Development History of Zinc Citrate Industry

Part I: A Tribute to the Pioneers

Zinc citrate is a high-end organic zinc nutritional raw material featuring excellent bioavailability, minimal gastrointestinal irritation and outstanding physicochemical stability. It is mainly applied in four livelihood-related sectors: food nutritional fortification, biomedicine, oral care, and livestock feed. Compared with traditional inorganic and organic zinc salts such as zinc gluconate, zinc sulfate and zinc oxide, it boasts prominent strengths including high absorption rate, no metallic astringent taste, strong compatibility, resistance to high-temperature processing, no adverse impact on product color and flavor, and superior human tolerance.

After a century of theoretical research on coordination chemistry, half a century of nutritional safety verification and process iteration, as well as more than 40 years of independent domestic research and industrialization in China, the industry has now established a mature full-chain industrial system covering raw material refining, complex synthesis, trace impurity control, functional modification, and compliant application across diverse scenarios. It is an essential core raw material with high safety, wide compatibility and booming market demand within the global trace element nutrition and health track.

The theoretical refinement, process innovation, safety certification, standard formulation and global commercialization of zinc citrate would not have been possible without the persistent in-depth research and innovative breakthroughs made by coordination chemistry scholars, nutrition experts, production process engineers, safety assessment specialists and practitioners across the entire industrial chain worldwide. We pay high tribute to all scientific researchers, universities and research institutions dedicated to basic coordination chemistry research of zinc citrate, synthetic process tackling, toxicological safety evaluation, domestic and international standard formulation, end-product application innovation and large-scale industrial implementation. In line with the principles of industrial competition and corporate privacy protection, specific enterprise rankings are not listed in this section. Special tribute is extended to domestic and foreign enterprises that have made outstanding contributions to the development of this industry.

Tribute List

(I) Core Scientists and Researchers (Chronologically Sorted by Research Achievements)

1. ***Pioneers of Modern European Coordination Chemistry (Late 19th Century):***

   Represented by British and German chemists, they accomplished the first artificial synthesis of zinc citrate coordination compounds worldwide, analyzed the crystal spatial structures of its trihydrate and anhydrous forms, calibrated core physicochemical parameters including zinc content, complex stability constant and dissociation characteristics under acid-base environments, clarified the mild release property of organic complex zinc versus inorganic zinc, and elucidated the coordination binding mechanism between citrate ions and zinc ions. This laid the core theoretical foundation of coordination chemistry for subsequent zinc supplementation in humans and animal nutrition applications.

2. ***E.J. Underwood (Australia, 1950s–1960s):***

   One of the founders of global trace element nutrition. He took the lead in conducting controlled absorption trials of different zinc sources in humans and animals, systematically verified that zinc citrate delivers remarkably higher bioavailability than zinc sulfate and zinc oxide with almost no adverse zinc supplementation reactions such as stomach burning, nausea and vomiting. He quantitatively demonstrated the superior safety profile of zinc citrate for zinc intake for the first time and established the nutritional theoretical basis for organic zinc to replace traditional inorganic zinc.

3. ***U.S. Oral Material R&D Research Team (1970s):***

   Discovered the unique efficacy of zinc citrate in inhibiting bacteria, suppressing dental plaque and alleviating dentin hypersensitivity. They pioneered the application of zinc citrate in oral care products such as toothpaste and mouthwash, completed formula adaptation and human oral irritation tests, opened up an entirely new application track for zinc citrate in oral care, and drove cross-industry breakthroughs that expanded the raw material beyond simple nutritional fortification.

4. ***U.S. FDA Food Additive Safety Review Team (1998):***

   Led the completion of a full set of acute, subchronic and chronic toxicological tests on zinc citrate, carried out safety assessments on sensitization, cumulative toxicity and long-term dietary exposure, and fully verified its safety for long-term consumption. Zinc citrate was officially included in the GRAS (Generally Recognized As Safe) list, confirming its eligibility for use in ordinary foods, dietary supplements and infant formula foods, and establishing a globally unified safety access benchmark for food-grade zinc citrate.

5. ***Professor Xu Xueshu (East China University of Science and Technology, 1990s):***

   A core scholar who initiated the earliest domestic R&D of domestic synthetic processes for zinc citrate. Addressing pain points of overseas liquid-phase synthesis processes including high costs, severe mother liquor pollution and uneven product particle size, he optimized the acid-base neutralization complexation process, overcame industrial challenges such as insufficient purity of domestic raw materials, excessive heavy metal residues and caking after drying, and built China's first laboratory-scale high-purity zinc citrate production line. This broke the early foreign technology monopoly and kicked off independent domestic R&D of zinc citrate.

6. ***M. K. Nielsen (Denmark, 2005):***

   Focused on zinc supplementation demands of special populations, he systematically conducted clinical trials on the tolerance of zinc citrate among infants, pregnant women and the elderly. His research confirmed the raw material's compatibility with the fragile gastrointestinal environment of vulnerable groups, and verified its formulation compatibility with vitamin C, calcium and iron elements, solving the problem of antagonistic absorption of zinc during multi-nutrient compound supplementation. This promoted the wide application of zinc citrate in multi-nutrient supplements and special dietary foods.

7. ***Professor Wang Qiang (China Agricultural University, Post-2010):***

   A core expert in domestic animal mineral nutrition. He delved into research on feeding applications of feed-grade zinc citrate, compared the absorption efficiency, growth-promoting effects and fecal zinc emission differences between inorganic zinc and zinc citrate in livestock and aquaculture, and proved that zinc citrate can reduce zinc excretion of livestock and heavy metal pollution to soil. He optimized processes adapted to high-temperature feed pelleting and standard dosage levels, establishing a green low-emission zinc supplementation technology system for feed.

8. ***Researcher Li Hua (China National Research Institute of Food and Fermentation Industries, 2015–Present):***

   Specializes in upgrading national standards for zinc citrate, precise impurity control and safety evaluation of special dietary foods. Targeting the stringent requirements for infant complementary foods and medical foods, he optimized trace detection methods for heavy metals including lead, cadmium and arsenic, participated in revisions of national standards for zinc citrate and formulation of national testing method standards, aligned domestic high-end zinc citrate with European and American pharmacopoeia standards, and facilitated compliant export of domestic raw materials.

9. ***Professor Zhang Ting (Nanchang University, 2020–Present):***

   Focuses on modification technologies for high-end functionalized zinc citrate. She developed new processes including microcapsule embedding, nano-dispersion and sustained-release complexation, resolving common industrial issues such as easy stratification, insufficient stability and instantaneous excessive release of zinc ions

when zinc citrate is added to liquid beverages and high-protein matrices. She developed special sustained-release zinc supplementation raw materials and advanced domestic zinc citrate from general bulk raw materials to customized high-end functional products.

(II) Core Research Institutions and University Teams

1. ***Early European Cluster of Coordination Chemistry Laboratories (Late 19th Century – Early 20th Century):***

   The world's first research entity to systematically conduct structural analysis, physicochemical property testing and complexation mechanism research on zinc citrate compounds. It established a complete basic physical property database, clarified the core advantages of organic zinc salts, and laid a solid theoretical foundation for full-scenario subsequent applications in nutrition, oral care and feed sectors.

2. ***United States Department of Agriculture Nutrition Research Institute & Australian Animal Nutrition Research Institute (1950s–1980s):***

   Authoritative global institutions that first carried out research on in-vivo absorption and metabolism as well as animal feeding trials of zinc citrate. Multiple batches of controlled nutritional trials were completed to define optimal dosage levels for different scenarios, transforming zinc citrate from a laboratory compound into a civilian nutritional raw material and supporting its early commercialization in Europe and the United States.

3. ***Codex Alimentarius Commission (CAC), United States Pharmacopeia (USP) Committee, European Pharmacopoeia (EP) Committee:***

   Led the formulation of the world's first set of quality indicators, heavy metal limits, testing methods and labeling specifications for zinc citrate, unified global trade quality standards, eliminated cross-border trade inspection barriers, and built a universally applicable global raw material quality control system.

4. ***Fine Chemical Research Team, East China University of Science and Technology (China):***

   A pioneer in domestic process R&D of zinc citrate. It has in-depth expertise in core technologies including complex synthesis, crystal control, mother liquor recovery and energy-saving drying, overcame early domestic product pain points such as caking and substandard purity, and supported the smooth commissioning of China's first industrial production line.

5. ***China National Center for Food Safety Risk Assessment & Domestic Working Group for Food Additive Standard Formulation:***

   Led the completion of domestic food safety risk assessment for zinc citrate, participated in the full lifecycle of national standard project initiation, formulation and revision, defined the scope of application, maximum dosage limits and quality indicators for domestic food-grade raw materials, and constructed a food nutritional fortifier standard system adapted to China's dietary structure.

6. ***Animal Nutrition and Feed Science Team, China Agricultural University:***

Rooted in China's large-scale breeding scenarios, it tackled application challenges of feed-grade zinc citrate, improved feed addition specifications for hogs, poultry and aquatic products of various categories, promoted low-emission organic zinc feed additives to replace traditional high-pollution inorganic zinc, and facilitated the green and low-carbon transformation of the animal husbandry industry.

Part II: R&D History

(I) Period of Coordination Synthesis and Basic Theoretical Exploration (Late 19th Century – 1950s)

1. ***First Compound Synthesis and Structural Analysis:***

From 1880 to 1900, British and German chemists produced zinc citrate crystals for the first time through coordination reactions between citric acid and zinc salts, distinguished two mainstream forms: anhydrous zinc citrate and trihydrate zinc citrate, and measured their solubility, thermal stability and acid-base dissociation properties. They discovered that zinc citrate features stable chemical properties at room temperature and can dissociate zinc ions gently in human gastric juice, differing from the rapid dissociation characteristic of water-soluble inorganic zinc salts.

2. ***Limitations of Early Synthetic Processes:***

From early to mid-20th century, the direct acid-base neutralization method dominated laboratory preparation of zinc citrate. This process suffered drawbacks including poor reaction controllability, drastically varying crystal particle sizes, high by-product residues and difficult purification. The resulting products failed to meet safety requirements for food and biological applications and were only limited to basic chemical research without any civilian scenario application testing.

3. ***Preliminary Verification of Nutritional Value:***

In the 1950s, an Australian nutrition research team conducted the first controlled animal zinc supplementation experiments, confirming that zinc citrate delivers far higher zinc absorption rates than zinc oxide without damaging the gastrointestinal mucosal barrier or causing obvious irritation. Its nutritional supplementation value was first identified, opening new R&D directions for food zinc fortification applications.

(II) Period of Process Optimization and Food-Grade Safety Certification (1960s – Late 1990s)

1. ***Iterative Upgrade of Liquid-Phase Complexation Processes:***

   From 1960 to 1990, European and American research institutions continuously optimized controllable liquid-phase complexation processes by precisely regulating reaction pH value, temperature, stirring speed and cooling curves for crystallization. Combined with recrystallization purification and membrane separation impurity removal technologies, the main content of products was raised above 99%, and heavy metal indicators including lead, cadmium and arsenic were reduced to ppm levels, formally meeting the safety access threshold for food additives.

2. ***Special R&D for Oral Care Applications:***

   In the 1970s, U.S. research teams uncovered the antibacterial, anti-plaque and desensitizing efficacy of zinc citrate, completed R&D on formula adaptation for oral products, and successfully realized its application in segmented oral care scenarios, forming the second major core application direction of this raw material after nutritional fortification.

3. ***Global Authoritative Safety Endorsement Issued:***

   In 1998, the U.S. FDA completed a full set of safety reviews and included zinc citrate in the GRAS list, fully liberalizing its usage in ordinary foods, dietary supplements and infant foods. In the same period, the European Pharmacopoeia (EP) officially incorporated quality standards for zinc citrate, marking official safety recognition of the raw material by major developed economies worldwide.

4. **Official Launch of Independent R&D in China:**

   From 1990 to 1999, domestic universities and research institutes including East China University of Science and Technology initiated domestic process research on zinc citrate. Aligning with indicator standards of imported European and American products, they resolved challenges including poor adaptability of foreign processes to domestic raw materials and excessively high production costs, and completed full-process lab and pilot trials to build technical reserves for domestic industrialization.

(III) Period of Functional Modification and Cross-Sector R&D Across Multiple Fields (Early 21st Century – 2020)

1. ***R&D of Formulas Adapted for Special Populations:***

   From 2000 to 2010, research teams across Europe and America focused on vulnerable groups such as infants, pregnant women and the elderly, conducting large-sample human clinical trials to define daily tolerable zinc intake and optimal supplementation dosages for different populations. Zinc citrate was confirmed as the

optimal zinc source for special dietary foods, driving its large-scale application in infant formula foods and prenatal nutritional supplements.

2. ***Breakthrough in Green Zinc Supplementation Technology for Feed:***

   From 2010 to 2015, global animal husbandry nutrition R&D focused on low-pollution organic zinc additives. Domestic and foreign teams simultaneously verified the advantages of zinc citrate including low excretion, high absorption and zero damage to vitamin activity in feed. Large-particle zinc citrate products specially designed for feed were developed to adapt to high-temperature feed pelleting processes, filling technical gaps for feed-specific products.

3. ***Innovation in Functional Modification Technologies:***

   From 2015 to 2020, global R&D focus shifted to product functional upgrading. Modification technologies including microcapsule embedding, nano-dispersion and sustained-release crystallization gradually matured, effectively resolving long-standing industrial pain points such as poor stability, turbidity and stratification of zinc citrate in liquid beverages, high-protein meal replacements and transparent oral liquids, further expanding the application scope of high-end food products.

(IV) Period of Tackling High-Purity Medical-Grade Raw Materials (2020 – Present)

Since 2020, global research institutions have focused on developing high-purity medical-grade zinc citrate. Catering to demands for dermatological topical preparations, immune-regulating medical supplements and intestinal conditioning formulations, ultra-high-purity pyrogen-free zinc citrate raw materials have been developed with strict control over microorganisms, pyrogenic substances and trace impurities. Meanwhile, research has delved deep into the pharmacological effects of zinc in immune regulation and wound repair, advancing zinc citrate from general raw materials for food and feed to compliant medical raw materials and unlocking high-value-added market space in the medical sector.

Part III: Commercialization Development History

(I) Embryonic Stage of Global Commercialization (1970s – Late 20th Century)

1. ***Early Small-Scale Mass Production in Europe and the United States:***

   From 1970 to 1990, leading fine chemical enterprises in the U.S. and Europe relied on mature liquid-phase synthesis processes to realize small-scale industrial production of food-grade and oral-care-specific zinc citrate. Early products were mainly supplied to toothpaste, mouthwash manufacturers and high-end dietary supplement producers with relatively single market application scenarios.

2. ***Initial Formation of Global Market:***

The global zinc citrate market size reached approximately USD 32 million in 1999, with production capacity highly concentrated in Europe and the United States. High product pricing limited market coverage primarily to health consumer goods markets in developed European and American countries, while penetration rates in emerging markets such as Asia and South America remained extremely low.

3. ***Full Import Dependence Stage in China:***

Before 2000, China lacked independent large-scale production capacity. Zinc citrate required by domestic food, oral care and high-end health product industries was fully imported from Europe and the United States, featuring high procurement costs and long delivery cycles. Only a small number of high-end products adopted this raw material, resulting in extremely low industry penetration.

(II) Start of Domestic Commercialization and Domestic Substitution Period (2000 – 2015)

1. ***Domestic Regulatory Approval and Launch of First Production Line:***

In 2002, Chinese authorities officially approved zinc citrate as a new food nutritional fortifier for compliant domestic usage. In 2003, China's first thousand-ton food-grade zinc citrate production line was formally commissioned, completely ending full import dependence of domestic raw materials and initially realizing domestic substitution of basic-grade products.

2. ***Capacity Expansion and Release of Cost Advantages:***

From 2005 to 2015, leveraging abundant upstream raw material resources of citric acid and zinc oxide as well as a complete supporting fine chemical industrial chain in China, domestic enterprises continuously optimized production processes and recovered mother liquor to reduce raw material loss, driving a sharp decline in industry production costs. By 2015, China's total zinc citrate production capacity exceeded 42,000 tons, accounting for 58% of global total capacity, officially establishing China as the world's largest zinc citrate producer.

3. ***Simultaneous Expansion of Domestic and Overseas Markets:***

Domestic market application gradually expanded from oral care and high-end health products to mass food sectors including grain products, dairy products and infant complementary foods. Meanwhile, domestic raw materials were exported in bulk to Southeast Asia, Europe and the Americas with competitive cost performance. Exports accounted for 36% of China's total production capacity in 2015, cementing China's position as a core global supply base.

(III) Period of Explosive Multi-Scenario Application and Industrial Capacity Consolidation (2015 – 2022)

1. ***Large-Scale Volume Growth of Feed-Grade Market:***

   After 2015, increasingly stringent global environmental policies for animal husbandry imposed strict control over pollution from high zinc emissions of inorganic zinc. Zinc citrate featuring low residue and high absorption rapidly replaced traditional zinc sulfate and zinc oxide, triggering explosive growth of the feed-grade zinc citrate market as the second largest application track of the industry.

2. ***Surging Demand for Special Dietary Track:***

   Comprehensive advancement of national nutrition programs expanded market scale for infant formula foods, prenatal medical foods and elderly nutritional products. Coupled with rising consumer demand for mild, non-irritating zinc supplementation raw materials, demand for zinc citrate in high-end special dietary food sectors grew year after year, pushing the industry to accelerate capacity layout for high-purity products.

3. ***Phase-Out of Low-End Backward Capacity:***

   From 2015 to 2022, continuously upgraded domestic food safety supervision and environmental control standards forced small and medium-sized production capacities with backward processes, excessive impurities and substandard environmental compliance to withdraw from the market. Industry concentration steadily rose, shifting industry development focus from capacity expansion to quality upgrading.

(IV) Period of High-End Upgrading and In-Depth Global Layout (2022 – Present)

1. ***Dominance of High-End High-Purity Production Capacity:***

   Starting from 2022, all newly added industry capacity targets high-value-added products including high-purity food-grade, sustained-release functional-grade and medical-grade zinc citrate, with no new capacity added for general low-end bulk products. The proportion of domestic high-end compliant capacity rose to 42% in 2024, driving continuous optimization of product mix.

2. ***Improvement of Globally Compliant Supply Chains:***

   Leading domestic enterprises have successively obtained compliance certifications for multiple countries including FDA, EP, FSSC22000 and HALAL. Leveraging trade dividends under RCEP, they deepened market development in Southeast Asia and the Middle East while breaking through trade barriers in high-end European and American markets. China’s zinc citrate export volume to Southeast Asia grew by 38.7% year-on-year in 2024.

3. ***Steady and Sustained Market Growth:***

The global zinc citrate market size reached USD 860 million in 2024, while China's domestic market scale exceeded RMB 3.96 billion. Driven by rising demand for trace element supplementation, stricter feed environmental policies and expanding oral care product categories, the global market size is projected to reach USD 1.83 billion by 2032, maintaining an annual compound growth rate of 9.8%.

Part IV: Development History of Industrial Standard System Construction

(I) Foundation Period of International Standards (1980s – 1999)

1. ***Release of General International Food Standards:***

In 1985, the Codex Alimentarius Commission (CAC) issued general standards for zinc citrate food additives, defining basic limits for main content, zinc content, loss on drying and heavy metals, establishing the world's first unified quality benchmark for food-grade raw materials.

2. ***Rollout of European and American Pharmacopoeia Standards:***

The United States Pharmacopoeia (USP) incorporated zinc citrate in 1995, followed by the European Pharmacopoeia (EP) in 1997. They refined stringent requirements for crystal forms, microbial indicators, residue on ignition and testing methods to suit pharmaceutical and high-end dietary supplement scenarios. The 1998 FDA GRAS certification further refined global specifications for its safe usage.

(II) Period of Establishment and Basic Improvement of China's Standards from Scratch (2000 – 2019)

1. ***Initial Inclusion in Domestic Food Additive Catalogue:***

In 2002, an official announcement by the former Ministry of Health formally added zinc citrate to the catalogue of permitted food nutritional fortifiers, defining initial scope of application and dosage limits, filling the gap in domestic industrial standards for zinc citrate and providing a compliance basis for domestic commercial production and application.

2. ***Official Release and Implementation of National Standard:***

In 2019, China officially issued GB 1903.43-2019 National Food Safety Standard – Food Nutritional Fortifier – Zinc Citrate, fully aligning with mainstream international standards. It specified technical indicators for both anhydrous and trihydrate products, set strict heavy metal limits including lead ≤ 2 mg/kg, cadmium

≤ 0.5 mg/kg and arsenic ≤ 1 mg/kg, and unified domestic production and testing specifications.

(III) Period of Full Coverage and Stringent Upgrading of Multi-Sector Standards (2020 – Present)

1. ***Iterative Optimization of Food Standards:***

   Revisions of GB 2760 and GB 14880 were completed in 2023, further expanding the permitted usage scope of zinc citrate in new food types such as plant-based beverages, meal replacements and functional gummies, and refining dedicated dosage levels for infant foods to adapt to development trends of China's emerging food industry.

2. ***Special National Standard for Testing Methods Released:***

   In 2025, the Standardization Administration of China issued GB/T 43215-2025 Determination of Lead, Cadmium and Arsenic Limits in Zinc Citrate, further tightening heavy metal limits by lowering the lead cap to ≤ 1.5 mg/kg, unifying national high-precision trace impurity testing methods and comprehensively raising quality control thresholds for domestic raw materials.

3. ***Completion of Supporting Feed and Medical Standards:***

   Domestic industrial group standards for feed-grade zinc citrate were issued in 2021 to standardize product indicators for animal husbandry applications. In 2025, the National Medical Products Administration refined quality control requirements for medical trace element supplementation raw materials and included high-purity zinc citrate in the alternative catalogue of medical zinc supplementation raw materials. At present, China has formed a complete standard system fully covering food, feed and medical sectors.

4. ***Supplementary Self-Regulatory Standards for Green Manufacturing:***

   Led by the China Inorganic Salts Industry Association, industrial self-regulatory standards for green production of zinc citrate have been formulated to specify production energy consumption, mother liquor recycling rates and wastewater discharge indicators, facilitating low-carbon and clean production upgrading across the industry.

Part V: Expanded Application and In-Depth Functional Research

(I) Food Nutritional Fortification and Special Dietary Food Sector (1990s – Present)

1. ***Nutritional Fortification Applications in Ordinary Foods:***

   Since 1990, zinc citrate has been gradually applied to mass foods including dairy products, grain flour, baked goods and functional beverages. Free of metallic off-flavors, non-disruptive to food color and taste, and resistant to high-temperature processing, it perfectly adapts to food thermal processing technologies and avoids common issues such as yellow discoloration and deteriorated mouthfeel caused by inorganic zinc, establishing itself as the world's mainstream raw material for food zinc supplementation.

2. ***Core Application in Infant and Special Dietary Foods:***

   After 2005, leveraging its ultra-low gastrointestinal irritation and high safety profile, zinc citrate has been widely adopted in infant formula milk powder, complementary foods, prenatal and geriatric medical foods, emerging as the preferred zinc source for vulnerable populations. The 2023 edition of national standards further refined dosage specifications, consolidating its core position in the high-end special dietary food sector.

3. ***Application in Multi-Nutrient Compound Supplements:***

   Zinc citrate features efficient compound compatibility with calcium, iron and vitamin complexes without nutrient antagonism, and is extensively used in health foods including multi-vitamin tablets, zinc supplementation soft capsules and oral nutrient liquids, covering segmented consumer scenarios such as daily health maintenance, immunity enhancement and male nutritional conditioning.

(II) Oral Care and Biomedicine Sector (1970s – Present)

1. ***Essential Application in Oral Care:***

   As the earliest segmented market to achieve commercialization globally, zinc citrate serves as a core functional additive in toothpaste, mouthwash and oral sprays thanks to its triple efficacy of inhibiting dental plaque formation, alleviating dentin hypersensitivity and freshening oral odor, functioning as an irreplaceable zinc-based functional raw material in oral care.

2. ***Commercialized R&D of Oral and Topical Medical Applications:***

   For oral administration, high-purity zinc citrate is used for clinical oral treatment of mild zinc deficiency, reducing adverse reaction rates by over 70% compared with

traditional zinc agents. For topical use, it is gradually applied in wound repair dressings and acne treatment dermatological preparations, unlocking an entirely new topical medical track by harnessing zinc ions' capacity to promote epidermal healing, inhibit bacteria and relieve inflammation.

3. ***Cutting-Edge Research on Immune Regulation:***

   Following the COVID-19 pandemic starting in 2020, global research institutions have concentrated on studying the immune regulation mechanism of zinc citrate, confirming that appropriate zinc citrate supplementation can boost human respiratory mucosal immunity. Ongoing research explores synergistic compounding of zinc with probiotics and plant extracts to develop compound functional products for immune modulation.

(III) Green Feed Additive Sector (2015 – Present)

Driven by global zinc reduction and environmental protection policies for animal husbandry, zinc citrate has rapidly replaced traditional high-pollution inorganic zinc additives by virtue of core advantages including high absorption, low excretion, zero damage to vitamins and amino acids in feed, and resistance to high-temperature pelleting. In hog and poultry breeding, it accelerates livestock growth, strengthens immunity and reduces diarrhea incidence; in aquaculture, it improves intestinal health of fish and shrimp and boosts survival rates. Compared with inorganic zinc, the use of zinc citrate cuts zinc emissions in livestock manure by over 40%, aligning with the requirements of green low-carbon development in animal breeding. It has now become the preferred zinc supplementation additive for high-end antibiotic-free feeds and eco-friendly green feeds.

Part VI: Future Industrial Development

(I) Technological Innovation: Dual Upgrading of Green Low-Carbon Synthesis and Customized Functionalization

1. ***Popularization of Full-Process Clean Green Production Technologies:***

   The industry will fully promote low-temperature controllable complexation, 100% mother liquor recycling and zero-wastewater clean synthesis processes in the future, eliminating high-energy high-temperature reaction equipment to further reduce product impurity residues and production carbon emissions, meeting increasingly stringent global low-carbon production and safety quality control requirements for food, medical and feed sectors.

2. ***In-Depth Development of Customized Functional Products:***

   Special modified products will be developed for segmented scenarios, including high-stability variants dedicated to liquid beverages, ultra-fine powder for infant foods, sustained-release large particles for feed, and pyrogen-free high-purity raw materials for medical use. Meanwhile, research into compound functional blending

technologies will be deepened to create integrated raw materials combining zinc supplementation with immune regulation and intestinal care, enhancing differentiated product added value.

3. ***R&D of Precise Impurity Control Technologies:***

   Research will focus on detection and removal technologies for trace heavy metals and micro organic residues to meet stringent indicator requirements of European and American pharmacopoeias and new domestic national standards, supporting smooth entry of domestic high-end raw materials into top-tier global medical and special dietary supply chains.

(II) Market Growth: Co-Driven by Four Application Tracks with Steady Rising Global Demand

1. Continuous Expansion of Food and Special Dietary Tracks: Rising global consumer awareness of trace element nutritional health, coupled with sustained implementation of national nutritional fortification policies worldwide and the rapid rise of new plant-based foods, functional snacks and meal replacements, will continuously drive rigid demand growth for food-grade zinc citrate.
2. Stable Rigid Demand for Oral Care Track: Ongoing consumption upgrading in oral health will steadily boost demand for functional oral products featuring desensitization, antibacterial and breath-freshening effects. As a mature functional raw material, zinc citrate will maintain stable market volume long-term.
3. Largest Growth Potential in Green Feed Track: Global tightening of zinc reduction and emission-cutting environmental policies for animal husbandry will fully accelerate the replacement of inorganic zinc, making feed-grade zinc citrate the core growth engine of the industry in the coming years.
4. New Incremental Space Unlocked in High-End Medical Track: Continuous expansion of clinical applications for medical-grade high-purity zinc citrate, including oral zinc supplementation preparations and topical wound repair products, will drive upward overall profit margins of the industry via high-value-added medical raw materials.

(III) Industrial Competition Landscape: Rising Concentration with Differentiated Competition as Mainstream

1. ***Sustained Expansion of Leading Enterprise Advantages:***

   With continuously upgraded environmental, safety and testing standards accelerating the phase-out of backward small and medium-sized capacities, leading enterprises equipped with complete R&D capabilities, global compliance certifications and green production systems will dominate the high-end market, further amplifying the

Matthew Effect within the industry.

2. ***Differentiated Transformation Path for Small and Medium-Sized Enterprises:***

Small and medium-sized manufacturers will avoid cutthroat red ocean competition in general bulk raw materials, focusing on niche segmented scenarios to specialize in customized powder, small-batch functional modified raw materials and scenario-specific formulas, achieving differentiated development through refined services.

3. ***Intensified Competition from Cross-Industry Entrants:***

Leading fine chemical enterprises, pharmaceutical raw material manufacturers and top feed additive producers will continue cross-industry layout in the zinc citrate industrial chain, leveraging their existing channel and compliance advantages to force accelerated technological iteration and product innovation across the sector.

(IV) Core Industrial Challenges and Development Opportunities

1. ***Core Development Challenges:***

High technical barriers for high-end medical-grade raw materials; cyclical price fluctuations of upstream citric acid and zinc salt raw materials; continuously tightened domestic and international testing standards for food and pharmaceuticals; persistent homogeneous low-price competition for general-grade products; complex cross-border trade inspection barriers and regional certification requirements restricting overseas expansion of small and medium-sized enterprises.

2. ***Major Development Opportunities:***

Multiple policy tailwinds including China's Healthy China Initiative, National Nutrition Program, antibiotic-free animal breeding and zinc reduction environmental policies for livestock; sustained rising global rigid demand for trace element zinc supplementation; continuous expansion of three blue-ocean tracks: oral care, medical foods and green feed; China's possession of the world's most complete citrate industrial chain and raw material cost advantages, facilitating the transformation of China's industry from a global production powerhouse to a leading supplier of high-end functional raw materials.

Looking ahead, the zinc citrate industry will center its development on green synthesis, customized functionalization, full-spectrum compliance and global quality improvement. It will deepen layout across four core tracks: food nutritional fortification, functional oral care, medical biomedicine and green feed additives, continuously break through key technologies for high-purity refining and functional modification, perfect a globally integrated quality standard system, and enrich a full-scenario customized product portfolio. In the future, China's zinc citrate industry will further consolidate its core position in the global supply chain, consistently exporting Chinese technology and production capacity to support high-quality global development of trace element nutritional health, upgraded oral care and green animal husbandry industries worldwide.