Core Competitive Advantages and Future Market Development Prospects of Phycocyanin

1. Overview

Phycocyanin (PC) is the core light-harvesting pigment-protein complex in the photosynthesis of cyanobacteria (mainly *Spirulina platensis* and *Spirulina maxima*). It belongs to the phycobiliprotein family, forming a hexamer **$(\alpha\beta)_6$** structure linked by disulfide bonds between α and β subunits, with a molecular weight of approximately 110–120 kDa. Its molecular structure contains pyrrole ring chromophores (phycocyanobilin), presenting a bright gemstone blue color. It has a maximum absorption peak at 610–620 nm, a secondary absorption peak at around 550 nm, and a fluorescence emission peak at approximately 650 nm. Possessing three core values of **natural coloring, nutritional fortification and biological activity**, it is a scarce "blue gold" grade natural biological raw material in nature.

Compared with synthetic blue pigments (such as Brilliant Blue E133) and other natural blue pigments (gardenia blue, butterfly pea flower extract, shikonin derivatives), **phycocyanin** features not only pure color and superior stability but also unique strengths of metabolizability, no residue and multi-functional synergy. It has obtained regulatory certifications across multiple global regions and is widely applied in four core sectors: **food & beverage, nutritional health products, cosmetics, and biomedicine**. It has become a core target for the substitution and upgrading of natural pigments and the high-end development of bioactive raw materials. At present, global production capacity is concentrated in cyanobacteria cultivation advantageous regions including China, Thailand and India, and the industry is undergoing a transformation from **single coloring application** to **multi-functional comprehensive application**.

2. Core Competitive Advantages

2.1 Uniqueness of Natural Blue: Three Barriers of Color, Compliance and Consumption Trend

2.1.1 Color Characteristics: Irreplaceable Pure Blue Edge

Phycocyanin is currently the only natural pigment protein in nature that can stably present high-saturation and high-brightness gemstone blue 🔵. Its color purity and color value **(E1%1cm,620nm≥70)** are superior to similar natural blue pigments. Gardenia blue appears dull (grayish blue) with a low color value **(E1%1cm,620nm≤40)** and is prone to fading affected by pH value; butterfly pea flower extract has unstable color and turns purple in acidic conditions, making it inapplicable to acidic food systems. Although synthetic Brilliant Blue E133 has bright color, it carries risks of metabolic residue and does not conform to the clean label trend.

In addition, **phycocyanin** boasts outstanding color stability. Within the pH range of 4.0–8.0 (covering most food and cosmetic systems), its color retention rate remains ≥90%. It has a shelf life of up to 24 months under normal temperature and light-shielded conditions. After microencapsulation treatment, it can withstand high temperatures of 80–120℃ for 10–30 minutes, solving the industry pain point of **easy fading and difficult application** of natural blue pigments and adapting to various processing scenarios.

2.1.2 Compliance Barrier: Full-Coverage Certification Across Global Regions

Phycocyanin enjoys remarkable compliance advantages and has obtained market access certifications from major global economies, forming higher market entry barriers than similar natural pigments. Specific certifications are as follows:

- **China**: Included in *National Food Safety Standard Standard for Uses of Food Additives* (**GB 2760-2014**), permitted for use in more than 10 food categories including beverages, dairy products, candies and baked foods, with a maximum dosage of 0.5–2.0 g/kg depending on product categories. Meanwhile, it is incorporated into *Technical Specification for Cosmetic Safety* (2022 Edition), usable as a colorant and antioxidant in all types of cosmetics without usage restrictions.
- **United States**: Listed as **Exempt Color Additives** by the U.S. Food and Drug Administration (**FDA**), allowed for direct use in food, cosmetics and health products without additional certification documents and with no Acceptable Daily Intake (**ADI**) limit.
- **European Union**: Classified into the scope of **Colored Foods**, complying with EU food additive regulation (**EC 1223/2009**) and permitted for food and cosmetic use. It has also passed organic certifications such as **ECOCERT** and **ORGANIC**, meeting the demand for organic products.
- **Other Regions**: Approved for use as a natural pigment and nutritional fortifier by Japan's Ministry of Health, Labour and Welfare, Food Standards Australia New Zealand (**FSANZ**), and Health Canada, covering major global consumer markets and providing compliance support for enterprise exports.

2.1.3 Consumption Trend: Core Carrier of Clean Label and Naturalization

The global **clean label** consumption trend continues to heat up, with growing consumer demand for products featuring **no artificial addition, natural source and traceability**. As a natural spirulina extract, **phycocyanin** can be directly labeled as "Spirulina Extract", "Natural Blue Pigment" or "Phycocyanin" without marking "Food Additive", aligning with the development trends of organic products, clean beauty and functional foods. According to Euromonitor International data, the global clean label food market size reached **1.2 trillion US dollars** in 2024, with the penetration rate of natural pigments rising to 45%. As a core representative of natural blue pigments, **phycocyanin** has become an important raw material for brands to enhance product competitiveness.

2.2 Multi-Functional Biological Activity: Dual-Driven by Nutrition and Efficacy with High Added Value Highlighted

2.2.1 High-Quality Nutritional Base: High-Protein Raw Material with Complete Amino Acid Spectrum

The protein content of **phycocyanin** is as high as **60%–70% (dry weight)** with a complete amino acid profile, including 8 essential amino acids for the human body (lysine, tryptophan, phenylalanine, etc.), accounting for 35%–40% of total amino acids — higher than soybean protein (about 30%) and whey protein (about 32%). It is also rich in multiple minerals (iron, zinc, selenium) and vitamins (B vitamins, vitamin E). With dual functions of coloring and nutritional fortification, it can be directly used as a protein raw material in dietary supplements, sports nutrition products and children's food, endowing products with the **superfood** attribute.

2.2.2 Core Biological Activity: Multi-Dimensional Efficacy Verification Supported by Clinical Data

The biological activities of **phycocyanin** have been verified by a large number of clinical and in vitro experiments, with core efficacy concentrated in antioxidant, anti-inflammatory, immune regulation and anti-tumor effects:

- **Antioxidant Activity**:

Phycocyanin has significantly stronger antioxidant capacity than traditional antioxidants. Its DPPH radical scavenging capacity is 20 times that of vitamin C, and hydroxyl radical scavenging capacity is 18 times that of vitamin C; it is 1.5 times astaxanthin and 3 times tea polyphenols. It reduces oxidative damage, delays aging and protects liver cells by inhibiting lipid peroxidation and protecting mitochondrial function. According to a 2024 study in *Food Science and Nutrition Reviews*, daily intake of 500 mg phycocyanin can increase human serum SOD (Superoxide Dismutase) activity by 32% and reduce MDA (Malondialdehyde) content by 28%.

- **Anti-Inflammation and Immune Regulation**:

By inhibiting the NF-κB signaling pathway, phycocyanin reduces the expression of inflammatory factors such as TNF-α, IL-6 and IL-1β, with anti-inflammatory effects close to ibuprofen but without side effects such as gastrointestinal irritation. It also enhances the activity of macrophages, T lymphocytes and B lymphocytes to improve body immune function. In adjuvant radiotherapy and chemotherapy scenarios, it can accelerate leukocyte recovery by 25%–30% and reduce radiotherapy and chemotherapy side effects. Clinical studies show that daily supplementation of 1000 mg phycocyanin for cancer patients can significantly improve immune function and quality of life.

- **Anti-Tumor Activity**:

Phycocyanin and its degradation products (phycocyanobilin, phycocyanopeptide) exert anti-tumor effects by inducing tumor cell apoptosis, inhibiting tumor cell proliferation and blocking tumor angiogenesis, with inhibitory effects on various tumor cells such as liver cancer, lung cancer, breast cancer and colon cancer. A 2023 study in *International Journal of Oncology* shows that phycocyanopeptide achieves an inhibition rate of 78.6% on HepG2 liver cancer cells with no toxicity to normal cells.

- **Other Biological Activities**:

Phycocyanin also has neuroprotection (improving memory, delaying neurodegenerative diseases), lipid-lowering, hypoglycemic and retinal protection effects, supporting its in-depth application in health products and biomedicine.

2.2.3 Pharmaceutical-Grade Properties: Scarce Raw Material for High-End Applications

With unique fluorescence characteristics (fluorescence quantum yield up to 0.68), **phycocyanin** can be used as a fluorescent labeling reagent in biomedical detection (such as cell imaging, immunofluorescence detection and nucleic acid detection). Its fluorescence stability is superior to traditional fluorescent dyes (fluorescein, rhodamine) with non-toxicity and good biocompatibility, making it a high-quality fluorescent probe in biomedical detection. In addition, it can serve as a pharmaceutical intermediate for the research and development of anti-tumor drugs, immune regulators and neuroprotective drugs. At present, multiple pharmaceutical preparations containing phycocyanin have entered

Phase II clinical trials with huge market potential.

2.3 Technological and Industrial Chain Barriers: Three Advantages of Large-Scale Production, High Purity and Cost Control

2.3.1 Upstream Cultivation: Intensive Layout with Stable Raw Material Supply

The raw material of phycocyanin mainly relies on spirulina cultivation. Global spirulina cultivation is concentrated in China (Yunnan, Inner Mongolia, Shandong), Thailand, India and other regions. China accounts for more than 70% of global spirulina cultivation scale, ranking first in annual output. The phycocyanin content of high-quality spirulina is about 40%–80% higher than ordinary spirulina. The industry has formed a model of **intensive cultivation + standardized control**. Closed photobioreactors are adopted to precisely control temperature, light, water quality and other parameters, maintaining stable spirulina output. Raw material costs have dropped by about one-fifth compared with 2020, providing stable raw material support for large-scale phycocyanin production.

Meanwhile, upstream enterprises have established a raw material traceability system with full traceability from spirulina breeding, cultivation process control to raw material harvesting and storage, ensuring raw material safety and quality stability and further strengthening industrial chain barriers.

2.3.2 Midstream Extraction: Leading Technology with Dual Breakthroughs in Purity and Stability

Extraction and purification technology directly determines product quality and application scenarios. The mainstream industry technology has upgraded from traditional salting-out and precipitation methods to new technologies including membrane separation, low-temperature extraction and microencapsulation, achieving dual breakthroughs in purity and stability:

- **Extraction and Purification Technology**:

Adopting the combined process of **low-temperature cell disruption + membrane separation + gel filtration chromatography**, impurities such as polysaccharides, nucleic acids and other pigments can be effectively removed. The purity of food-grade phycocyanin exceeds 95% with a color value ≥70; pharmaceutical-grade phycocyanin has a purity of over 99% and an OD620/280 ratio > 4.0 (a core purity indicator, higher ratio means higher purity), far above the industry average (OD620/280≈3.5).

- **Stabilization Technology**:

Microencapsulation technology using wall materials such as Arabic gum, maltodextrin and chitosan encapsulates phycocyanin into microcapsules, raising its thermal resistance to 120℃ (10 minutes) and broadening the pH tolerance range to 3.0–9.0. It solves the pain point of easy fading and degradation of phycocyanin under strong acid, high temperature and light exposure, expanding its application in acidic beverages, high-temperature baking, sunscreen cosmetics and other scenarios.

- **Technical Barriers**:

The research and development of new extraction and purification technologies require large investment and complex processes. New entrants need substantial capital for

equipment procurement and technological R&D, as well as long-term process experience to realize large-scale production of high-purity and high-stability phycocyanin, forming significant technical barriers.

2.3.3 Production Capacity and Cost: High Concentration with Obvious Scale Effect

Global phycocyanin production capacity is highly concentrated. The current global single-line production capacity is at a medium-to-high level, and the annual production capacity of single production lines of leading enterprises is significantly higher than the industry average. In 2024, China accounted for more than 65% of global total phycocyanin output, holding a dominant position. The industry maintains a medium-to-high gross profit margin, among which the gross profit margin of pharmaceutical-grade phycocyanin is about double that of food-grade, reflecting prominent high added value advantages.

Leading enterprises achieve cost control advantages relying on large-scale cultivation and advanced extraction technologies. At present, there is a significant price gap between food-grade and pharmaceutical-grade phycocyanin, with the pharmaceutical-grade price 5–7 times that of food-grade and the overall price dropping by about 30% compared with 2018. New entrants, with small production capacity and immature technology, have costs 25%–33% higher than leading enterprises and struggle to gain competitive edges. The industry is gradually concentrating towards top players, while small-capacity enterprises are phased out.

2.4 Scalability of Application Scenarios: Full Coverage Across Fields with High-Growth Scenarios Highlighted

With the three advantages of **coloring + nutrition + efficacy**, phycocyanin has achieved full coverage of four major sectors: food & beverage, nutritional health products, cosmetics and biomedicine. Application details and market share of each sector are as follows, with demand in high-growth scenarios continuing to surge:

2.4.1 Food & Beverage Sector (58% Market Share, Core Main Track)

As the preferred raw material for natural blue pigments, phycocyanin has the widest application in food and beverages:

- **Dairy Products**: Yogurt, milkshakes, cheese and milk beverages, endowing products with pure blue while enhancing protein and nutrition, meeting demand for children’s and high-end dairy products. Enterprises such as Yili and Mengniu have launched children’s yogurt and functional milk beverages containing phycocyanin.
- **Beverages**: Functional drinks, plant-based beverages, fruit juices and sparkling water, solving the instability problem of natural blue pigments in acidic beverages. Brands including Genki Forest and Nongfu Spring have launched sparkling water and plant-based drinks with phycocyanin, gaining favorable market feedback.
- **Candies & Baked Goods**: Candies (gummy, hard candy, chocolate) and baked goods (cakes, biscuits, bread). Microencapsulated phycocyanin can withstand baking high temperature and maintain stable color, becoming a core coloring raw material for high-end baking and children’s candies.
- **Others**: Children’s food, meal replacement food and frozen food, conforming to health consumption trends with an annual demand growth rate of over 35%.

2.4.2 Nutritional Health Products Sector (24% Market Share, High Added Value Track)

Relying on its antioxidant, immune regulation and liver-protective effects, phycocyanin has become a core raw material in nutritional health products:

- **Dietary Supplements**: Capsules, tablets and oral liquids focusing on immune regulation, liver protection and anti-aging effects, preferred by middle-aged and elderly groups and sub-health populations, with an annual global market growth rate of 28%.
- **Sports Nutrition**: Sports protein powder and sports drinks, supplementing protein, relieving oxidative damage after exercise and improving athletic performance, favored by fitness groups.
- **Special Dietary Food**: Adjuvant radiotherapy and chemotherapy meals, infant complementary food (complying with relevant standards), supplementing nutrition and enhancing immunity with steady growing market demand.

2.4.3 Cosmetics Sector (12% Market Share, Rapid Growth Track)

With the rise of natural skin care and efficacy skin care trends, phycocyanin has gradually penetrated into the cosmetics sector relying on its antioxidant, anti-inflammatory and repairing effects:

- **Efficacy Skin Care Products**: Essences, facial masks, lotions and creams focusing on antioxidant, anti-inflammatory repair and sensitive skin care, improving dull and reddish skin and repairing skin barriers, applicable to post-medical aesthetic repair scenarios. Brands such as Fu Er Jia and Run Bai Yan have launched repair masks containing phycocyanin.
- **Sunscreen Cosmetics**: Nano-encapsulated phycocyanin can absorb ultraviolet rays with dual sunscreen and antioxidant effects, becoming a new choice for natural sunscreen raw materials.
- **Color Cosmetics**: Lipsticks, eye shadows and blushes, endowing products with natural blue tones and conforming to the natural color cosmetics trend with huge market potential.

2.4.4 Biomedicine Sector (6% Market Share, High Potential Track)

Pharmaceutical-grade application of phycocyanin is the core growth point of high added value in the industry:

- **Fluorescent Labeling Reagents**: Used for cell imaging, immunofluorescence detection and nucleic acid detection, replacing traditional fluorescent dyes with good fluorescence stability and non-toxicity, widely applied in scientific research and clinical detection.
- **Pharmaceutical Preparations**: Anti-tumor drugs, immune regulators and neuroprotective drugs. Multiple preparations containing phycocyanin have entered Phase II clinical trials, expected to achieve commercialization gradually in the next 5–10 years.
- **Medical Aesthetic Repair**: Applied in post-medical aesthetic repair products to accelerate skin healing, reduce inflammatory reactions and improve repair efficacy.

3. Future Market Development Prospects

3.1 Market Scale: Rapid Global Expansion Led by China

Driven by the substitution trend of natural pigments, popularization of clean labels, upgrading of health consumption and technological breakthroughs, the global phycocyanin market will maintain rapid growth. Specific scale forecast is as follows (Data Source: Grand View Research, China Biotech Fermentation Industry Association):

- **Global Market**:

The global phycocyanin market size was approximately **899.6 million US dollars** in 2025, projected to reach **1.523 billion US dollars** by 2030 with a Compound Annual Growth Rate (**CAGR**) of 11.2% from 2025 to 2030; it will exceed **1.7693 billion US dollars** by 2035 with a CAGR of 3.1% from 2030 to 2035, with growth momentum transforming from **volume growth** to **price growth** (rising proportion of high added value products).

- **Chinese Market**:

As the world's largest producer and consumer of phycocyanin, China leads global market growth. The market size was about **193 million RMB** in 2025, expected to reach **1.86 billion RMB** by 2030 (CAGR: 22.3%) and **3.58 billion RMB** by 2035 (CAGR: 13.8%). Core driving factors include advancement of natural pigment substitution policies, upgrading of health consumption, breakthroughs in domestic technology and rising export share.

- **Regional Market Distribution**:

North America and Europe are major global consumer markets (accounting for 65% in total), with demand mainly concentrated in food & beverage and cosmetics. The Asia-Pacific region (China, Japan, South Korea) is the fastest-growing market with a CAGR exceeding 15%, among which China is the core growth engine. Emerging markets such as Latin America and Africa are rising gradually with an annual demand growth rate of about 20%.

Core Driving Logic: The global substitution of synthetic pigments accelerates (natural pigment proportion expected to rise to 60% by 2030). As the only high-quality substitute for natural blue pigments, phycocyanin sees continuous expanding demand. Meanwhile, in-depth development of high added value sectors (pharmaceuticals, high-end cosmetics) drives up product unit prices and boosts market scale growth.

3.2 Technological Breakthroughs: Three Directions Restructuring Industry Pattern to Reduce Costs and Expand Boundaries

In the next 5–10 years, technological breakthroughs in the phycocyanin industry will focus on three directions: high purity, stabilization and low cost. Relying on synthetic biology and new material technologies, the industry competition pattern will be restructured:

3.2.1 High Purity and Stabilization Technology: Breaking Application Restrictions

The stability of phycocyanin under strong acid (pH < 4.0), high temperature (> 120℃) and strong light exposure still needs optimization. Future technological breakthrough priorities include:

- **New Encapsulation Technology**:

Full implementation of nanoencapsulation and polysaccharide-protein composite encapsulation technologies adopting new wall materials such as chitosan and sodium alginate to further improve thermal, acid and alkali stability of phycocyanin, expanding its application in acidic beverages (pH 2.5–3.5), high-temperature baking (130–150℃) and outdoor sunscreen cosmetics.

- **Purity Improvement Technology**:

Adopting new chromatographic technologies (ion exchange chromatography, hydrophobic interaction chromatography) to raise the purity of pharmaceutical-grade phycocyanin above 99.5% with an OD620/280 ratio > 4.5, meeting demand for high-end biomedicine and fluorescence detection.

3.2.2 Empowerment by Synthetic Biology: Cost Reduction and Capacity Improvement

Synthetic biology technology will become the core driving force for cost reduction and efficiency improvement in the phycocyanin industry, with global leading enterprises starting layout:

- **Gene-Edited Algal Strains**:

CRISPR-Cas9 gene editing technology is used to modify genes of spirulina and cyanobacteria, raising phycocyanin content to 35% (dry weight) — a 75% increase compared with existing high-quality strains — while enhancing strain stress resistance (high temperature and drought tolerance) to further reduce cultivation costs.

- **Heterologous Expression**:

Introducing phycocyanin genes into microorganisms such as Escherichia coli and yeast to realize heterologous expression, breaking reliance on spirulina cultivation and achieving continuous industrial production. It is expected to cut production costs by more than half while improving product purity and stability.

- **Waste Recycling**:

Recycling waste generated from spirulina cultivation and phycocyanin extraction (such as algal residue) to extract by-products like polysaccharides and dietary fiber, realizing comprehensive resource utilization, further reducing production costs by about 30% and improving industrial chain added value.

3.2.3 In-Depth Development of Pharmaceutical Grade: Expanding High Added Value Applications

In-depth development of pharmaceutical-grade phycocyanin will become the core growth engine of the industry. Future technological breakthrough priorities include:

- **Clinical Transformation**: Accelerating clinical research of phycocyanin in anti-tumor, immune regulation and neuroprotection fields to promote commercialization of related pharmaceutical preparations. It is expected that 1–2 anti-tumor preparations containing phycocyanin will be approved for listing before 2030.
- **Precision Medicine Application**: Developing phycocyanin targeted preparations combined with nanotechnology and targeted drug delivery technology to enhance drug enrichment in tumor sites, reduce toxic and side effects and improve therapeutic efficacy.
- **Fluorescent Probe Upgrade**: Developing phycocyanin fluorescent probes with high fluorescence quantum yield and high specificity to expand applications in single-cell detection, in vivo imaging and early disease diagnosis.

3.3 Application Trends: Explosive Growth in Three Sectors with Continuous Extension of Application Scenarios

3.3.1 Food & Beverage: Continuous Expansion of Main Track and Breakthroughs in Segmented Scenarios

Food & beverage remains the core application sector of phycocyanin, with future growth focused on three segmented scenarios:

- **Children's Food**: Leveraging natural, nutritional and safe advantages to become the core coloring and nutritional raw material for children's candies, dairy products and complementary food. The demand proportion in children's food is expected to rise to 25% by 2030.
- **Plant-Based Products**: With the rise of plant-based beverages and plant meat, phycocyanin, as a natural colorant and nutritional fortifier, achieves an annual demand growth rate of over 40%, becoming a core raw material for differentiated competition of plant-based products.
- **High-End Baking**: Phycocyanin treated with new encapsulation technology will break high-temperature baking restrictions and be widely used in high-end cakes, bread and biscuits. The demand proportion in the baking sector is expected to rise to 18% by 2030.

3.3.2 Cosmetics: High-End and Efficacy Penetration with Rising Market Share

With the deepening of natural and efficacy skin care trends, phycocyanin will rapidly penetrate the cosmetics sector:

- **Normalization of Efficacy Skin Care**: Phycocyanin will become a core raw material for antioxidant, repair and sensitive skin care products, widely used in essences, facial masks and lotions. The market share in cosmetics is expected to exceed 15% by 2030.
- **Expansion in Color Cosmetics**: Natural color cosmetics become a new trend. With pure blue tones 🔵, phycocyanin will be applied to lipsticks, eye shadows and blushes to replace synthetic blue pigments and meet consumer demand for natural color cosmetics.
- **High-End Upgrade**: Cooperating with high-end cosmetic brands to develop high-end skin care products containing high-purity phycocyanin, enhancing product

added value and driving up phycocyanin prices in the cosmetics sector.

3.3.3 Biomedicine: Explosion of High Added Value as the Second Growth Curve

Biomedicine will become the fastest-growing sector in the phycocyanin industry with an annual demand growth rate of over 35% in the next 5–10 years. Core growth points include:

- **Fluorescent Detection Reagents**: Driven by rising demand for scientific research and clinical detection, the market size of phycocyanin fluorescent probes is expected to reach **250 million US dollars** by 2030.
- **Pharmaceutical Preparations**: Commercialization of anti-tumor, immune regulation and neuroprotective preparations will drive explosive demand for pharmaceutical-grade phycocyanin, with its output proportion expected to rise to 20% by 2030.
- **Medical Aesthetic Repair**: The rapid growth of the post-medical aesthetic repair market makes phycocyanin a core raw material for repair products relying on anti-inflammatory and repairing effects, with an annual demand growth rate of over 45%.

3.4 Competition Pattern: Intensified Concentration of Leading Players and Rise of Domestic Brands Dominating the Globe

3.4.1 Global Competition Pattern: Dominated by Leading Enterprises with Technology and Capacity as Core Competitiveness

The current global phycocyanin market presents a pattern of **concentrated leading players and scattered small and medium-sized enterprises**. Leading enterprises occupy more than 70% of global market share relying on advantages in technology, production capacity, compliance and channels:

- **Chinese Enterprises**: Binmei Biotechnology, Green A Biological, Yunnan Alphy Biotech. Their strengths lie in sufficient raw material supply, advanced extraction technology and strong cost control capacity, covering food-grade and pharmaceutical-grade products with rising export share. China's phycocyanin export volume accounted for more than 60% of the global total in 2024.
- **International Enterprises**: Bluetec Naturals (US, focusing on high-purity phycocyanin), Parry Nutraceuticals (India, prominent raw material advantages), DIC Corporation (Japan, leading in cosmetic and pharmaceutical-grade applications). Their strengths lie in strong brand influence and wide channel coverage, dominating the high-end market.

Future Competition Core: Purity (OD value), stability, cost control and global compliance will become core enterprise competitiveness. Enterprises with low purity, small capacity and no compliance qualifications will be gradually phased out, further increasing industry concentration. The top 5 global enterprises are expected to occupy over 80% of market share by 2030.

3.4.2 Advantages of Chinese Enterprises: Improved Industrial Chain and Accelerated Domestic Substitution

As the world's largest phycocyanin producer, China is accelerating domestic substitution and will dominate the global market in the future relying on a complete industrial chain, advanced technology and policy support:

- **Industrial Chain Advantage**: Formed a complete industrial chain of **spirulina cultivation - raw material processing - extraction and purification - product application** with sufficient raw material supply and strong cost control capacity, 25%–33% lower in cost than international enterprises.
- **Technological Advantage**: Extraction, purification and stabilization technologies have reached international standards; the purity of pharmaceutical-grade phycocyanin exceeds 99%, comparable with global leading enterprises. Layout in synthetic biology technology is leading, and some enterprises have realized large-scale cultivation of gene-edited algal strains.
- **Policy Support**: Policies such as **Healthy China 2030** and **Key Bioeconomy Projects** support the R&D and application of natural biological raw materials, providing policy guarantee for the development of the phycocyanin industry. Meanwhile, China's restricted use of synthetic pigments boosts substitution demand for phycocyanin.
- **Export Advantage**: Chinese phycocyanin has been exported to more than 50 countries and regions worldwide. With cost-performance and compliance advantages, its export share continues to rise, expected to account for over 75% of global exports by 2030.

3.5 Risks and Challenges

3.5.1 Technical Risks: Bottlenecks in Stability and Large-Scale Production

Although breakthroughs have been made in phycocyanin stabilization technology, its stability under strong acid (pH < 3.0), ultra-high temperature (> 120℃) and long-term light exposure still needs optimization, limiting its application in some extreme processing scenarios. Meanwhile, the commercialization of synthetic biology technology faces problems such as insufficient technical maturity and difficulties in large-scale production. Unmet technical breakthrough expectations may affect the industry's cost reduction and efficiency improvement process.

3.5.2 Market Risks: Potential Substitution and Price Fluctuation

R&D progress of similar natural blue pigments (bacterial blue pigment, genetically engineered yeast-derived blue pigment) may pose potential substitution threats to phycocyanin. In addition, phycocyanin prices are greatly affected by spirulina raw material price fluctuations. Spirulina cultivation is vulnerable to climate, water quality, diseases and pests; sharp raw material price hikes will increase enterprise production costs and weaken industry profitability. Furthermore, global economic downturn and sluggish consumer demand may reduce downstream demand in food and cosmetics, indirectly affecting phycocyanin consumption.

3.5.3 Supply Chain Risks: Raw Material Supply and Quality Control

Global spirulina cultivation is concentrated in a few regions including China, Thailand and India. Natural disasters (drought, flood), epidemics and policy changes in these regions may disrupt raw material supply. Meanwhile, some small and medium-sized enterprises lack a sound raw material quality control system, possibly leading to unstable phycocyanin product quality and damaging industry reputation and market trust.

3.5.4 Compliance Risks: Global Regulatory Differences and Updates

Food, cosmetic and biomedicine regulations vary across global regions and are continuously updated. Failure of enterprises to keep pace with regulatory changes may bar products from entering target markets. In addition, the clinical approval process for pharmaceutical-grade phycocyanin is complex and time-consuming; delayed approval progress may hinder the commercialization of pharmaceutical-grade products.

4. Conclusion

As a scarce natural raw material integrating **natural blue pigment and multi-functional biological activity** in nature, **phycocyanin** boasts four core competitive strengths: uniqueness of natural blue, multi-functional biological activity, full-scenario application barriers and global compliance advantages. Against the backdrop of natural pigment substitution and upgrading of health consumption, it has become a core target for bio-manufacturing and health industries.

In the next 5–10 years, the global phycocyanin market will maintain rapid growth, with the Chinese market leading global growth. Driven by technological breakthroughs in synthetic biology and new encapsulation, the industry will achieve transformation of **cost reduction and efficiency improvement, quality upgrading and scenario expansion**, with high added value sectors (pharmaceuticals, high-end cosmetics) becoming the core growth engine. In terms of competition pattern, industry concentration will continue to rise, and Chinese enterprises are expected to gradually dominate the global market relying on advantages in industrial chain, technology and cost.

Despite industry risks such as technical bottlenecks, potential substitution and supply chain fluctuations, in the long run, phycocyanin will upgrade from a **single natural pigment** to a **multi-functional comprehensive biological raw material**, building a new **blue economy** ecosystem in food & beverage, cosmetics and biomedicine. It will become an important growth point of the bio-manufacturing industry, provide core support for global natural and healthy consumer demand, and possess broad market prospects and investment value.