# Analysis of the Unique Properties of Nucleotides

Nucleotides are small organic molecules composed of nitrogenous bases, pentose sugars, and phosphate groups. As the fundamental structural units of nucleic acids (DNA and RNA), they also serve as core functional ingredients in the food industry and pharmaceutical & healthcare sectors. Nucleotides offer three core values: **flavor enhancement, nutritional fortification, and physiological regulation**, and possess irreplaceable advantages in physicochemical stability, processing compatibility, bioavailability, formulation compatibility, and market compliance. With their core trait of **dual empowerment of flavor and function**, nucleotides have become benchmark functional ingredients in high-end food, infant nutrition, condiments, and healthcare products. The analysis of their properties must be grounded in scientific rigor, systemic integrity, and practical applicability. Below is a systematic analysis of their unique properties from six dimensions.

## I. Physicochemical Characteristics (Basic Core Attributes)

The physicochemical characteristics of nucleotides form the foundation for their processing applications and physiological functions. They center on four dimensions: **physical and chemical form, solubility properties, stability, and molecular structure**, with all indicators meeting international and domestic food-grade raw material standards. The detailed analysis is as follows:

### (I) Physical and Chemical Form

The mainstream nucleotides applied in the food industry mainly include **Disodium 5'-Ribonucleotide (I+G, a 1:1 mixture of Disodium 5'-Inosinate (IMP) and Disodium 5'-Guanylate (GMP))**, **Disodium 5'-Inosinate (IMP)**, and **Disodium 5'-Guanylate (GMP)**. All appear as **white or off-white crystalline powders/granules**, odorless, with characteristic umami taste (IMP delivers pure meaty umami, GMP offers intense mushroom umami), and free of visible impurities, complying with the sensory requirements for food-grade nucleotides in the GB 1886 series of national standards.

The powder exhibits stable physical and chemical parameters: **bulk density controlled at 0.8–1.0 g/cm³**, excellent flowability (angle of repose ≤ 35°), high looseness, low hygroscopicity (moisture absorption rate ≤ 2.0% at 25°C and 60% relative humidity), and resistance to caking and agglomeration. It is directly compatible with full-process food processing techniques such as powder blending, spray drying, granulation and tableting, and liquid formulation, featuring outstanding dispersion uniformity without local

agglomeration. Based on crystal water structure, they are classified into **hydrated forms (e.g., IMP·2H₂O, GMP·7H₂O)** and **anhydrous forms**. Hydrated products, with superior water solubility and powder flowability, are the mainstream specifications in the food industry, accounting for over 90% of market applications.

## (II) Solubility Properties

Nucleotide molecules contain multiple polar groups (phosphate groups, hydroxyl groups), resulting in **excellent water solubility**. At room temperature (25°C):

- Disodium 5'-Ribonucleotide (I+G): solubility ≥ 100 g/100 mL
- IMP: solubility ≥ 110 g/100 mL
- GMP: solubility ≥ 95 g/100 mL

Aqueous solutions are clear and transparent, free of precipitation or turbidity, with no stratification after standing for 24 hours. They are **slightly soluble in ethanol** (solubility ≤ 5 g/100 mL at 25°C) and **insoluble in organic solvents** such as diethyl ether and acetone, meeting the core requirements for water-soluble raw materials in food processing.
Aqueous solutions are **weakly acidic**, with a stable pH of 4.0–6.5, highly compatible with the conventional food processing pH range (4.0–8.0). The dissolution process is gentle, without sudden osmotic pressure changes, and the reconstituted solution delivers a pure taste, free of off-flavors, bitterness, or astringent aftertaste.
Its most prominent solubility-related property is the **umami synergy effect**: when combined with monosodium glutamate (MSG), it produces a significant synergistic flavor-enhancing effect. At a dosage of **5%–12% of MSG**, the overall umami intensity increases **8–10 times**, effectively suppressing sour, bitter, astringent, and fishy off-notes in food, enhancing sweetness and mouthfulness, and making the flavor closer to the natural taste of raw ingredients. This property is the core advantage of nucleotides as high-end flavor enhancers.

## (III) Stability

Nucleotides are **highly chemically stable** under conventional processing and storage conditions, with core stability covering **thermal stability, pH stability, and storage stability**, with specific indicators as follows:

### 1. Thermal Stability

- In conventional food systems (pH 4.0–8.0), molecular structure is **fully stable with no degradation** at temperatures ≤ 80°C;
- Under short-term high-temperature processing (80–120°C, e.g., UHT sterilization, cooking, baking), **active ingredient retention rate ≥ 98%**;
- Prolonged heating above 150°C causes slow degradation due to phosphate ester bond cleavage.

Thus, nucleotides **fully tolerate conventional food industry processes** (baking, UHT sterilization, extrusion, spray drying) with process temperatures ≤ 120°C, achieving **active ingredient retention rate ≥ 95%** during processing. Their stability is significantly superior to monosodium glutamate and disodium succinate, meeting both international and domestic dual standards.

### 2. pH Stability

Stable in **pH 4.0–8.0** (conventional food processing range), with no structural damage or activity loss. Slightly unstable under strong acidity (pH < 4.0) or strong alkalinity (pH > 8.0), but degradation is minimal under short-term conditions, fully meeting food processing requirements.

3. Storage Stability

- **Dry storage**: Sealed and stored in a cool, dry place (≤ 25°C, relative humidity ≤ 60%), **shelf life ≥ 24 months**, with active ingredient retention rate ≥ 98%, no caking or deterioration;
- **Aqueous solution storage**: Stable for ≥ 72 hours at room temperature, with no precipitation or activity loss; slightly degraded under long-term high-temperature storage, but fully compatible with conventional food shelf-life requirements.

### (IV) Molecular Structure

Nucleotides have a **stable molecular structure**, with the core skeleton composed of pentose sugar, nitrogenous base, and phosphate group. Food-grade nucleotides (IMP, GMP, I+G) are **5'-nucleotide derivatives**, with phosphate groups linked to the 5'-carbon of the pentose sugar, forming a stable phosphate ester bond. This structure determines their **umami activity, physiological function, and processing stability**, and is the molecular basis for their dual role as flavor enhancers and nutritional fortifiers.

## II. Nutritional Properties (Core Functional Value)

Nucleotides are **semi-essential nutrients** for the human body. While the body can synthesize them endogenously, exogenous supplementation is critical for specific groups (infants, the elderly, postoperative patients, immunocompromised individuals). Their core nutritional properties are as follows:

### (I) Growth and Development Promotion

- **Infant nutrition**: Breast milk contains abundant nucleotides. Exogenous supplementation **compensates for insufficient endogenous synthesis** in infants, promoting **immune system development, intestinal mucosal maturation, and nutrient absorption efficiency**, supporting healthy growth.
- **Cell regeneration**: As basic units of nucleic acid synthesis, nucleotides **promote cell division, proliferation, and repair**, critical for tissue regeneration and recovery in postoperative or traumatized individuals.

### (II) Immune Function Enhancement

- **Boost immune cell activity**: Promote the proliferation and differentiation of lymphocytes, macrophages, and natural killer cells, enhancing **specific and non-specific immunity**.
- **Improve immune response**: Increase antibody production, strengthen resistance to bacteria, viruses, and other pathogens, **reducing infection risk**, especially beneficial for the elderly and immunocompromised groups.

### (III) Intestinal Health Protection

- **Promote intestinal mucosal development**: Accelerate the proliferation of intestinal epithelial cells, **thicken the intestinal mucosa**, enhance barrier function, and prevent intestinal permeability issues.
- **Regulate intestinal flora**: Promote the growth of beneficial bacteria (e.g., *Bifidobacterium*, *Lactobacillus*), inhibit harmful bacteria, **maintain intestinal microecological balance**, and improve digestion and absorption.
- **Alleviate intestinal damage**: Repair intestinal mucosal injury caused by stress, drugs, or disease, **relieve diarrhea, constipation, and intestinal discomfort**.

### (IV) Liver Function Protection

- **Promote liver cell repair**: Accelerate the regeneration of damaged liver cells, **enhance liver detoxification and metabolic functions**.
- **Reduce liver fat accumulation**: Regulate lipid metabolism in the liver, **prevent fatty liver**, and protect liver health.

### (V) Antioxidant and Anti-Aging

- **Scavenge free radicals**: Inhibit oxidative stress, **reduce free radical damage to cells**, delay cellular aging.
- **Improve metabolic efficiency**: Enhance energy metabolism, **reduce fatigue**, and boost physical endurance.

## III. Processing Adaptability (Industrial Application Value)

Nucleotides demonstrate **excellent processing adaptability**, compatible with almost all food industry processes, with core advantages as follows:

### (I) Wide Process Compatibility

- **Powder processing**: Suitable for dry blending, granulation, tableting, capsule filling; excellent flowability, no caking, uniform mixing.
- **Liquid processing**: Highly soluble, fast dissolution, no precipitation; compatible with blending, homogenization, pasteurization, UHT sterilization.
- **Thermal processing**: Tolerates baking (180–220°C short-term), extrusion (120–150°C), spray drying (160–180°C inlet temperature); **active ingredient retention rate ≥ 95%**.
- **Low-temperature processing**: Stable under freezing (-18°C) and refrigeration (0–4°C); no degradation or activity loss.

### (II) Formulation Compatibility

- **Compatible with most food ingredients**: No adverse reactions with proteins, carbohydrates, fats, vitamins, minerals, or other additives.
- **Synergistic with flavor enhancers**: Strong synergy with MSG; **reduces MSG usage by 30%–50%** while enhancing umami, achieving **salt reduction and flavor optimization**.
- **Stable in complex systems**: Stable in high-salt, high-sugar, acidic, or alkaline environments; no flavor deterioration or activity loss.

### (III) Easy Operation and Cost Efficiency

- **Low dosage, high efficiency**: Typical usage 0.01%–0.1% in food; **significant flavor enhancement and nutritional fortification**.
- **Simple application**: Direct addition, no special equipment; reduces production complexity and costs.
- **Stable quality**: Consistent performance, low batch variation; ensures product quality stability.

## IV. Safety and Compliance (Market Entry Guarantee)

Nucleotides have **high safety profiles** and **global regulatory compliance**, making them core advantages for market application:

### (I) High Safety

- **Acute toxicity**: $LD_{50}$ > 10 g/kg (oral, rats), **non-toxic**.
- **Chronic toxicity**: No carcinogenic, teratogenic, or mutagenic effects in long-term trials; **safe for long-term consumption**.
- **Allergenicity**: No allergenicity reported; **suitable for all age groups**, including infants and pregnant women.
- **Metabolic safety**: Normal metabolism in the body; decomposed into nucleosides, bases, and phosphate, absorbed and utilized or excreted; **no accumulation or side effects**.

### (II) Global Regulatory Compliance

- **China**: Approved as food additives/flavor enhancers/nutritional fortifiers in **GB 2760, GB 14880, GB 10765**; compliant with national standards.
- **International**: Approved by **FAO/WHO JECFA, EU, Codex Alimentarius (CAC)**; listed as GRAS (Generally Recognized as Safe) by the FDA; **globally accepted**.
- **Labeling compliance**: Clear identification standards; compliant labeling avoids regulatory risks for domestic and export markets.

### (III) Safety Assurance

- **Suitable for all ages**: No safety risks; avoids brand crises from product safety issues; supports long-term large-scale deployment and brand competitiveness.

## V. Economic Value (Commercial Competitiveness)

Nucleotides offer **outstanding economic value**, with core advantages:

### (I) High Cost-Effectiveness

- **Low dosage, high efficiency**: 0.01%–0.1% usage achieves significant effects; **reduces raw material costs**.
- **Synergistic cost reduction**: Replaces 30%–50% MSG; **cuts overall flavor costs** while improving quality.
- **Extended shelf life**: Improves product stability; **reduces loss from deterioration**.

### (II) Product Premium Capacity

- **High-end positioning**: Enhances flavor and nutrition; **differentiates from ordinary products**; supports premium pricing.
- **Healthier image**: Enables **salt reduction, MSG reduction, clean label**; aligns with consumer health trends.
- **Wider application**: Expands to infant food, healthcare products, pet food; **increases market share and profitability**.

### (III) Market Competitiveness

- **Unique dual function**: Combines flavor enhancement and nutrition; **irreplaceable by single-function additives**.
- **Mature industrial chain**: Stable supply, mature technology, controllable costs; **supports large-scale applications**.
- **Strong market demand**: Growing demand in health consumption upgrading; **high-growth, high-value market segment**.

## VI. Target Application Markets (Industrial Deployment Scenarios)

With superior physicochemical properties, physiological advantages, and commercial value, nucleotides are widely applied in **food, healthcare, pharmaceuticals, pet nutrition**, with clear scenarios and core values:

### (I) High-End Condiments

- **Core scenarios**: Chicken essence, chicken powder, concentrated stocks, premium soy sauce, oyster sauce, compound sauces, instant noodle seasonings, hot pot bases, barbecue seasonings.
- **Core value**: Powerful umami, salt/MSG reduction, optimized flavor layers, improved quality; **high-end positioning** and premium capacity. Application rate > 80% in high-end condiments; core flavor raw material.

### (II) Infant Formula Foods

- **Core scenarios**: Infant formula, medical-purpose infant formula, infant supplements, nutritional rice flour, infant oral solutions.
- **Core value**: Mimics breast milk nucleotide composition; **supplements infant endogenous deficiency**; promotes immune/intestinal development; boosts nutrient absorption. Dosage follows **GB 10765-2021**; core nutritional fortifier.

### (III) Convenience & Snack Foods

- **Core scenarios**: Instant noodles, frozen dumplings/sweet dumplings, meat products (ham, sausage, bacon), seafood, potato chips, extruded snacks, vegetarian products.
- **Core value**: Enhances umami/meatiness, optimizes taste, masks off-notes; **extends shelf life, salt/sugar reduction**; meets modern convenient/healthy demands.

### (IV) Nutritional Healthcare Products

- **Core scenarios**: Multivitamins, protein powder, meal replacement, elderly healthcare, immune regulators, postoperative recovery, intestinal health products.
- **Core value**: Efficient nucleotide supplementation; **enhances immunity, repairs intestinal mucosa, accelerates recovery**; mild, low-irritation, long-term use suitable; ideal for immunocompromised, sensitive gut, postoperative groups.

### (V) Pet Food

- **Core scenarios**: Premium cat/dog food, nutritional pastes, compound supplements, pet cans.
- **Core value**: Improves palatability (umami); **supplements essential nucleotides**; boosts pet immunity/intestinal health; supports growth and coat quality; cost-effective; preferred for high-end pet food.

### (VI) Other Fields

1. **Pharmaceuticals**: Adjuvant treatment for leukopenia/thrombocytopenia; liver-protective agents, energy metabolism regulators; **promotes cell repair/regeneration, improves metabolism**.
2. **Personal care**: Skin/hair care products; **regulates electrolyte balance, repairs skin barrier, anti-oxidation/aging/moisturizing**.
3. **Feed industry**: Livestock/aquaculture feed fortification; **enhances immunity, growth, stress resistance**; reduces disease, improves product quality.

## Summary

As a benchmark functional ingredient with **dual core of flavor and function** in food and healthcare, nucleotides deliver five core performances: **powerful flavor enhancement, high bioavailability, diverse physiological functions, stable processing compatibility, global regulatory compliance**. They solve industry pain points of traditional flavor enhancers (single flavor, no nutrition, high sodium) and ordinary fortifiers (poor absorption, gut irritation, weak compatibility).

Nucleotides integrate five comprehensive advantages: **functional integration, physicochemical stability, physiological mildness, cost optimization, safety compliance**, achieving **unified empowerment of flavor upgrade, nutrition fortification, health regulation, quality improvement, cost optimization, and safety compliance**.

Suitable for **all age groups, all food processes, multi-industry applications**, nucleotides face **surging demand** amid health consumption upgrading and food high-end/functionalization trends. They have become **indispensable, high-growth, high-value core ingredients** in food, condiments, infant nutrition, healthcare, and pet food. With a complete performance system, authoritative standards, and broad scenarios, nucleotides hold **strong market necessity and long-term commercial prospects**, continuing to empower industrial upgrading and drive innovative development of functional/healthy products.