JOURNAL OF PLANT RESEARCH AND INNOVATIONS
Jul-Dec 2025, VOL. 3, ISSUE 2, pp. 11-21
https://doi.org/10.61577/jpri.2025.100008

REVIEW ARTICLE

OPEN ACCESS

Industrial applications of soybean-derived materials: Beyond food to sustainable manufacturing

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ABSTRACT

Soybean (*Glycine max L.*) is increasingly recognized as a strategic bioresource for sustainable industrial production in addition to its role in traditional food and feed systems. Although there is great potential for soybean-derived materials such as epoxidized soybean oil (ESO), soy protein isolate (SPI), soy protein concentrate (SPC), and textured vegetable proteins (TVP) in adhesives, coatings, bioplastics, and alternative protein products, their industrial applications are often discussed within isolated subdisciplines. However, systematic understanding and integration of material properties, processing technologies, and industrial performance remain limited.To fill this gap, the present review critically consolidates recent processing developments of soybean oil- and protein-based industrial materials, with a focus on bio-adhesives, bio-based polymers, biodegradable plastics, and high-moisture extruded protein systems. The chemical modification of soybean oil, such as epoxidation and polyol synthesis, as well as recent developments in protein extraction, functionalization, and extrusion-based texturization, are reviewed. Structure–property–performance relationships that dictate adhesion strength, mechanical stability, water resistance, and processability are presented.In addition, the review emphasizes the technical, economic, and regulatory challenges constraining large-scale acceptance of soybean-based materials, including moisture sensitivity, thermal stability limitations, cost competitiveness, and regulatory harmonization. Molecular breeding, enzymatic modification, and biorefinery-based technologies for the future development of soybean-utilized industrial materials are also evaluated. This review provides a comprehensive and application-focused compilation to demonstrate the significance of soybean as a foundational crop for driving circular bioeconomy-based sustainable manufacturing ecosystems.

KEY WORDS

Soybean-derived materials; Epoxidized soybean oil (ESO); Bio-based polymers; Soy protein isolate (SPI); Textured vegetable protein (TVP); Industrial applications; Bioplastics

ARTICLE HISTORY

Received 27 November 2025; Revised 18 December 2025; Accepted 25 December 2025

Introduction

The growing environmental load caused by petroleum-based polymers, adhesives, and packaging materials has led to intensified research focused on the search for renewable and environmentally compatible substitutes. Conventional fossil feedstock–based materials have high greenhouse gas emissions, are non-biodegradable, and have limited end-of-life possibilities, which contribute considerably to plastic waste and climate change. In response, the circular bioeconomy (CBE) concept has recently received considerable attention, emphasizing the use of renewable biological resources for manufacturing materials with lower emissions and higher sustainability [1,2].

Soybean (*Glycine max L.*) is one of the most important crops as an agricultural feedstock because it has high oil and protein contents and possesses well-developed global production and supply networks [3]. Soybeans are usually grown for edible oil and protein. Nonetheless, developments in chemical modification, polymer science, and protein engineering technologies have broadened the use of soybean to many non-food industrial applications [4,5]. These developments have made soybean an attractive multifunctional bioresource for sustainable

Soybean oil is a triglyceride mainly consisting of unsaturated fatty acids, which provide reactive sites for chemical modification. Soybean oil is a precursor of epoxidized soybean oil (ESO) and can be prepared by epoxidation of carbon–carbon preparation of bio-based adhesives, coatings, plasticizers, and polymer networks. ESO has drawn great attention as an eco-friendly substitute for petroleum-based epoxy resins owing to its non-toxic nature, low volatile organic compound emissions, and compatibility with existing polymer processing equipment [6,1]. ESO derivatives can also be modified to produce ESO-based polyols that are applicable to polyurethane foams, sealants, inks, and surface coatings as replacements for fossil-based polyols.

Soybean proteins, together with those derived from oil processing, comprise one of the most significant classes of industrial biomaterials. Desolventized soybean meal (DSM) is the key starting material for the preparation of soy protein concentrate (SPC) and soy protein isolate (SPI) following oil extraction. Soy protein concentrate (SPC), typically containing 65–90% protein, is produced by selectively removing water-soluble non-protein components from defatted soybean meal, resulting in improved functional properties such as water-holding capacity and emulsification. Meanwhile, SPI (>90%) exhibits higher purity and consistency [7]. These protein fractions have recently been the subject of increasing research interest for their potential applications in biodegradable and bio-based plastics, films, coatings, and molded biopolymer products [4].

Textured vegetable protein (TVP), particularly those produced by high-moisture extrusion from SPC or SPI, is a soy protein material modelled to mimic the fibrous texture of animal muscle. High-moisture extrusion is a process involving simultaneous

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thermal and mechanical treatment, which induces protein denaturation, aggregation, and stretching into anisotropic fibrous network structures stabilized by covalent (disulfide bonding) and non-covalent interactions [8, 5]. TVP has become increasingly relevant in the growing alternative protein sector, driven by sustainability concerns and changing consumer dietary preferences. The major processing routes and industrial applications of soybean-derived oil- and protein-based materials are summarized schematically in Figure 1, while the key chemical structures and functional groups relevant to their industrial applications are illustrated in Figure 2.

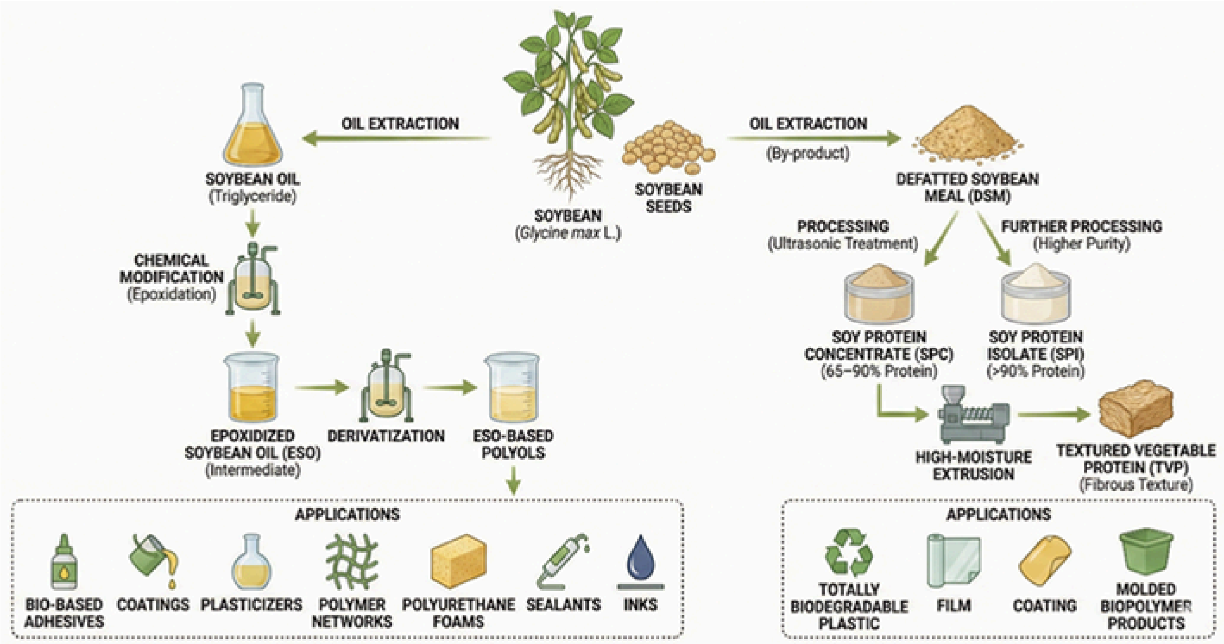

Figure 1. Schematic representation of soybean-derived industrial materials.

Soybean seeds are processed to obtain soybean oil and defatted soybean meal. Soybean oil is chemically modified to produce epoxidized soybean oil (ESO) and ESO-based polyols, which are used in bio-based adhesives, coatings, plasticizers, foams, sealants, and inks. Defatted soybean meal is further processed to produce soy protein concentrate (SPC) and soy protein isolate (SPI), which are used for biodegradable plastics and textured vegetable protein (TVP). The figure summarizes the main processing routes and industrial applications.

Globally, soybean has been one of the most widely produced oilseed crops, with annual production exceeding 350 million metric tons in recent years [9]. Although most soybean biomass is still utilized mainly for food and feed applications, the use of other materials derived from soybean has steadily increased over the past decade [2]. Concomitant with this trend, parallel developments in bioplastics, bio-based polymers, and plant protein markets have driven interest in soybean as a renewable industrial feedstock [1, 5]. During this evolution, the fraction of soybean directed to high-value industrial applications remains modest relative to that used for food and feed purposes, suggesting significant potential for additional valorization.

However, several technical and economic obstacles hinder the commercialization of soy protein–based industrial materials. Bioplastics made from soy protein generally exhibit inherent water sensitivity and lower thermal stability than synthetic polymers, often requiring chemical crosslinking, blending, or surface modification to achieve the desired performance [4,7]. Soybean oil–based polymers require sophisticated chemical processing conditions, which can increase production costs. Moreover, competition among food, feed, and industrial uses leads to price variability and potential shortages of sustainable resources [2]. Regulatory uncertainty surrounding new bio-based materials, particularly for food-contact and consumer goods applications, further complicates commercialization pathways [6].

While soybean oil–based polymers and soy protein–based materials have been widely studied, a systematic summary of recent progress remains scarce. Most existing reviews on plasma-treated polymer composites or food-relevant protein applications are narrow in scope and provide limited attention to cross-functional structure–property–performance relationships and industrial viability. The purpose of this review is to systematically summarize and critically evaluate state-of-the-art progress in soybean-derived industrial products, including both oil-based materials (additives, adhesives, polymers) and protein-based materials (bioplastics and textured products), with a focus on processing technology development, functional properties, and sustainability claims.

Molecular breeding, enzymatic modification, and green polymer chemistry are expected to support future studies on soybean-based materials. Improvements in soybean cultivars with specific oil compositions and enhanced protein functionality would improve the performance of the resulting composites. The inclusion of soybean oil and protein valorization within biorefinery concepts also presents potential to increase resource efficiency and economic performance. Together, these strategies underscore the opportunities represented by soybean as an archetypal nitrogen-fixing crop for sustainable production within a circular bioeconomy.

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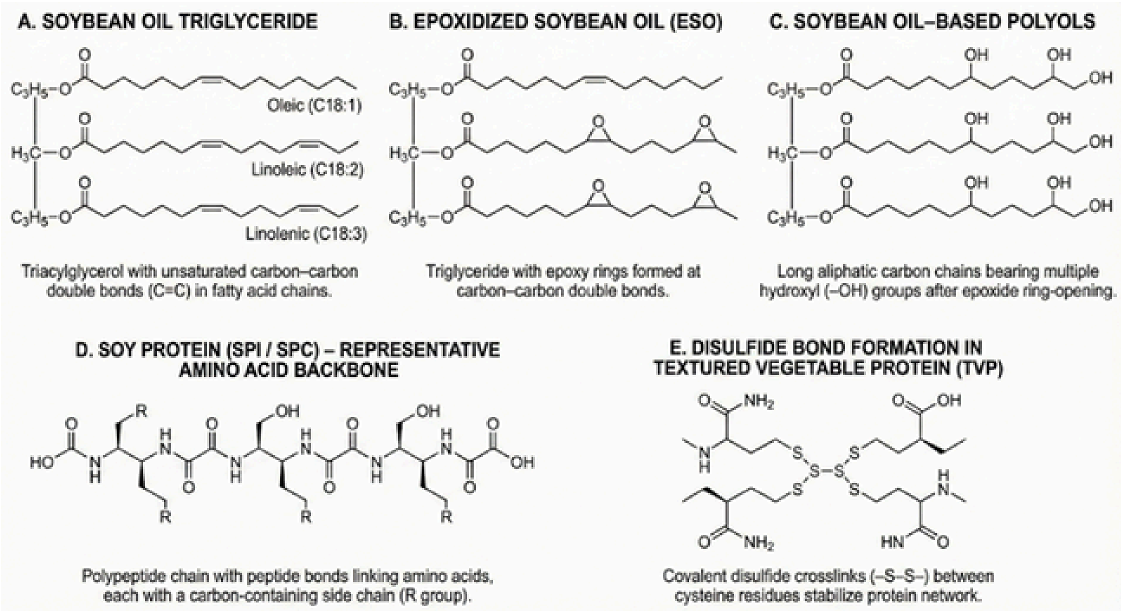

Figure 2. Representative chemical structures of major soybean-derived industrial materials: (a) Soybean oil triglyceride containing unsaturated carbon–carbon double bonds, (b) Epoxidized soybean oil (ESO) with epoxy (oxirane) rings formed at former double-bond positions, (c) ESO-derived soybean oil polyols containing hydroxyl (–OH) functional groups, (d) Representative amino acid backbone of soy proteins (SPI/SPC) showing peptide linkages and carbon-containing side chains, and (e) Disulfide bond (–S–S–) formation between cysteine residues contributing to protein network stabilization in textured vegetable protein (TVP). Structures are schematic and intended to highlight key functional chemical features rather than exact molecular distributions.

Collectively, soybean oil, epoxidized soybean oil, soybean oil–based polyols, defatted soybean meal, soy protein concentrate, soy protein isolate, and textured vegetable protein represent a diverse portfolio of soybean-derived materials with distinct chemical structures, processing requirements, and industrial applications (Table 1).

Table 1. Industrial applications of soybean-derived materials.

Soybean-Derived Material	Industrial Application	Key Functional Attributes	Supporting References
Epoxidized Soybean Oil (ESO)	Structural & wood adhesives	High bonding strength, epoxy functionality, isocyanate-free	[1,2,6]
Soybean Oil Polyols	Coatings, inks, sealants, foams	Renewable polyols, good film-forming ability	[1,2]
Soy Protein Isolate (SPI)	Biodegradable plastics, films	Bioplastic film formation, moldability	[4]
Soy Protein Concentrate (SPC)	High-moisture extrusion proteins	Functional properties: WHC, NSI, emulsification	[7]
Textured Vegetable Protein (TVP)	Plant-based meat analogues	Fibrous texture, good water retention, chewiness	[8]
Defatted Soy Meal	Biopolymer feedstocks	High protein fraction, cheap raw material	[5]

Soybean Oil-Derived Bio-Based Materials

Bio-adhesives based on soybean oil and epoxidized soybean oil (ESO)

Soybean oil is a naturally occurring triglyceride composed of a glycerol backbone esterified with long-chain fatty acids, primarily oleic, linoleic, and linolenic acids, each of which possesses multiple unsaturated carbon–carbon double bonds. The unsaturated sites of soybean oil are chemically reactive centers; these characteristics make soybean oil a highly suitable platform for producing bio-based polymers, resins, and adhesive systems. Compared to traditional fossil petrochemical feedstocks, soybean oil has gained renewed interest due to its renewability, low toxicity, biodegradability, and lower environmental burden; thus, it can serve as a promising primary raw material for sustainable adhesive formulations [10,11].

The chemical modification of soybean oil has been well reported over the years, with epoxidation being the most extensively studied process because of its effectiveness and adaptability for use with other vegetable oil sources. Epoxidized soybean oil (ESO) is obtained by converting carbon–carbon double bonds present in the unsaturated fatty acid structure into epoxy (oxirane) rings, which are typically formed through peracid-mediated or catalytic epoxidation processes. This modification yields highly reactive epoxide functional groups, which provide extensive chemical reactivity in the form of ring-opening polymerization and cross-linking reactions with amines, acids, and alcohols. The resulting transformation enables ESO to function as a green substitute for traditional petroleum-derived epoxy resins in adhesive, coating, and composite applications [12].

ESO-based adhesive systems are receiving increasing interest due to their capability to deliver competitive mechanical performance while avoiding toxic components such as isocyanates and volatile organic solvents. The high epoxy functionality of ESO is favorable for cross-linking through covalent bonding, particularly for the formation of three-dimensional polymer networks required for effective load transfer and adhesion strength. Moreover, due to the flexible aliphatic nature of fatty acid chains, polymers derived from ESO

https://doi.org/10.61577/jpri.2025.100008

can overcome the brittleness typically associated with petroleum-based epoxies and exhibit improved toughness and flexibility, which are desirable for applications requiring impact resistance and durability [13]. The major chemical transformation pathways of soybean oil leading to epoxidized soybean oil, polyols, and cross-linked bio-adhesive networks are illustrated in Figure 3.

Recent research has demonstrated that the cross-linking of ESO with multifunctional polyamines represents a viable route toward high-performance bio-adhesives. Branched and flexiblediamines, such as melamine-based diamines, promote extensive network formation through epoxy ring-opening and amidationreactions. The coupling of these reactive building blocks enhances interfacial bonding and cohesive strength. Such ESO–diamine systems have demonstrated lap shear strengths that are comparable to or exceed those of conventional epoxy adhesives, particularly on metallic and lignocellulosic substrates. This adhesion mechanism, which includes covalent bonding, hydrogen bonding, and physical interactions, results in strong adhesion across a wide variety of surfaces [6].

In addition to structural adhesives, ESO is also an important intermediate for the synthesis of soybean oil–based polyols through epoxide ring-opening reactions that introduce hydroxyl functional groups along the fatty acid chains. These polyols are commonly utilized in polyurethane adhesives, coatings, sealants, and foams, where they partially or completely replace fossil-based polyols. The presence of multiple hydroxyl groups allows precise control over cross-linking density and enables tunable mechanical properties, making it possible to formulate adhesives with tailored flexibility, hardness, and thermal stability.

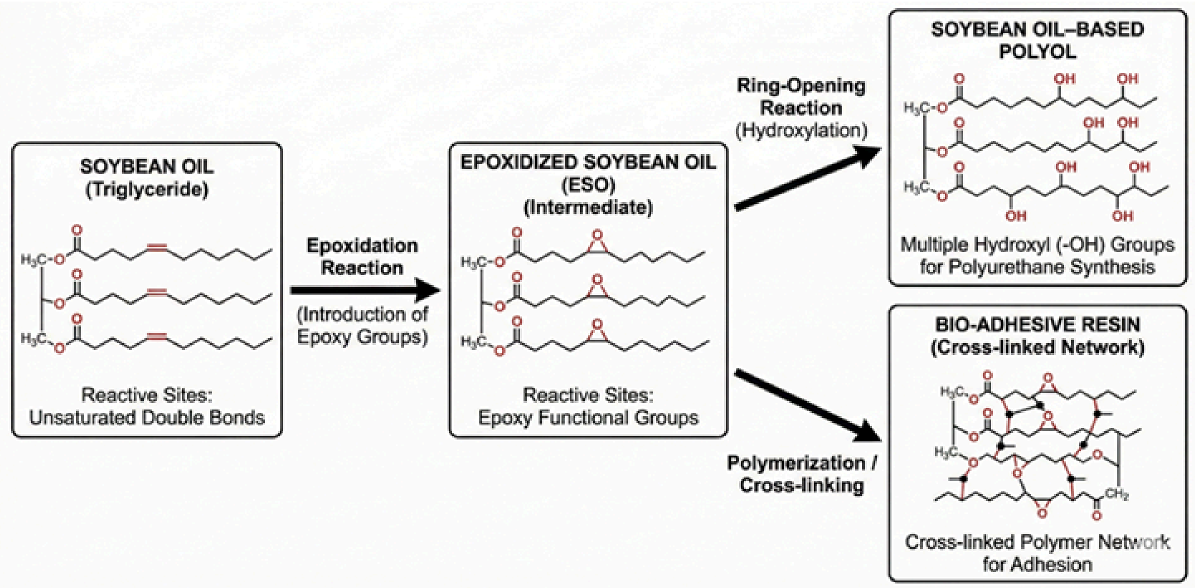

Figure 3. Schematic illustration of the chemical transformation pathways of soybean oil into epoxidized soybean oil (ESO) and its subsequent conversion into soybean oil–based polyols and cross-linked bio-adhesive resins. Unsaturated carbon–carbon double bonds in soybean oil are converted into epoxy functional groups through epoxidation. The epoxy groups undergo ring-opening reactions to form hydroxyl-functional polyols or participate in polymerization and cross-linking reactions to generate three-dimensional adhesive networks. The figure is conceptual and intended to highlight key reaction pathways rather than detailed reaction stoichiometry.

Soybean oil-based adhesives offer significant advantages from both environmental and occupational safety perspectives. Several ESO-based systems are solvent-free and isocyanate-free, which reduces volatile organic compound (VOC) emissions and minimizes health hazards during processing and application. Furthermore, the use of renewable feedstocks contributes to reduced life-cycle greenhouse gas emissions compared to petroleum-based adhesives, making these materials well-suited to meet sustainability and regulatory requirements in construction, automotive, and packaging applications [11,13].

Despite these advantages, curing kinetics, thermal resistance, and long-term durability of ESO-based adhesives remain challenges under demanding service conditions. Ongoing research focuses on hybrid formulations, the incorporation of bio-based fillers, and the molecular design of cross-linkers to improve performance while maintaining sustainability. Collectively, these advances highlight the strong potential of soybean oil-based bio-adhesives as commercially viable and eco-friendly alternatives to conventional epoxy-based materials in industrial applications (Table 2).

Table 2. Properties of ESO-based adhesives.

Property	Observed Findings	Notes / Performance Evaluation	References
Lap Shear Strength	~2,000 kPa (MPD–ESO on stainless steel at 180 °C cure)	Comparable or superior to petroleum-derived epoxies	[6]
Crosslinking Chemistry	Epoxy ring-opening, amidation polymerization	Leads to strong covalent bonded networks	[6]
Flexibility & Toughness	Improved with longer-chain diamines (e.g., MPD)	Enhances durability and ductility	[6]
Environmental Profile	Isocyanate-free, solvent-free, low VOC	Safer processing & reduced environmental burden	[2,6]

https://doi.org/10.61577/jpri.2025.100008

Substrate Adhesion	Stainless steel > copper > aluminum	Due to surface oxide chemistry & hydrogen bonding potential	[6]

Potential Uses in Adhesives, Inks, and Coatings

Outside of structural adhesives, soybean oil polyols produced by epoxidation and polymerization are used in a variety of industrial coatings, adhesives, sealants, inks, vehicle panels, and rigid urethane foam applications. Soybean polyol–based formulations are renewable substitutes for fossil fuel–based polyols, which reduce environmental load without compromising the performance required for critical industrial applications.

The binding characteristics of ESO-derived materials stem from their reactive epoxy functionality and their capacity to generate permanent covalent bonds with a wide variety of substrates. Such substrate-specific interactions are driven by chemical composition and cross-linking architecture, and while stainless steel substrates yield higher adhesion strengths than copper and aluminum coupons, this behavior is attributed to competing surface oxide layers on copper and aluminum that prevent surface hydroxyl bond formation and reduce hydrogen-bonding capacity with the hydroxyl and amine moieties embedded within the ESO-based adhesive matrix [6].

Bio-Based Polymers and Biodegradable Materials

Materials derived from soybean oil are increasingly incorporated into biodegradable and compostable polymer matrices. Soy protein isolate (SPI) is a highly accessible protein candidate for bioplastic production, being obtained from defatted soybean meal after oil extraction. SPI-based materials are processed using conventional techniques such as casting, extrusion, and injection molding, as well as emerging processing techniques in additive manufacturing, with mechanical and thermal properties comparable to, or even similar to, petroleum-derived thermoplastics [4]. Such protein-based biopolymers offer significant benefits for the food packaging industry and agro-plastics due to their biodegradable and environmentally friendly properties. Acylation and cross-linking using natural compounds, such as tannic acid or genipin, can also be implemented to enhance water resistance, mechanical strength, and functional properties for specific applications.

Protein Processing Technologies and Textured Vegetable Protein

Protein extraction and concentration

Through technological advancements in soy protein extraction, concentration, and functional modification processes, soy proteins have become one of the most widely used plant protein sources for food and industrial applications. Specifically, soy protein concentrate (SPC) and soy protein isolate (SPI) are the main soy protein ingredients used at this production scale for downstream material processing, as they differ in protein purity, level of processing, and functional properties.

Soy protein concentrate usually contains 65–90% protein (dry weight) and is produced from defatted soybean meal by emoving water-soluble non-protein compounds, including soluble carbohydrates and other low-molecular-weight components. Common commercial techniques include aqueous alcohol extraction, acid leaching, or enzyme-assisted treatments, which preserve structural polysaccharides and other minor components that beneficially contribute to functional properties such as water-holding capacity, emulsification, and gelling [14, 7]. This composition enables SPC to serve as a valuable raw material for high-moisture extrusion and structured protein systems.

Soy protein isolate, on the other hand, has a protein content exceeding 90% and is therefore a more compositionally pure and consistent product. SPI is usually produced through alkaline extraction followed by isoelectric precipitation or membrane-based ultrafiltration, processes that remove most non-protein fractions. As a result, SPI is favourable for applications such as biodegradable plastics and high-value textured protein products, where controlled gelation, emulsification, and film-forming behaviour are required due to its high protein purity and well-defined functional profile (Lam et al., 2018) [15].

The functional properties of SPC and SPI are strongly influenced by raw material characteristics such as nitrogen solubility index (NSI), water-holding capacity (WHC), emulsifying activity, foaming capacity, gel strength, and the content of soluble sulfhydryl groups. These parameters dictate protein dispersibility, hydration behaviour, and the ability to form networks during subsequent processing. However, variations in extraction conditions, solvent chemistry, drying temperature, and storage environment can drastically alter these functional properties and ultimately impact processability and end-product quality [7].

Textured Vegetable Protein Production

Textured vegetable protein (TVP) is typically produced by high-moisture extrusion cooking (HME), a thermomechanical process generally conducted at moisture contents ≥40% and barrel temperatures of approximately 150–160 °C. This process employs twin-screw extruders to apply simultaneous heat, shear, and pressure, resulting in extensive structural modification of soy proteins. During extrusion, native protein secondary and tertiary structures are disrupted, leading to reversible unfolding, aggregation, and alignment of proteins in the direction of material flow [8,16]. The high-moisture extrusion process leading to protein alignment and fibrous structure formation in textured vegetable protein is illustrated in Figure 4.

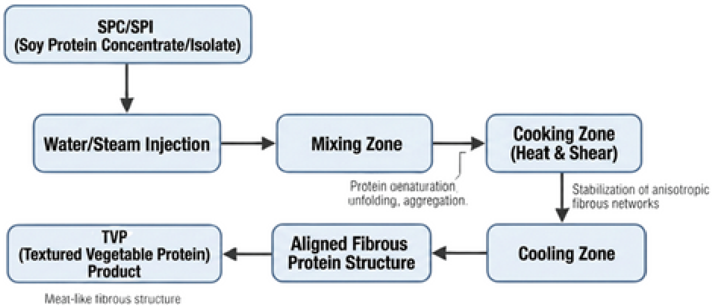

Figure 4. Schematic flow of textured vegetable protein (TVP) production.

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The characteristic fibrous, meat-like structure of TVP arises from the formation of anisotropic protein networks stabilized by both covalent interactions primarily disulfide bond formation between cysteine residues and non-covalent interactions such as hydrogen bonding and hydrophobic interactions. At the die exit, shear-induced cooling further stabilizes these ordered structures into highly aligned fibrous matrices that closely resemble the texture and visual appearance of animal muscle tissue [17, 8]. The process outlines the transformation of SPC/SPI through a twin-screw extruder. Key phases include hydration in the mixing zone, protein denaturation in the cooking zone, and fiber stabilization in the cooling zone.

The functional attributes of SPC and SPI used as extrusion feedstocks have a critical influence on the textural and mechanical properties of the resulting TVP. Nitrogen solubility index (NSI) is an important indicator for plant protein utilization in meat analogues, as higher NSI values improve protein dispersion and fiber formation, while greater WHC enhances hydration and juiciness of the final product. Likewise, foaming and emulsifying properties are closely related to protein–fat interactions, chewiness, and toughness of extruded TVP. Table 3 summarizes the relationships between functional properties of SPC and SPI and the resulting quality attributes of textured vegetable protein.

Table 3. Functional properties of SPC/SPI influencing textured vegetable protein (TVP).

Functional Property	Role in TVP Formation	Effect on Final Texture / Quality	References
Nitrogen Solubility Index (NSI)	Indicates protein dispersibility	Higher NSI → better fiber formation	[7]
Water Holding Capacity (WHC)	Determines hydration during extrusion	Higher WHC → juicier & softer texture	[7]
Emulsifying Activity Index (EAI)	Stabilizes fat-protein interfaces	Higher EAI → ↑ springiness, adhesiveness; ↓ hardness	[8]
Foaming Capacity & Stability	Reflects air incorporation ability	Influences resilience, chewiness, texturization degree	[8]
Gel Strength	Determines protein network integrity	Strong gels → firmer, meat-like fibers	[7,8]
Amino Acid Composition	Influences protein–protein interactions	Methionine, threonine, arginine linked to adhesiveness & springiness	[8]
Sulfhydryl Content	Drives disulfide bond formation	Critical for cross-linked fibrous structure	[7]

Functional and Nutritional Optimization

In addition to textural performance, soy protein–based TVP products exhibit favorable nutritional characteristics due to their well-balanced amino acid composition. Soy protein concentrates and isolates are rich in essential and semi-essential amino acids, with aspartic acid, glutamic acid, arginine, leucine, and lysine accounting for approximately 55% of total amino acids. The relatively high presence of sulfur-containing and charged amino acids significantly influences protein crosslinking behavior and network strength during extrusion processing [8,14].

Extrusion feedstocks containing higher levels of methionine, threonine, and arginine have been reported to exhibit increased springiness, adhesiveness, and free sulfhydryl content in the resulting textured vegetable protein, indicating improved fibrous structure formation. Furthermore, the distribution of protein secondary structures including α-helices, β-sheets, β-turns, and random coils plays a decisive role in protein alignment, aggregation behaviour, and the overall degree of texturization achieved during the HME process [16,17].

Selective breeding, extraction optimization, and enzymatic modification strategies have collectively facilitated the development of high-functionality soy protein ingredients with tailored molecular characteristics. These advances have enabled the production of novel TVP products with improved nutritional value, enhanced mouthfeel, and superior sensory attributes. Such developments strongly support the rapidly expanding alternative protein industry by enabling plant-based meat analogues with organoleptic and technological properties that increasingly approximate those of animal-derived products [5].

Industrial Scale-Up and Commercial Applications

Market development and regulatory pathways

In the end, the technical strength, economic viability, regulatory acceptance, and market penetration of soybean-derived industrial materials across various applications will dictate their commercial viability. Although laboratory- and pilot-scale studies have demonstrated the practicality of soybean oil– and protein–based materials, the next step involves evaluating engineering polymers under industrial processing and service conditions. Among soybean-derived platforms, epoxidized soybean oil (ESO)–derived adhesives have demonstrated particularly strong promise for scale-up owing to their relatively simple synthesis processes, compatibility with existing epoxy resin manufacturing facilities, and lower dependence on toxic chemicals.

Market analyses suggest that formulations based on ESO may be more economically attractive than glycerol-derived epoxide systems, as lower raw material costs, reduced processing complexity, and the absence of volatile organic compounds (VOCs) and isocyanate-based chemistries can drive down the cost of ESO-based epoxies. These features also reduce occupational health risks and contribute to lower environment-related costs during manufacturing and application. Consequently, there is growing interest in and adoption of commercial ESO-derived adhesive products in wood-based panel bonding, construction materials, structural assembly, and, to a lesser extent, selected automotive applications, where sustainability credentials are increasingly becoming an important procurement criterion [6].

From a regulatory standpoint, soybean protein–based materials, including bioplastics and textured vegetable protein (TVP), have a long history of safe use in food and feed

https://doi.org/10.61577/jpri.2025.100008

systems [18]. The regulatory status of soy protein isolates and concentrates as food-contact materials, as well as critical components of plant-based meat analogues, has been established in a range of regions, including North America, the European Union, and parts of Asia. By contrast, regulatory frameworks for soybean oil–derived polymers intended for non-food industrial uses, such as coatings, sealants, and structural adhesives, are still emerging in some regions. Such materials often require case-by-case assessment of toxicity, migratory behavior, thermal stability, and long-term durability. Ongoing interaction with regulatory authorities and standard harmonization are therefore needed to accelerate broader market adoption [12,1].

Supply Chain Integration and Sustainability

The logistical feasibility and economic considerations associated with substituting soybean-derived materials into existing industrial value chains are influenced by the availability of defatted soybean meal, a co-product of oil extraction that is produced in large quantities during soybean processing and has traditionally been used primarily as animal feed. The recovery of this protein-rich by-product into high-functionality protein concentrates, bioplastics, and adhesive precursors presents an important opportunity for resource efficiency and waste valorization from a circular economy perspective. This cascading utilization of soybean biomass supports the goals of sustainable development by extracting maximum value from the same agricultural feedstock [2].

However, for soybean oil–based adhesives and polymers, the need for specialized chemical modification infrastructure, including epoxidation reactors and controlled curing systems, may initially restrict adoption to manufacturers with existing chemical processing capabilities [19]. Nevertheless, these technologies are largely compatible with current resin and polymer manufacturing facilities, thereby facilitating technology transfer and scale-up with relatively limited capital reinvestment. At the same time, the production of textured vegetable protein relies on twin-screw extrusion technology with precise control of moisture, temperature, and shear conditions. Extrusion capacity and processing expertise are increasingly available in response to the growing demand for plant-based protein products, enabling industrial-scale textured vegetable protein (TVP) production [16,17].

Soy-based materials offer a clear sustainability advantage in terms of renewable sourcing and reduced fossil carbon input. However, their overall environmental performance can be influenced by the energy requirements of chemical modification, protein extraction, and extrusion processing. Life-cycle assessment studies highlight the necessity of integrating energy-efficient processing, solvent recovery, and waste-minimization strategies to ensure that environmental benefits are realized at scale [1].

Emerging Technologies and Future Prospects

Advanced protein processing and bioengineering

Prospective protein processing approaches are likely to extend these potential functional and commercial applications of soybean-derived materials. Protein molecular weight distribution, surface charge and interfacial behaviour can be tailored by using enzymatic modification and controlled hydrolysis approaches, offering the possibility of designing functionality for targeted industrial and food applications. Key innovation pathways and future research directions for soybean-derived materials are summarized schematically in Figure5. Furthermore, precision fermentation and bio-catalytic approaches provide opportunities to produce soybean protein variants with improved solubility, emulsification, and network-forming properties. In addition to the native TVP production type, the crosslinking of soy proteins with polysaccharides, phenolic compounds, or other bio-based polymers opens a new avenue to obtaining new hybrid materials with multifunctional character and stability-enhanced properties [14].

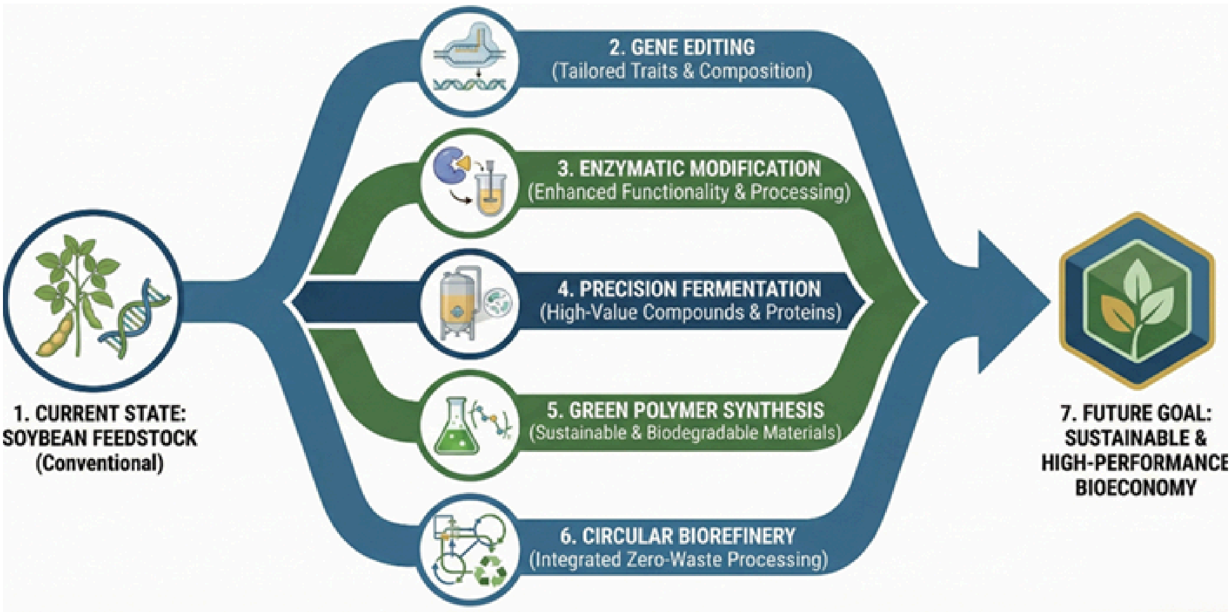

Figure 5. Roadmap illustrating emerging technologies and future innovation pathways for soybean-derived industrial materials.

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Starting from conventional soybean feedstocks, advancements in gene editing, enzymatic modification, precision fermentation, green polymer synthesis, and circular biorefinery integration are expected to enable the development of sustainable, high-performance materials and products. The figure highlights strategic research directions and long-term goals rather than specific technological timelines.

At agriculture level, marker-assisted breeding and new gene-editing technologies can be applied for developing soybean cultivars with a specific composition of proteins and a better nutritional profile [20]. Manipulating the proportion of storage globulins (11S/7S ratio), increasing the content of essential amino acids and optimizing the content of sulfur-containing amino acids may improve protein functionality and broaden the application of protein in food and non-food industries.

Polymer Chemistry and Green Synthesis

Simultaneously, advances in polymer chemistry are expanding the design window for soy oil-based polymers [21]. Synthetic strategies such as ring-opening polymerization, reductive amination, thiol–epoxy reactions, and photopolymerization allow for the conversion of renewable soybean oil into macromonomers, which can produce materials with tunable mechanical, thermal, and chemical properties. Especially the self-healing, thermally recyclable and dynamically cross-linked soybean-based polymers may enhance service life and enhance recyclability at end-of-life. These new classes of materials help to establish soybean oil as an essential platform for the design of next-generation sustainable polymer systems [11,12].

Integration with the Circular Bioeconomy

The integration of soybean-based materials into integrated biorefinery schemes is a targeted step toward circular bioeconomy action. The simultaneous valorization of soybean protein into food products, feed ingredients, and industrial bioplastics, paired with the subsequent conversion of the oil into ESO-based adhesives and polymers, utilizes all biomass fractions in an efficient manner. These integrated systems generate less waste, strengthen the economy's resilience, and minimize the environmental impact of soy value chains. With the ongoing development and maturation of biorefinery models that will ultimately solidify the roles soybean-derived materials will play in closed-loop, sustainable manufacturing ecosystems [1,2], the potential returns of soybean-derived products far outweigh the costs of production. The integration of soybean-derived materials within a circular bioeconomy and industrial value chain is illustrated in Figure 6.

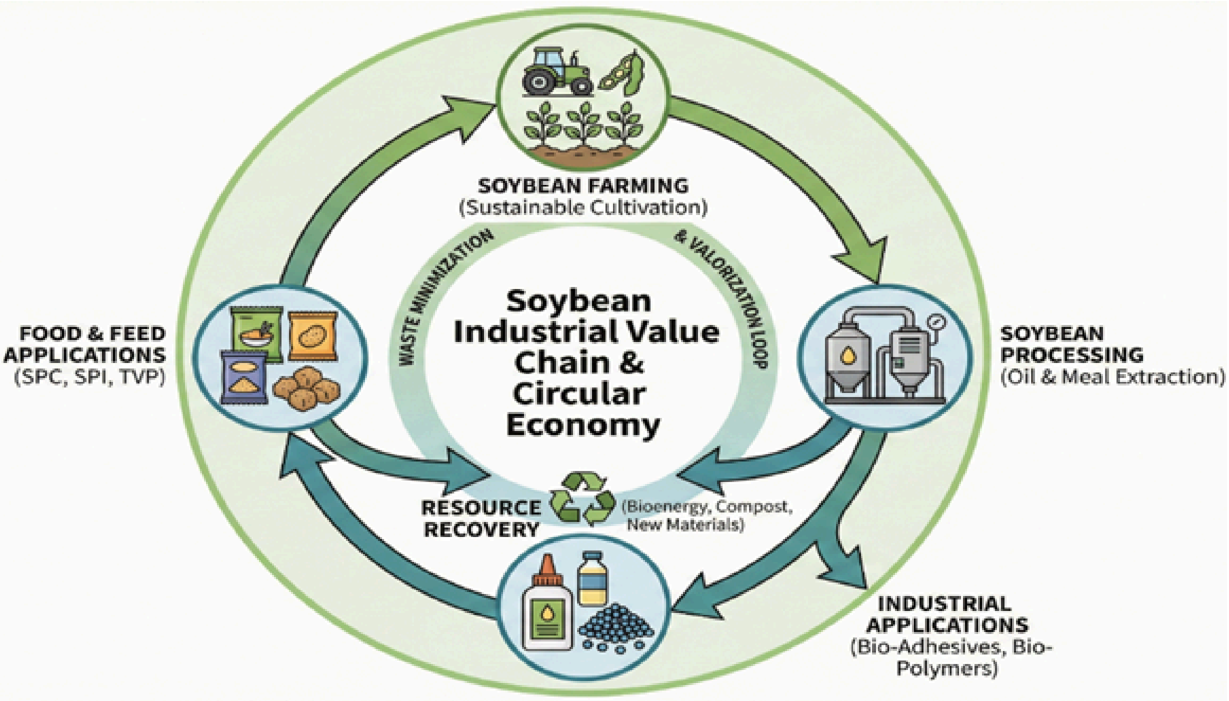

Figure 6. Conceptual representation of the soybean-based industrial value chain integrated within a circular bioeconomy framework.

Soybean cultivation supplies raw material for oil and meal processing, which are subsequently converted into food and feed products (SPC, SPI, TVP) as well as industrial materials such as bio-adhesives and biopolymers. Residual streams are directed toward resource recovery pathways, including bioenergy generation, composting, and secondary material production, thereby minimizing waste and enabling continuous valorization of soybean biomass. The figure highlights major value flows rather than quantitative process efficiencies.

Challenges and Limitations

While there is growing interest in soybean-based materials as renewable alternatives to key petroleum-derived products, their large-scale industrial application is still limited by several technical, economic, and regulatory hurdles [22]. These challenges are distinct for oil-based polymers, protein-based materials, and textured vegetable protein systems and therefore need to be critically addressed if large-scale commercialization is to be achieved.

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Technical Limitations

The inherent characteristics of soy protein systems make them sensitive to moisture, which is one of the major technical challenges in developing soy-based materials. The higher density of hydrophilic functional groups, such as hydroxyl, carboxyl, and amino groups, in soy protein isolate (SPI) and soy protein concentrate (SPC) facilitates moisture absorption. Consequently, unmodified bioplastics and films based on soy protein exhibit considerable loss of mechanical strength, including increased water vapor permeation, reduced dimensional stability, and swelling under wet environments. Due to this moisture sensitivity, their application in packaging and structural uses is limited unless chemical modification, blending, or surface treatment is employed [4,7].

Moreover, protein-based materials are still constrained by their thermal stability [23]. Unlike traditional synthetic polymers, soy proteins denature and degrade at much lower temperatures, resulting in a narrow processing window for extrusion, injection molding, and thermoforming. Crosslinking agents, plasticizers, and enzymatic treatments can improve thermal stability; however, such modifications often complicate processing steps and increase costs [5].

Controlled chemical modification of soybean oil–based polymers and adhesives is also required to achieve the performance expected in industrial applications. Processes such as epoxidation, polyol synthesis, and crosslinking require specialized chemical infrastructure and tightly controlled reaction conditions [24]. When solvent extraction of soybean oil is used without proper control, variations in fatty acid composition from different sources can lead to variability in epoxide content, hydroxyl number, and, consequently, the final material specifications, resulting in inconsistent material properties if not adequately managed [2].

Performance and Durability Concerns

Despite some mechanical performance advantages, ESO-based adhesives and polymers often suffer under humid environments or mechanical stress [25]. Although certain soy-based formulations demonstrate performance comparable to or better than petroleum-based epoxy systems, their resistance to long-term exposure to heat, ultraviolet radiation, and aggressive chemical environments is generally lower. These limitations can restrict their use in high-performance structural or outdoor applications unless they are hybridized with synthetic materials or reinforced with fillers [6].

Textured vegetable protein (TVP) is a product for which end-product quality is highly sensitive to variations in raw material characteristics and processing parameters [26]. Differences in protein content, nitrogen solubility index, sulfhydryl content, moisture level, and extrusion conditions result in inconsistent textural properties, which hinder process reproducibility at the industrial scale. As a result, maintaining uniform quality remains a significant challenge for manufacturers producing large batches [8].

Economic and Supply-Chain Constraints

The second major barrier to the industrial adoption of soybean-derived materials is economic feasibility. Although soy-based polymers and proteins offer sustainability advantages, their higher costs relative to low-priced, well-established petroleum-based materials reduce competitiveness in price-sensitive markets. The benefits of sourcing renewable materials are often offset by the costs associated with chemical modification, processing additives, and specialized equipment [1].

In addition, global soybean trade is influenced by competition among food, feed, and industrial demands. Natural variability in soybean crop yields, climate non-stationarity, and market dynamics drive raw material price volatility, leading to economic instability in soy-based industrial value chains. Such supply-chain uncertainties raise concerns regarding long-term scaling and investment [2].

Regulatory and Sustainability Challenges

There are inconsistencies in regulatory frameworks across different regions for soybean-based products. Despite the generally positive regulatory status of soy protein–based materials for food and feed applications, regulatory pathways for non-food uses such as bio-based adhesives, coatings, and polymer composites are still evolving. New formulations often require extensive toxicological testing, migration studies, and long-term performance assessments prior to approval, resulting in extended time-to-market and increased development costs [6].

As noted by Sheffield, soybean-based materials offer sustainability advantages by reducing dependence on fossil resources; however, their overall environmental performance is highly sensitive to processing intensity and other life-cycle factors. If not carefully optimized, energy-intensive chemical modifications, solvent use, and limited recyclability of certain formulations may offset net environmental benefits. These sustainability gains can only be fully realized through the integrated application of life-cycle assessment and circular design strategies [1].

Table 4 summarizes the specific technical, economic, regulatory, and environmental challenges facing the industrial use of soy-based materials, while Table 5 provides a comparative summary of the relative strengths and weaknesses of soy-based materials in terms of processing, performance, and sustainability.

Table 4. Challenges and limitations in industrial utilization of soybean-derived materials.

Category	Challenges / Limitations	Implications	References
Technical	Water sensitivity & low thermal stability of soy protein	Requires crosslinking or blending for high-performance products	[4,7]
Economic	Competes with low-cost petroleum-based materials	Market adoption depends on cost reduction & incentives	[2]
Supply Chain	Competing demand between food, feed, and industrial uses	Influences price volatility and resource allocation	[5]
Regulatory	Need for harmonized global standards for ESO-based polymers	Requires toxicological validation & performance testing	[6]
Environmental	Moisture susceptibility of SPI-based bioplastics	Limits usage in humid environments without modification	[4]

https://doi.org/10.61577/jpri.2025.100008

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Table 5. Advantages and disadvantages of soybean-based industrial materials.

Aspect	Advantages	Disadvantages	Key Open-Access References (new)
Renewability	Derived from renewable agricultural biomass; reduces dependence on fossil resources	Competes with food and feed uses, raising concerns over resource allocation	[27]
Environmental impact	Low VOC emissions; bio-based nature supports sustainability goals	Environmental performance depends strongly on formulation and processing intensity	[28]
Chemical versatility	Unsaturated C=C bonds in oil and reactive amino acid side chains enable diverse chemical modifications	Requires chemical modification (epoxidation, crosslinking) for industrial performance	[29]
Mechanical performance	ESO-based adhesives and modified soy polymers can reach competitive strength and flexibility	Unmodified soy protein materials show lower thermal and mechanical stability	[6]
Processing compatibility	Compatible with extrusion, molding, coating and resin-based processing routes	Controlled processing conditions and infrastructure increase cost	[30]
Biodegradable plastics	Suitable for biodegradable films, coatings, molded products	High moisture sensitivity limits use in humid or high-temperature environments	[7]
Protein-based materials	Excellent emulsifying, binding, and film-forming properties	Brittleness and water sensitivity require blending or chemical treatment	[4,7]
Textured vegetable protein (TVP)	Forms fibrous, meat-like structures via high-moisture extrusion	Strong dependence on raw material quality and processing parameters	[1,7,8]
Economic considerations	Potential lower carbon footprint and long-term sustainability benefits	Soybean price volatility affects cost competitiveness	[2]
Regulatory acceptance	Soy protein materials widely approved for food and feed uses	Regulatory pathways for non-food soy polymers still evolving	[31]

Conclusion

Soybean-based materials are potential green substitutes for petroleum-derived products used in many industrial applications, such as adhesives, bio-based polymers, coatings, biodegradable plastics, and structured plant protein products. The co-existing oil and protein fractions in soybean biomass enable multiple pathways for material conversion, and soybean should therefore be considered a multipurpose industrial feedstock rather than merely a food and feed crop. In addition to environmental pressures and regulatory efforts to reduce dependence on fossil resources, increasing interest in renewable materials continues to support the demand for soybean-based industrial materials.

Widespread commercial production of soy-based materials necessitates an integrated and application-oriented evaluation of recent breakthroughs in soybean oil– and protein-based materials, with a focus on processing approaches, functional performance, and industrial viability. To overcome the siloed nature of existing coverage, in which oil-based systems (e.g., epoxidized soybean oil–derived adhesives and polyols) and protein-based bioplastics and textured vegetable protein systems are addressed independently, this review examines oil- and protein-based systems jointly, thereby addressing a major gap in the literature. The discussion of structure–property–performance relationships underscore how material behaviour and eventual use are governed by a combination of chemical modification, protein functionality, and processing conditions.

While significant advancements have been made in the development of soy-based industrial materials, several factors continue to hinder their widespread adoption in large-scale applications. These include (i) moisture sensitivity and thermal limitations of protein-based systems, (ii) the requirement for well-controlled chemical processing of oil-based polymers, (iii) competition with food and feed uses, and (iv) regulatory uncertainty regarding the approval of novel bio-based products. Overcoming these limitations will require integrative approaches across materials science, crop improvement, process engineering, and policy.

Further breeding efforts focused on soybean cultivars with specific oil compositions and improved protein functionality are required to enhance the intrinsic properties of downstream materials. New opportunities arising from advances in enzymatic modification, green polymer chemistry, and efficient processing technologies offer promise for improving the stability and functionality of sustainable materials while enhancing compatibility with existing industrial technologies. Moreover, the incorporation of soybean oil and protein valorization into biorefinery-based production frameworks can improve resource utilization and economic efficiency, aligning their industrial application with the principles of the circular bioeconomy.

In summary, soybeans are a strategically important crop for sustainable manufacturing due to their chemical diversity, renewable nature, and established supply chain. Continued cross-disciplinary research and development are critically

https://doi.org/10.61577/jpri.2025.100008

needed to expand the performance envelope and application range of soybean-based industrial products, enabling their transition from niche applications to mainstream solutions within sustainable and circular production systems.

Disclosure of conflict of interest

The authors declare no conflict of interest.

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