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Opinion

Precision application of food and medicine with a multi-omics network and biomimetic delivery system

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1 Introduction

The ancient principle of 'food as medicine' is experiencing a renaissance in modern nutritional science. It represents a critical conduit between traditional wisdom and contemporary research, informing the development of functional foods that offer safe, sustainable, and long-term health interventions. Such ingredients can be seamlessly integrated into daily diets while conferring preventive and adjunctive therapeutic benefits, offering a safe, sustainable, and long-term means of intervention. Yet, achieving precise modulation within the complex and dynamic ecosystem of the gut microbiome remains a formidable challenge. This ecosystem—comprising host cells, diverse microbial communities, and their metabolites—is marked by pronounced inter-individual variability and spatiotemporal fluctuations. However, conventional development paradigms—often reliant on empirical formulation or reductionist single-compound approaches—fail to contend with this orders-of-magnitude greater systemic complexity. Compounding the difficulty, many edible and medicinal components are vulnerable to pH shifts, enzymatic degradation, and microbial metabolism within the gastrointestinal tract, resulting in diminished bioactivity, poor absorption, and limited site-specific targeting. To overcome these barriers, we propose a novel framework (Fig. 1) that synergistically integrates multi-omics network analyses to elucidate mechanistic pathways with engineered delivery platforms designed for precise microbiota modulation. This integrated strategy is essential for achieving targeted and efficacious edible–medicinal interventions. These challenges underscore not only the necessity but also define a new paradigm for future research: the integration of multi-omics network analyses to deconvolute mechanisms with advanced, microbiome-responsive delivery platforms to ensure precision targeting. Such a synergistic approach is critical for transforming the concept of food–medicine harmony from a traditional axiom into a precise and actionable therapeutic strategy.

2 Multi-omics network analysis: a new engine for precise target identification

2.1 From syndrome differentiation to molecular typing

In traditional Chinese medicine (TCM), the principle of "treating idiosyncrasies with idiosyncrasies" recognizes that distinct syndromes reflect specific constitutional patterns, each underpinned by shared biological features. For instance, the TCM classification of "damp-heat" may correspond to enrichment of inflammation-associated gut bacteria and elevated lipopolysaccharide levels, whereas "qi deficiency" might align with reduced short-chain fatty acid production and perturbed energy metabolism. Edible–medicinal ingredients—characterized by multi-target, gentle regulatory effects—naturally align with TCM's holistic therapeutic framework. By harnessing multi-omics network analyses, traditional syndrome differentiation can be translated into quantifiable, reproducible molecular subtypes. This transformation not only refines the precision of edible–medicinal interventions but also establishes a technological pathway for the modernization of TCM.

2.2 From panoramic views to fine resolution: mapping the host–microbe–metabolite axis

Advances in single-cell transcriptomics, spatial transcriptomics, metagenomics, metatranscriptomics, metabolomics, and proteomics now enable systematic dissection of the gut microbiome across multiple dimensions. Single-cell transcriptomics provides cellular-resolution insights into transcriptional programs of intestinal epithelial and immune cells under disease conditions. Integrated metagenomic and metabolomic profiling can link discrete microbial taxa to bioactive metabolites—such as short-chain fatty acids, indole derivatives, and phenolic acids—that mediate the physiological effects of edible–medicinal compounds. Because intestinal microenvironments differ among individuals, precision delivery requires personalization. Multi-omics data can stratify individuals into subgroups based on microbial enzyme activity, metabolite patterns, or pH signatures. For example, patients with elevated β-glucuronidase activity may benefit from carriers designed with glucuronidase-resistant linkages, while individuals with reduced SCFAs (short chain fatty acids) production may receive probiotic carriers optimized for restoring these metabolites. In addition, adaptive delivery systems—equipped with biosensors responsive to host- or microbe-derived cues—could be customized using

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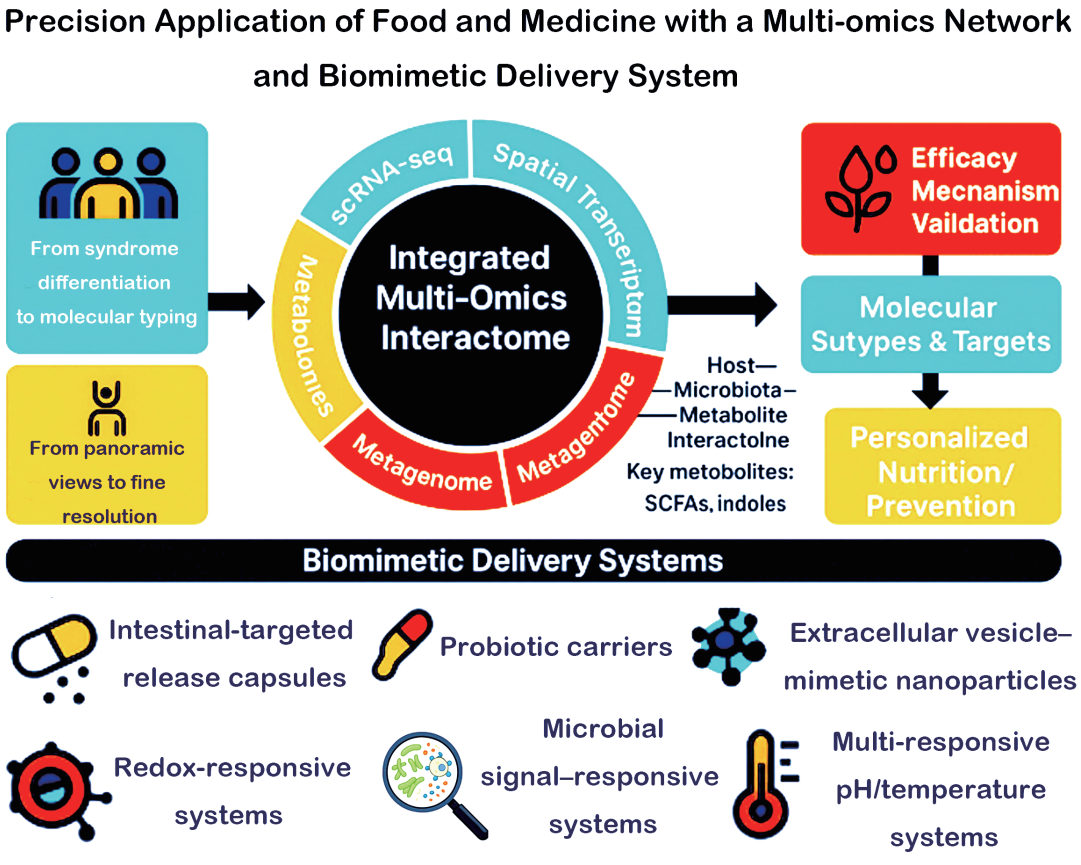


Figure 1 Precision application of food and medicine with a multi-omics network and biomimetic delivery system.

omics-informed biomarkers, ensuring individualized precision *in vivo*. For instance, integrated metabolomic and metagenomic analyses of ulcerative colitis patients have revealed reduced levels of butyrate-producing taxa and disrupted short-chain fatty acid pathways. This finding has guided the design of probiotic carriers encapsulating butyrate-producing *Clostridium butyricum* to restore intestinal metabolic balance. Another example comes from metagenomic evidence of polyphenol-degrading glycosidases in the inflamed gut, which prompted the development of enzyme-resistant nanocarriers that protect flavonoids until they reach the colon. These cases illustrate how multi-omics data serve as a blueprint for tailoring delivery systems to specific host–microbe–metabolite dysfunctions. Multi-omics network analysis weaves these data into a dynamic map of host–microbe–metabolite interactions, bridging macroscopic ecosystem views with molecular precision. This framework allows the rational screening or design of ingredient combinations with defined regulatory activities, paving the way for highly targeted edible–medicinal strategies.

3 Biomimetic delivery systems: overcoming bottlenecks in ingredient stability and targeting

Even with precise molecular targets, clinical translation is hindered if bioactive ingredients fail to reach their site of action *in vivo*. Biomimetic delivery systems—designed to replicate natural biological structures and transport pathways—can shield labile compounds from degradation and enable targeted, controlled release within the complex intestinal milieu. Current strategies include: 1) Intestinal-targeted release capsules – pH-sensitive or enzyme-degradable coatings permit site-specific release in the small intestine or colon, bypassing gastric degradation. 2) Probiotic carriers-live microbial vectors transport edible–medicinal ingredients or their precursors into the gut, where bacterial metabolism converts them into bioactive forms. 3) Extracellular vesicle–mimetic nanoparticles that mimic bacterial or mammalian extracellular vesicle membranes enhance penetration of the mucus barrier and cellular uptake, facilitating immune modulation and transcellular transport. 4) Redox-responsive systems – carriers incorporating ROS (reactive oxygen species)-sensitive linkages disassemble or change conformation in oxidative microenvironments, triggering rapid release of antioxidants such as polyphenols, flavonoids, and organosulfur compounds. This strategy enables lesion-specific, high-dose delivery while minimizing systemic exposure. 5) Microbial signal–responsive systems – platforms integrating biosensing units detect metabolic cues from specific microbial communities, such as elevated secondary bile acids or unique polysaccharidase activities, and release payloads upon recognition of these signals. 6) Multi-responsive pH/temperature systems – hybrid carriers combining pH-sensitive polymers (e.g., Eudragit® copolymers, chitosan derivatives) with thermoresponsive materials (e.g., poly-*N*-isopropylacrylamide) maintain gastric stability yet rapidly disassemble in the alkaline and locally elevated-temperature conditions of inflamed colonic sites. These strategies allow polyphenols and flavonoids from food–medicine homologues to be complexed with proteins, peptides, or polysaccharides for enhanced stability, or encapsulated within nanocarriers for

sustained, site-specific, and controlled release. Such designs markedly improve *in vivo* bioavailability and therapeutic precision. Despite the promising advances, biomimetic delivery systems face safety and compliance challenges. Potential immunogenicity of extracellular vesicle-mimetic nanoparticles, risks of horizontal gene transfer from engineered probiotics, and uncertainties regarding long-term accumulation of synthetic polymers require rigorous preclinical and clinical validation. In addition, regulatory approval pathways for hybrid systems combining food-derived compounds with nanomaterials are not yet standardized. These limitations underscore the need for comprehensive toxicological studies, transparent regulatory frameworks, and consumer-oriented compliance strategies to ensure safe translation into functional foods and therapeutic applications.

In conclusion, precision food–medicine congener strategies integrating multi-omics networks with biomimetic delivery systems are poised to define the next frontier in functional nutrition and therapeutic intervention. By uniting TCM syndrome differentiation with modern molecular stratification, this approach bridges the gap from macroscopic phenotypes to molecular mechanisms, and from empirical practice to targeted intervention. Such integration holds promise for advancing personalized nutrition and disease prevention. Looking ahead, the convergence of omics technologies, materials science, synthetic biology and artificial intelligence is expected to strengthen the link between fundamental research and clinical translation, paving the way for a new era in which the shared principles of medicine and food are rendered quantifiable, predictable and precisely controllable.

Conflicts of interest

The authors declare that there are no conflicts of interest in this work.