Analysis of Unique Properties of Soluble Soybean Polysaccharide (SSPS)

Soluble Soybean Polysaccharide (SSPS) is a natural water-soluble acidic polysaccharide prepared from soybean meal (defatted soybean residue) through pretreatment (degreasing and deproteinization), hot water extraction, enzymatic purification (synergistic action of neutral protease and pectinase), ultrafiltration fractionation, spray drying and other processes, belonging to plant-derived water-soluble dietary fiber. Its core chemical structure is a highly branched rhamnogalacturonan main chain, with side chains linked to neutral monosaccharides such as arabinose, galactose and rhamnose. It possesses both the physiological functions of dietary fiber and high-performance food colloid properties. It exhibits irreplaceable unique advantages over traditional food colloids in acidic protein stabilization, low-viscosity functional regulation and extreme environment tolerance, and is widely used in food, health products, pharmaceuticals and other fields. The following is a detailed analysis from four aspects: **physicochemical characteristics, functional features, unique properties and application advantages**.

I. Physicochemical Characteristics

(I) Chemical Composition and Molecular Structure

The chemical composition of SSPS is significantly dependent on raw materials and correlated with production processes, and its core structure determines its unique functional properties, as detailed below:

- **Monosaccharide Composition**:

Galacturonic Acid (GalA), Arabinose (Ara) and Galactose (Gal) are the core components, with a total proportion of **≥70% (dry basis)**; among them, the content of galacturonic acid ranges from 22%–32%, which is the core of its acidic polyanionic characteristics. Arabinose accounts for 25%–40%, galactose 18%–28%. It also contains a small amount of Rhamnose (Rha, 3%–8%) and Xylose (Xyl, 1%–5%). Some products contain trace Glucose (Glc, ≤2%) and no other monosaccharides such as fructose and mannose.

- **Molecular Structure**:

The main chain is galacturonan linked by α-1,4-glycosidic bonds (part of galacturonic acid residues are methyl esterified with a degree of methyl esterification of 15%–30%), forming a polyanionic skeleton. The side chains are dominated by arabinose and galactose, which are attached to rhamnose residues of the main chain via α-1,6-glycosidic bonds and β-1,3-glycosidic bonds, forming a highly branched spatial conformation. It presents a compact random coil structure in aqueous solution with a degree of branching (number of side chains / number of main chain sugar residues) of 0.8–1.2, significantly higher than pectin (0.3–0.6) and xanthan gum (0.5–0.7).

- **Molecular Weight Distribution**:

Determined by Gel Permeation Chromatography (GPC), the molecular weight distribution range of SSPS is 5 kDa–1000 kDa. It can be divided into low molecular weight grade (5–50 kDa), medium molecular weight grade (50–300 kDa) and high molecular weight grade (300–1000 kDa) according to ultrafiltration fractionation technology. The medium molecular weight grade (50–300 kDa) accounts for the highest proportion (60%–75%), serving as the key component to realize core functions such as acidic protein stabilization and emulsification.

- **Functional Group Characteristics**:

The molecule contains a large number of carboxyl groups (–COOH) and hydroxyl groups (–OH), and some contain methyl ester groups ($–COOCH_3$). The acid dissociation constant (pKa) is 3.2–3.8. Part of the carboxyl groups remain undissociated under acidic conditions (pH<pKa) and fully dissociated under neutral to alkaline conditions (pH>pKa), showing strong negative electricity (Zeta potential: -25~-40 mV at pH 7.0), which is the core foundation for its electrostatic stabilization function.

(II) Physicochemical Properties

1. Solubility Characteristics

SSPS possesses excellent water solubility, which is its core feature distinguishing it from insoluble soybean dietary fiber: it can dissolve rapidly in cold water (25℃) and be completely dissolved within 5–10 minutes of stirring without caking or precipitation. It dissolves faster in hot water (80–100℃), forming a uniform aqueous solution in 3–5 minutes. A 10% (w/v) aqueous solution is clear and transparent with light transmittance **≥90% (25℃, 550 nm)**, no turbidity or gelation occurs. Its solubility is not significantly affected by temperature (0–100℃) and stirring speed (50–500 r/min), superior to pectin (requires hot water dissolution and is prone to caking) and sodium alginate (slow cold water dissolution and easy to form gel particles).

2. Rheological Characteristics (Core Physicochemical Advantage)

The most prominent physicochemical property of SSPS is the balance of **low viscosity + strong functionality**, and its rheological behavior conforms to the characteristics of pseudoplastic fluid. The specific parameters are as follows:

- **Viscosity Grading**:

It can be divided into low-viscosity type (Type A), medium-viscosity type (Type B) and high-viscosity type (Type C) through process regulation. Specific indicators: 10% (w/v) aqueous solution, 25℃, measured by rotational viscometer (NDJ-1, Rotor No.2, 60 r/min). The viscosity of Type A is 10–30 mPa·s, Type B 30–100 mPa·s, Type C 100–300 mPa·s. Type A and Type B are the most widely used in the food industry, and their low-viscosity characteristics can maximally retain the original taste of products.

- **Shear Thinning Property**:

With the increase of shear rate (10–1000 s^{-1}), the viscosity decreases significantly. When the shear rate reaches 500 s^{-1}, the viscosity drops to 30%–40% of the initial value with obvious thixotropy (hysteresis loop area: 0.8–1.5 Pa·s), suitable for processing scenarios requiring stirring and pumping such as beverages and sauces.

- **Concentration Dependence**:

Viscosity is positively correlated with concentration but with weak correlation. When the concentration increases from 1% to 10%, the viscosity only rises 8–12 times. In contrast, the viscosity of pectin and xanthan gum increases 50–100 times under the same concentration change, which is the core embodiment of SSPS's **low viscosity and high functionality**.

3. Environmental Stability (Key to Full-Scenario Adaptation)

- **Acid-Base Stability**:

Its structure and viscosity remain stable without degradation or gelation within the pH range of 2.0–12.0. Especially under acidic conditions (pH 2.0–4.5), the viscosity change rate is **≤5%**, far better than pectin (prone to degradation with viscosity dropping by more than 30% when pH<3.5) and CMC (viscosity surges with greasy taste when pH<4.0). It can still maintain stability without precipitation or stratification even in strongly acidic systems (pH 1.5–2.0, such as lemon juice and acetic acid beverages).

- **Heat Resistance Stability**:

After high-temperature and high-pressure sterilization at 121℃ for 30 minutes, the molecular weight loss is **≤3%** and the viscosity change rate **≤4%** with no obvious structural degradation. It can still retain core functions even after Ultra-High Temperature (UHT) instantaneous sterilization at 135℃ for 5 minutes, suitable for thermal processing scenarios such as dairy products and beverages, superior to xanthan gum (viscosity decreases by 5%–8% after sterilization at 121℃).

- **Salt Tolerance Stability**:

In high-concentration metal ion systems (NaCl 0.5%–5%, $CaCl_2$ 0.1%–1%, KCl 0.5%–3%), there is no significant change in viscosity and light transmittance (change rate **≤3%**). It does not crosslink and gel with divalent metal ions (Ca^{2+}, Mg^{2+}), different from sodium alginate (rapid gelation with Ca^{2+}) and pectin (unstable in high-calcium systems), suitable for pickled food and high-salt sauces.

- **Freeze-Thaw Stability**:

After freezing at -18℃ for 24 hours and thawing at 25℃, repeated 5 times, the aqueous solution remains clear and transparent without precipitation or stratification, with a viscosity change rate **≤6%**, suitable for frozen food and quick-frozen rice and flour products.

4. Other Physicochemical Indicators

It complies with China's national standard **LS/T 3301—2005 Soluble Soybean Polysaccharide** and food additive standard **GB 2760—2014**.

Core indicators: Moisture **≤8.0%**, Ash **≤5.0%**, Protein **≤5.0%** (crude protein, determined by Kjeldahl method), Fat **≤1.0%**. Heavy metals (Lead ≤0.5 mg/kg, Arsenic ≤0.3 mg/kg) and microorganisms (Total Plate Count ≤1000 CFU/g, Mold and Yeast ≤100 CFU/g) all meet limit requirements. The surface tension is 38–45 mN/m (0.1% aqueous solution, 25℃) with certain surface activity, which can adsorb on the oil-water interface and lay a foundation for its emulsifying function.

II. Functional Features

(I) Protein Stabilization in Acidic Environment (Core Function, Most Widely Used in Industrial Applications)

SSPS exhibits excellent stabilizing effects on casein, whey protein, soybean protein, etc., under acidic conditions (pH 3.0–4.5). It is the core ingredient to solve stratification and precipitation problems of acidic milk beverages and plant protein beverages. Its stabilization mechanism is the dual effect of **electrostatic repulsion + steric hindrance**, as detailed below:

- **Electrostatic Repulsion**:

Under acidic conditions (pH 3.0–4.5) near the isoelectric point of protein (pI 4.5–5.5), protein molecules carry a small amount of positive charge, while part of carboxyl groups in SSPS molecules dissociate with negative charge (Zeta potential: -15~-25 mV). It adsorbs on the protein surface through electrostatic attraction, making the protein surface carry uniform negative charge and generating electrostatic repulsion between adjacent protein molecules to prevent protein aggregation.

- **Steric Hindrance**:

After adsorbing on the protein surface, the highly branched molecular structure of SSPS forms a dense spatial barrier (thickness: 5–10 nm), preventing close contact between protein molecules and avoiding aggregation and sedimentation caused by hydrophobic interaction. Meanwhile, its random coil conformation can disperse among protein molecules to further strengthen the stabilization effect.

- **Application Advantages**:

Long-term stability can be achieved with a low addition amount (0.1%–0.5%, w/v), and the shelf life of products such as acidic milk beverages and fermented milk is **≥6 months (25℃)** without changing product taste and transparency. Compared with traditional stabilizers, it does not need to compound a large number of emulsifiers and thickeners, simplifying the formula and conforming to the clean label trend. It can maintain stability even adapted to high-calcium acidic systems (Ca^{2+} 50–150 mg/100 mL), solving the instability pain point of pectin and CMC in high-calcium acidic systems.

(II) Emulsification and Fat Stabilization Function

SSPS has natural emulsifying capacity. The hydrophilic polysaccharide chains (hydroxyl and carboxyl groups) and hydrophobic fragments (a small amount of bound protein and methyl ester groups) in its molecule can adsorb on the oil-water interface, reduce interfacial tension and form stable O/W emulsions. The specific features are as follows:

- **Emulsification Efficiency**:

The Critical Micelle Concentration (CMC) is 0.05%–0.1% (w/v), much lower than traditional emulsifiers (e.g., sucrose ester, CMC 0.2%–0.5%). A stable emulsion can be prepared with an addition of 0.2%–0.8% (oil phase proportion: 10%–30%).

- **Emulsification Stability**:

Under acidic (pH 2.5–4.0), high-salt (NaCl 2%–4%) and high-temperature (121℃ sterilization) conditions, the stratification rate of emulsion is **≤3% (25℃, standing for 72 h)**, superior to synthetic emulsifiers such as Tween 80 and sucrose ester. It can stabilize grease and flavor substances, prevent oil-water separation and oil floating, and extend product shelf life.

- **Application Scenarios**:

Applied in salad dressing, condiment sauce, emulsion beverages, powdered oil, meat products (emulsified sausages), etc., it can improve system uniformity and taste, replace part of synthetic emulsifiers and enhance the naturalness of products.

(III) Starch Retrogradation Inhibition and Anti-Caking Function

SSPS can delay the retrogradation of starch products by inhibiting the recrystallization of starch molecules and reduce the caking of rice and flour products. The specific mechanism and applications are as follows:

- **Starch Retrogradation Inhibition Mechanism**:

Hydroxyl groups in SSPS molecules form hydrogen bonds with hydroxyl groups of starch molecules and adsorb on the surface of starch particles, inhibiting recrystallization (retrogradation) of starch molecules during cooling and storage and reducing the starch retrogradation rate. Meanwhile, its branched structure can hinder the interaction between starch molecules and delay the hardening of starch gel.

- **Anti-Caking Mechanism**:

The low-viscosity aqueous solution formed by dissolved SSPS can form a thin isolation film on the surface of rice and flour products, reducing caking between starch particles and improving product dispersibility.

- **Application Advantages**:

With an addition of 0.3%–1.0% (based on flour/starch), the retrogradation rate of rice, noodles, pastries and other products can be reduced by 30%–50%, and the fresh-keeping period extended by 2–3 times. Applied in quick-frozen rice and flour products, sushi, udon noodles, etc., it can significantly reduce caking and improve edible taste and appearance.

(IV) Film-Forming and Coating Function

SSPS can form edible films by solution casting, spraying and other methods, with excellent oxygen barrier, moisture barrier and flexibility properties, and can also be used as microcapsule wall materials. The specific features are as follows:

- **Edible Film Performance**:

The formed film is transparent and flexible, with elongation at break **≥15%** and tensile strength **≥2.5 MPa**. Oxygen permeability (25℃, RH 50%) **≤5.0 cm³/(m²·d·atm)**, moisture permeability (25℃, RH 85%) **≤3.0 g/(m²·d)**, superior to gelatin and starch films. It is degradable and residue-free, conforming to the green packaging trend.

- **Microcapsule Wall Material Function**:

As a wall material for embedding active substances such as flavors, pigments, vitamins and probiotics, the embedding rate is **≥80%**. It can realize slow release, color protection and fresh preservation of active substances and reduce the damage of external environment (light, heat, oxygen) to active ingredients, suitable for microcapsule preparation processes such as spray drying and freeze drying.

- **Application Scenarios**:

Used for surface coating of fruits (apples, citrus), nuts and meat products (sausages, cured meat) to extend the fresh-keeping period; applied as microcapsule wall materials in health products and functional food to improve the stability of active ingredients.

(V) Foam Stabilization and Texture Improvement Function

- **Foam Stabilization**:

It can adsorb on the gas-liquid interface, reduce interfacial tension and form a dense interfacial film to improve foam stability. Used in cakes, bread, beer, carbonated beverages and other products, it makes foam delicate and durable (foam half-life **≥30 min**) without easy collapse, enhancing product appearance and taste.

- **Texture Improvement**:

Applied in baked products (cakes, bread), it can increase the expansion rate by 10%–15%, improve internal texture, make products softer and fluffier and extend the fresh-

keeping period. Used in meat products, it can enhance water retention (water retention rate increased by 5%–10%), reduce cooking loss and improve meat taste.

(VI) Physiological Function of Water-Soluble Dietary Fiber (In Line with Health Trends)

The dietary fiber content of SSPS is **≥80% (dry basis)**. As a water-soluble dietary fiber, it can be fermented and utilized by human intestinal flora with definite physiological functions, meeting the demands of modern healthy food:

- **Regulate Intestinal Flora**:

It can selectively proliferate beneficial bacteria such as bifidobacteria and lactic acid bacteria, inhibit harmful bacteria such as Escherichia coli, regulate intestinal microecological balance and enhance intestinal barrier function. Daily intake of 5–10 g can increase the number of intestinal beneficial bacteria by 2–3 times.

- **Auxiliary Metabolic Regulation**:

It can delay the intestinal absorption of glucose and reduce the postprandial blood glucose peak (reduction by 15%–25%), suitable for diabetic patients. It can bind cholesterol in the intestine, promote its excretion and reduce serum total cholesterol (reduction by 8%–12%), assisting cardiovascular health.

- **Intestinal Moistening and Laxation**:

It has strong hydrophilicity, can absorb 5–10 times its own weight of water, soften feces, promote intestinal peristalsis and relieve constipation without diarrheal side effects.

- **Auxiliary Weight Management**:

It provides strong satiety to reduce food intake, is not digested and absorbed by the human body with low calorie (≤10 kcal/100 g), suitable for weight-loss groups.

III. Unique Properties

Compared with traditional food colloids such as pectin, CMC, xanthan gum and sodium alginate, SSPS has significant advantages in functional characteristics, environmental adaptability and application scenarios. Its unique properties are mainly reflected in the following 5 points, with detailed comparison shown in Table 1 (attached below):

(I) Irreplaceability in Acidic Protein Stabilization

Under acidic conditions (pH 2.0–4.5), traditional colloids have obvious limitations: Pectin is prone to degradation and gelation when pH<3.5 and unstable in high-calcium systems; CMC has a sharp viscosity increase with greasy taste under acidity and weak protein stabilization capacity; Xanthan gum is acid-resistant but poor in protein stabilization, and its high viscosity will change product taste; Sodium alginate gels rapidly with Ca^{2+} and cannot adapt to acidic protein systems. In contrast, SSPS can achieve efficient protein stabilization within pH 2.0–4.5 with low addition (0.1%–0.5%), low viscosity and no gelation, and is compatible with high-calcium systems. It is the preferred stabilizer for acidic protein beverages and fermented milk with no comparable alternative colloid.

(II) Uniqueness in Full Environmental Stability

SSPS is currently the only water-soluble polysaccharide that simultaneously possesses **acid resistance (pH 2.0–12.0), heat resistance (121℃, 30 min), high salt resistance (NaCl≤5%), ion resistance (Ca^{2+}≤1%) and freeze-thaw resistance**, adaptable to extreme processing, storage and transportation conditions (such as strongly acidic beverages, high-salt sauces, frozen food, UHT sterilized products). However, traditional colloids all have shortcomings in environmental adaptability: Pectin is not acid-resistant or high-calcium resistant; Sodium alginate is not calcium-resistant or acid-resistant; Xanthan gum is heat-resistant but not resistant to extreme acidity; CMC is not acid-resistant or high-temperature resistant, failing to meet multi-scenario adaptation needs.

(III) Perfect Balance of Low Viscosity and High Functionality

The functional realization (stabilization, emulsification, thickening) of traditional colloids (pectin, xanthan gum, CMC) often relies on high viscosity, resulting in greasy taste and decreased transparency of products. SSPS can realize efficient stabilization, emulsification, anti-aging and other functions at low viscosity (10% aqueous solution ≤100 mPa·s) without changing the original taste, flavor and transparency of products. It is suitable for products with high taste requirements such as refreshing beverages and low-fat sauces, while simplifying the formula and conforming to the clean label trend, which is an irreplaceable core advantage of traditional colloids.

(IV) Compatibility and Adaptability with Multiple Systems

SSPS is compatible with various food components such as protein, starch, grease, salt and acid without antagonistic effects. It can also compound with pectin, xanthan gum, emulsifiers (sucrose ester, monoglyceride) to achieve synergistic effects — for example, compounding with pectin can improve the stability of acidic milk beverages; compounding with xanthan gum can improve sauce texture; compounding with emulsifiers can strengthen emulsification effects. In contrast, traditional colloids (such as sodium alginate and calcium ions, pectin and high calcium) are prone to antagonistic reactions with poor compatibility, limiting their application scope.

(V) Natural Source and Clean Label Advantages

SSPS is extracted from soybean by-products (soybean meal) through physical and enzymatic processes without chemically synthetic additives, featuring naturalness, safety and non-GMO, conforming to the global **Clean Label** trend. Meanwhile, its production process realizes high-value utilization of soybean by-products with green and environmental protection properties. In comparison, CMC and xanthan gum are chemical synthetic or microbial fermentation products with low acceptance among some consumers; Pectin is mostly derived from fruit pomace with high raw material cost and easy pollution in the extraction process. SSPS is more advantageous in naturalness, economy and environmental protection.

Table 1 Performance Comparison of Soluble Soybean Polysaccharide and Traditional Colloids

Performance Index	SSPS	Pectin	CMC	Xanthan Gum	Sodium Alginate
Water Solubility (25℃)	Excellent, fast dissolution, no caking	Poor, requires hot water dissolution, easy caking	Good, soluble in cold water	Good, soluble in cold water	Poor, slow cold water dissolution, easy gelation
10% Aqueous Solution Viscosity (mPa·s)	10–100 (Type A/B)	100–500	50–200	500–1000	200–800
Acid Resistance (pH 2.0–4.5)	Stable, no degradation or gelation	Unstable, prone to degradation and gelation	Unstable, sharp viscosity increase	Relatively stable, slight viscosity decrease	Unstable, prone to precipitation
High Salt Resistance (NaCl≤5%)	Stable, no viscosity change	Relatively stable, unstable in high-calcium systems	Unstable, viscosity decrease	Stable	Unstable, gelation with Ca^{2+}
Acidic Protein Stabilization Capacity	Extremely strong (stable with 0.1%–0.5% addition)	Weak (requires high addition, unstable in high-calcium systems)	Weak	Weak	None
Naturalness	Natural (extracted from soybean by-products)	Natural (extracted from fruit pomace)	Chemically synthetic	Microbial fermentation	Natural (extracted from seaweed)
Clean Label Adaptability	Excellent	Good	Poor	Poor	Good

IV. Summary and Application Prospect

Soluble Soybean Polysaccharide (SSPS) features core unique properties of **low viscosity, strong acidic protein stabilization, full environmental tolerance and natural dietary fiber**. Its highly branched polyanionic structure determines its irreplaceability in physicochemical properties and functions — breaking through the application limitations of traditional colloids in extreme systems such as acidity, high temperature and high salt, and realizing the perfect balance of **functional efficiency** and **taste compatibility**. As a multifunctional natural food ingredient integrating stabilization, emulsification, anti-aging, film-forming and dietary fiber physiological functions, SSPS has been widely used in beverages (acidic milk beverages, plant protein beverages, fruit juices), rice and flour products (rice, noodles, quick-frozen rice and flour), baked products (cakes, bread), meat products, health products and other fields with continuously growing market demand.

In the future, with the development of the food industry towards naturalization, healthiness and functionalization, the application of SSPS will be further expanded: In the pharmaceutical field, it can be used as drug carriers and intestinal regulators; In the cosmetic field, it can serve as humectants and emulsifiers. Meanwhile, process optimization (such as directional modification and fractional purification) can further enhance its functional properties, develop high-value-added products, promote the high-value utilization of soybean by-products and achieve a win-win situation of economic and environmental benefits.