Analysis of Unique Properties of Phycocyanin

Phycocyanin (PC) is a water-soluble phycobiliprotein unique to algae such as cyanobacteria and red algae. It is fundamentally composed of **α and β subunits** combined with phycocyanin prosthetic groups. It possesses three essential attributes: **natural pigment, high-quality protein and highly active biological factor**, holding irreplaceable application value in food, pharmaceutical, cosmetic and biotechnology fields. Its unique properties are mainly reflected in three dimensions: **physicochemical characteristics, functional features and core advantages**.

Ⅰ. Physicochemical Characteristics: Structure Determines Fundamental Properties

1. Molecular Structural Characteristics

1.1. Basic Composition:

It exists as a heterodimer **(αβ)**, which further polymerizes to form **$(αβ)_3$ trimers** or **$(αβ)_6$ hexamers**, with a molecular weight of approximately 40–110 kDa (depending on the degree of polymerization). Each subunit is covalently bound to phycocyanobilin (an open-chain tetrapyrrole chromophore) via thioether bonds, serving as the core source of its blue color and optical activity.

1.2. Structural Hierarchy:

- **Primary Structure**: Complete amino acid sequence with a high proportion of essential amino acids, conforming to the FAO/WHO ideal protein model.
- **Higher-Order Structure**: The secondary structure is dominated by **α-helices**, featuring a compact three-dimensional conformation that ensures stable pigment binding and structural stability.

3. **Type Classification**: Mainly divided into **C-Phycocyanin (from cyanobacteria)** and **R-Phycocyanin (from red algae)**. **C-PC** dominates industrial applications. Purity standards: Food grade A620/A280≥0.7, Analytical grade ≥4.0, Reagent grade ≥6.0.

2. Physical and Chemical Properties

2.1. Appearance and Solubility:

Bright blue or dark blue powder/granule, **fully water-soluble**, insoluble in organic solvents such as ethanol, acetone and oils, compatible with water-based food, beverage and cosmetic systems.

2.2. pH Stability:

Isoelectric point at pH 3.4; stable conformation and bright color at pH 4.5–8.0 (weakly acidic to neutral); prone to precipitation below pH 4.2, rapid decolorization and protein denaturation above pH 9.0.

2.3. Thermal and Photostability:

Maintains structural integrity and biological activity below 60℃, degrades rapidly above 70℃; sensitive to ultraviolet light and strong light, with significantly improved stability under light-shielded conditions.

2.4. Optical Properties:

Characteristic absorption peak at 610–620 nm (orange-red light region) and fluorescence emission peak at 650–660 nm. It has a high fluorescence quantum yield and strong stability, acting as a high-value natural fluorescent marker.

2.5. Other Properties:

Good salt tolerance, adaptable to salt concentrations below 0.5 mol/L; compatible with most food additives and auxiliary materials, suitable for food processing systems.

II. Functional Features: Biological Activity and Core Value

1 Antioxidant Activity: Potent Free Radical Scavenger

- The tetrapyrrole structure of the phycocyanin prosthetic group directly quenches hydroxyl radicals, superoxide anions and lipid peroxides, with a scavenging capacity **20 times that of vitamin C and 1.5 times that of astaxanthin**.
- Enhances the activity of antioxidant enzymes such as **SOD and GSH-Px** in vivo, inhibits oxidative stress, reduces cellular oxidative damage, and maintains the integrity of cell membranes, mitochondria and DNA.

2. Anti-Inflammatory and Immunomodulatory Functions

2.1. Anti-Inflammatory Mechanism:

Targetedly inhibits inflammatory pathways including **NF-κB, COX-2 and iNOS**, reduces the release of pro-inflammatory factors such as **TNF-α and IL-6**. Its anti-inflammatory effect is comparable to non-steroidal anti-inflammatory drugs without side effects such as gastrointestinal injury and liver-kidney burden.

2.2. Immunomodulation:

Activates the activity of macrophages, NK cells and T/B lymphocytes, enhancing both non-specific and specific immunity; promotes the production of white blood cells and immunoglobulins, and accelerates leukocyte recovery (an increase of about 25%) during radiotherapy and chemotherapy.

3 Anti-Tumor and Cytoprotective Functions

- Arrests tumor cells at the **G0/G1 phase**, inhibits DNA synthesis and cell proliferation, and induces tumor cell apoptosis. It exerts significant inhibitory effects on liver cancer, lung cancer, breast cancer and other cell lines; animal experiments show an over **65% increase in survival rate** in liver cancer models.
- Protects normal cells from damage caused by radiation and chemotherapeutic drugs, alleviates treatment side effects, inhibits tumor angiogenesis and blocks metastatic pathways.

4 Hepatoprotective and Metabolic Regulatory Functions

- Repairs damaged hepatocytes, reduces transaminase and hepatic MDA levels, and improves alcoholic liver disease, fatty liver and drug-induced liver injury; promotes hepatocyte regeneration and maintains hepatic metabolism and detoxification functions.
- Regulates lipid metabolism, lowers serum triglycerides and cholesterol, improves insulin sensitivity, and

assists in ameliorating glucose and lipid metabolism disorders.

5 Neuroprotective and Cosmetic Skincare Functions

- Penetrates the blood-brain barrier, inhibits **β-amyloid deposition and tau protein hyperphosphorylation**, alleviates neuroinflammation, improves memory and cognitive ability, and serves as a potential intervention factor for Alzheimer's disease and Parkinson's disease.
- Inhibits tyrosinase activity to reduce melanin production (whitening effect); scavenges free radicals and resists photoaging; promotes collagen synthesis. Compound formulation with hyaluronic acid strengthens moisturizing, anti-wrinkle and skin repair effects.

III. Unique Properties: Core Advantages Distinct from Similar Substances

1 Uniqueness as a Natural Blue Pigment

- One of the very few natural blue pigments in nature, it can replace synthetic blue pigments (e.g., Brilliant Blue, Indigo Carmine). It is safe and non-toxic, complying with **FDA GRAS and GB 2760 food additive standards**, meeting the natural coloring demands of high-end food, beverages and cosmetics.
- Features bright and pure color with soft light perception, superior to plant-derived blue pigments (e.g., butterfly pea flower, blueberry pigment) in stability and coloring power.

2 Triple Attributes of Pigment-Protein-Active Factor

- Integrates coloring, nutritional and bioactive functions: provides high-quality complete protein with a full amino acid profile and natural blue color, while exerting antioxidant, anti-inflammatory and immunomodulatory effects, making it an **all-in-one multifunctional raw material**.
- Distinct from single-function substances (pure pigment only for coloring, pure protein only for nutrition, pure active substance only for physiological functions) with extremely high application added value.

3 Excellent Biocompatibility and Safety

- Extracted from natural algae sources, with no genotoxicity, no sensitization and no cumulative toxicity. The acute toxicity test shows **LD50 > 15 g/kg** (practically non-toxic) and safe for long-term consumption.
- High human absorption and utilization rate, efficiently absorbed through intestinal tracts and skin, suitable for oral administration, external application and injection (pharmaceutical grade) in multiple scenarios.

4 Irreplaceable Fluorescent Characteristics

- Among natural fluorescent proteins, it boasts high fluorescence quantum yield, strong stability and long emission wavelength (red light region), low background interference and high detection sensitivity. Widely applied in immunofluorescence, cell labeling, bioimaging and flow cytometry, replacing synthetic fluorescent dyes which are toxic and prone to quenching.

5 Resource Availability and Processing Adaptability

- Its core source Spirulina (Arthrospira platensis) supports large-scale cultivation, with a phycocyanin content of 15–20% (dry weight), the highest level in nature, enabling cost control.
- Good water solubility and strong processing adaptability, applicable to liquid, semi-solid and solid food, as well as water-based, cream and powder cosmetics, and tolerant to mild processing conditions.

Ⅴ. Conclusion

Based on its unique phycobiliprotein structure, **Phycocyanin** integrates stable physicochemical properties, diverse biological activities and triple core functions, making it a rare category in natural raw materials. Its irreplaceable natural blue color, high safety and activity, and all-in-one multifunctional attributes establish it as a core raw material for the food, pharmaceutical, cosmetic and biotechnology industries. With the growing demand for natural and healthy products, its application value and market potential continue to rise.