polyhydroxyalkanoates (PHAs) from food waste using mixed microbial cultures, achieving a PHA content of 48% and productivity of up to 20 g/L per day, while also showing potential for integration with municipal waste treatment systems [81]. In Brazil, an integrated polylactic acid (PLA) production facility utilized sugarcane ethanol and bagasse to achieve a competitive production cost of approximately USD 1.41/kg PLA and a high internal rate of return (29.4%), while also demonstrating net negative greenhouse gas emissions (-0.25 kg CO₂-eq/kg PLA), highlighting the environmental and economic advantages of biorefinery integration [82].

5.3. Technical Challenges

Despite these benefits, several technical challenges hinder the broader adoption of soy molasses valorization. The complex composition of soy molasses, which includes sucrose, raffinose, and phenolic compounds, can complicate fermentation processes. While raffinose and stachyose are valuable as prebiotics, they also act as fermentation inhibitors, requiring enzymatic or microbial pre-treatment, increasing the time and investment needed in processing [7,50].

Variability in soy molasses composition due to differences in soybean varieties and processing methods further complicates its utilization. This inconsistency necessitates customized process designs and adaptive technologies, increasing production costs [11].

Additionally, phenolic and saponin compounds in soy molasses can act as antimicrobial agents, inhibiting the growth of certain microbial strains used in bioprocesses. Strategies such as detoxification or selective microbial engineering are required to address these challenges. Some environmental risks also need to be taken into consideration due to the possibility of some impact from the increase in these valorization processes, which may contribute to contamination by the chemicals used [20,68].

5.4. Economic and Scalability Challenges

Although soy molasses is a low-cost substrate, scaling up its valorization presents economic hurdles. Infrastructure for large-scale bioprocesses, including fermentation and purification systems, requires significant investment [13,17]. Furthermore, the cost of enzymatic and detoxification treatments or microbial strain engineering can offset the economic advantages of using soy molasses as a raw material [18,19].

The commercialization of soy molasses-derived products faces substantial regulatory challenges, particularly in the food and pharmaceutical sectors, where stringent quality and safety standards apply. Prebiotic oligosaccharides and biodegradable plastics must meet specific criteria to gain market approval, necessitating extensive testing and documentation [10,65]. In the U.S., prebiotic oligosaccharides derived from microbial processes are regulated under the GRAS (Generally Recognized as Safe) framework by the FDA [83]. For use in foods and infant formulas, these ingredients require extensive safety and toxicological evaluations. For example, Tata Chemicals' GRN 000605 received GRAS status for fructooligosaccharides (FOS) produced via microbial fermentation [83]. Similarly, 2'-Fucosyllactose (2'-FL), another microbial-derived prebiotic, was granted GRAS status but required comprehensive toxicological data and consumer intake assessments [84]. These

approval processes typically take 1–3 years and involve significant financial investment. For bioplastics, especially in food-contact applications, compliance with EU Regulation No. 10/2011 is mandatory, requiring migration testing to ensure safety. Products marketed as industrially compostable must meet criteria such as at least 90% biodegradation within 6 months and low levels of heavy metals [85]. These processes involve costly testing, long certification audits, and can delay market entry by 1–2 years. Overall, while soy molasses is a low-cost raw material, these regulatory requirements significantly increase development costs and time-to-market, reducing its economic advantage. Addressing these challenges early is essential for successful commercialization strategies. Additionally, consumer acceptance and awareness are crucial for market penetration. Products derived from agro-industrial byproducts, including soy molasses, require effective marketing to highlight their sustainability, safety, and quality, facing the current unethical consumer culture [8,9].

5.5. Future Perspectives

Addressing the challenges of soy molasses valorization requires a multidisciplinary approach. Advancements in strain engineering, such as developing robust microorganisms capable of utilizing complex substrates, will be pivotal, avoiding the need for pre-treatment steps and the costs associated with them [50,68]. The management of process optimization and integration of pre-treatment methods into existing bioprocess workflows can further enhance scalability and economic viability, saving both time and resources and facilitating the logistics of the process [9,19].

Additionally, government financial incentives for innovative research and industry collaborations, due to the accumulated experience in the processes into which soy molasses can be integrated, can play an important role in promoting soy molasses valorization. Policies supporting the industrial adoption of biotechnological innovations and consumer awareness campaigns emphasizing the sustainability of soy molasses-derived products are necessary to drive market growth [10,18].

In addition to the environmental and economic advantages, the valorization of soy molasses can yield significant socioeconomic benefits, particularly in rural and agricultural regions. By creating new markets for what is often treated as waste, soy molasses valorization supports income diversification for small and medium soy-processing enterprises and local cooperatives. Establishing decentralized bioprocessing units for the conversion of soy molasses into biofuels, enzymes, or functional foods can foster job creation, skill development, and technology transfer in rural communities. This is especially relevant in major soybean-producing countries like Brazil, Argentina, and India, where agro-industrial residues are abundant but often underutilized. In these contexts, integrating soy molasses into local bioeconomy initiatives can strengthen regional value chains, reduce socioeconomic inequality, and contribute to rural resilience.

The valorization of soy molasses varies significantly across countries depending on regulatory frameworks, industrial maturity, and research investment. In Brazil, the world's largest soybean producer [4], soy molasses is still predominantly used in animal feed or discarded, despite ongoing academic research highlighting its potential for biofuel [18,42], enzyme, and prebiotic production. In China, where functional foods and nutraceuticals represent a booming market, soy molasses has gained traction for producing functional oligosaccharides [19], leveraging microbial and enzymatic processes at pilot scale [68]. European countries, constrained by stricter environmental regulations and circular economy targets, have explored soy molasses in biopolymer and biosurfactant production [58] but are limited by supply chain access. In the United States, while soybean crushing is extensive, soy molasses is underexplored due to the dominance of corn-based feedstocks

in industrial fermentation [7]. This heterogeneity illustrates both the opportunities and the limitations in scaling soy molasses biovalorization globally, underscoring the need for policy alignment, infrastructure development, and international collaboration.

6. Conclusions

The valorization of soy molasses represents a transformative approach to addressing the dual challenges of waste management and sustainable industrial development. As a byproduct of soy protein concentrate production, soy molasses is rich in carbohydrates, proteins, lipids, and bioactive compounds, making it an attractive substrate for diverse biotechnological applications. The conversion of this underutilized resource into high-value products, such as organic acids, biofuels, bioplastics, enzymes, and prebiotics, demonstrates its potential to contribute significantly to a circular bioeconomy.

From an environmental perspective, leveraging soy molasses reduces waste generation and supports renewable energy production, while economically, it enhances the profitability of the soybean industry by creating new revenue streams. Moreover, the development of sustainable materials, such as bacterial cellulose and polyhydroxyalkanoates, underscores its role in addressing global environmental challenges, including plastic pollution.

However, several challenges must be overcome to fully realize the potential of soy molasses. Variability in composition, the presence of inhibitory compounds, and scalability issues require advanced bioprocessing techniques and innovative solutions. The integration of pre-treatment methods, strain engineering, and process optimization is essential for improving efficiency and reducing costs. Furthermore, the successful commercialization of soy molasses-derived products depends on meeting regulatory requirements and fostering consumer acceptance.

Future research and development efforts should focus on bridging the gap between laboratory-scale studies and industrial applications. Interdisciplinary collaboration, coupled with supportive policies and industry partnerships, will be pivotal in unlocking the full potential of soy molasses as a valuable resource. By addressing these challenges, soy molasses can transition from an agricultural byproduct to a cornerstone of sustainable biotechnological innovation, offering significant environmental, economic, and societal benefits.

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