

Review Article

The innovative application of plasma technology in food and medicine homology resources

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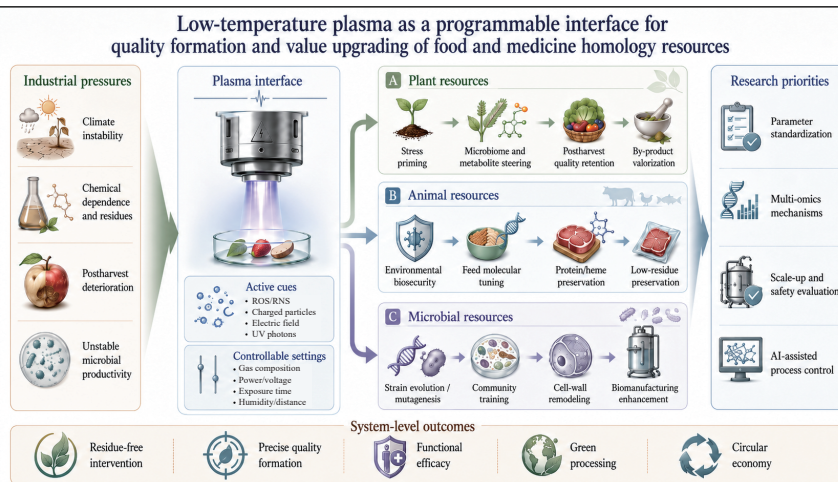
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Abstract: Food and medicine homology resources are increasingly constrained by climate-driven production instability, chemical-residue control, postharvest deterioration, and the demand for function-oriented products. Low-temperature plasma (LTP), also referred to in the literature as cold plasma or non-thermal plasma, is a non-equilibrium physical technology that generates reactive oxygen species (ROS), reactive nitrogen species (RNS), charged particles, electric fields, and ultraviolet (UV) photons under ambient or near-ambient bulk-temperature conditions. This review establishes an



end-to-end LTP application framework for plant-, animal-, and microbial-derived food and medicine homology resources. Different from single-sector reviews, the present framework distinguishes substrate-specific regulatory logic across the whole value chain. In plant-derived resources, LTP mainly acts through physical signal-mediated stress priming, secondary metabolism regulation, microbiome modulation, postharvest quality maintenance, detoxification, sensory improvement, and waste valorization. In animal-derived resources, its application logic is centered on environmental biosecurity, feed molecular modification, protein and heme chemistry, and low-loss preservation. In microbial-derived resources, LTP is closely associated with mutagenesis breeding, cell-wall remodeling, community selection, metabolic reprogramming, and biomanufacturing efficiency. The main bottlenecks remain the absence of standardized parameter databases, incomplete

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understanding of plasma-biomolecule interactions, insufficient scale-up of continuous equipment, and inadequate safety evaluation systems for food and traditional medicinal materials. Future research should prioritize substrate-specific parameter standardization, multi-omics-based mechanistic elucidation, and integration with smart agriculture, precision nutrition, circular economy, and AI-assisted process control. Overall, LTP should be regarded not only as a sterilization or preservation tool, but also as a programmable physical-regulatory platform for full-chain quality formation and high-value utilization of food and medicine homology resources.

Keywords: low-temperature plasma; food and medicine homology; green processing; microbial regulation; postharvest quality; functional resources

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1 Introduction

Food and medicine homology resources are increasingly affected by production instability, processing losses, and safety risks along the whole industrial chain. For plant-derived resources, major constraints include pesticide residues in Chinese herbal medicines, mycotoxin contamination during cultivation and storage, continuous-cropping obstacles, soil microbiome imbalance, and the degradation of heat-sensitive active compounds during drying, extraction, decoction, and post-harvest preservation. For animal-derived resources, excessive dependence on antibiotics and chemical disinfectants increases the risk of drug residues and compromises green production. For microbial-derived resources, low strain productivity, insufficient stress tolerance, and unstable functional metabolite output remain central bottlenecks in industrial fermentation.

Compared with conventional thermal processing and chemical treatments, low-temperature plasma (LTP) provides a distinct combination of near-ambient bulk-temperature operation, residue-free intervention, low risk of resistance induction, and multi-factor physicochemical synergy^[1]. Thermal processing mainly depends on heat-mediated microbial inactivation and can reduce the content or bioactivity of thermolabile compounds. Chemical fumigants, pesticides, preservatives, and antibiotics may introduce exogenous residues and often act through relatively limited molecular targets. In contrast, LTP simultaneously delivers reactive oxygen species (ROS), reactive nitrogen species (RNS), charged particles, electric fields, and ultraviolet (UV) photons, enabling multi-target microbial inactivation, surface functionalization, controlled molecular modification, and moderate biological stress regulation without persistent chemical input^[2,3]. Its effect is nevertheless matrix-dependent and must be quantified through plasma source type, gas composition, discharge power or voltage, exposure time, treatment distance, humidity, moisture content, and biological substrate characteristics.

Existing reviews have mainly addressed isolated applications of plasma technology, such as seed priming, plant disease control, post-harvest preservation, food sterilization, meat quality maintenance, polysaccharide or protein modification, and microbial mutagenesis. These studies provide essential mechanistic and technical foundations, but most of them focus on a single agricultural sector or a single processing scenario. A systematic framework that integrates medicinal and edible resources across plant, animal, and microbial origins, and that follows the whole chain from cultivation/breeding to processing, safety regulation, waste valorization, and industrial implementation, remains insufficiently developed.

Accordingly, this review is organized into three major sections: Plant-derived, animal-derived, and microbial-derived food and medicine homology resources. The plant section discusses seedling stress tolerance, green agricultural inputs, microbiome

regulation, post-harvest quality control, sensory improvement, detoxification, efficacy enhancement, and waste valorization. The animal section focuses on environmental sanitation, controlled-atmosphere rearing, dynamic functional feeds, and preservation/color retention. The microbial section discusses LTP-induced mutagenesis, dominant microbiota training, ready-to-eat functional products, cell-wall remodeling, solubility enhancement, and bioavailability improvement. The review finally proposes three research priorities: Standardized parameter systems, microscopic plasma-biomolecule interaction mechanisms, and interdisciplinary integration with smart agriculture, precision nutrition, circular economy, and AI-driven optimization.

2 Plant-derived food and medicine homology resources

Plant-derived food and medicine homology resources represent the most complex and dynamic interface between environmental stress, primary production, secondary metabolism, and post-harvest quality preservation. In this domain, LTP should not be viewed merely as a non-thermal sterilization or preservation tool, but as a programmable physical-regulatory platform capable of intervening across the entire plant resource value chain. Through the coordinated action of reactive oxygen and nitrogen species, charged particles, electric fields, and ultraviolet photons, plasma can modulate seed vigor, stress adaptation, nutrient transformation, plant microbiome interactions, phytochemical accumulation, safety control, sensory quality, and waste reutilization in an integrated manner. Its frontier value lies in enabling a transition from chemically dependent cultivation and processing toward precision, residue-free, low carbon, and metabolite-oriented resource management. For plant-derived resources, the key scientific challenge is therefore to establish controllable plasma-plant-microbiome-metabolite regulatory networks that simultaneously safeguard yield stability, authentic quality, bioactive efficacy, and circular utilization under increasingly unstable climatic and agricultural conditions (Fig. 1).

2.1 Enhancing seedling stress tolerance

The increasing frequency of extreme climatic events, including severe cold, drought, hypobaric and hypoxic conditions, extreme heat, and strong winds, poses a significant threat to the stable production of plant-derived food and medicine homology resources. LTP, applied during germination, seedling development, and vegetative growth, generates a non-equilibrium environment rich in reactive species, charged particles, and UV radiation. This environment triggers broad-spectrum stress responses within the plant^[4-6]. By activating intracellular calcium signaling, mitogen-activated protein kinase cascades, and abscisic acid-dependent transcriptional networks, the process induces the expression of genes encoding antifreeze proteins, heat shock

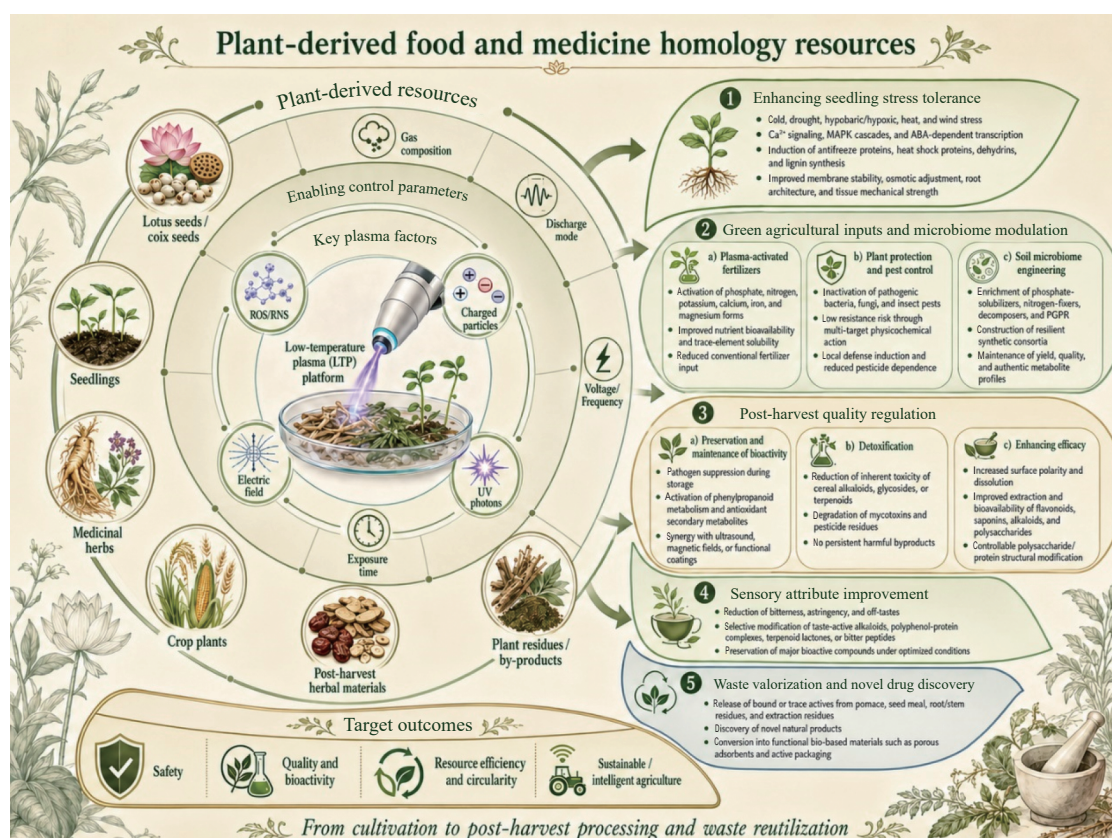


Figure 1 Conceptual schematic diagram of LTP application logic in plant-derived food and medicine homology resources.

proteins, dehydrins, and enzymes involved in lignin synthesis. This systemic enhancement of membrane stability, osmotic adjustment capacity, and tissue mechanical strength occurs without altering the plant's genetic material. Crops treated with optimized plasma parameters can acquire cross-tolerance to multiple stressors, evidenced by reduced membrane lipid peroxidation under cold stress, deeper root system architecture during drought, alleviated photoinhibition under high temperatures, and increased stem bending strength in windy conditions. This plasma-based intervention requires no exogenous chemicals, consumes low energy, and is suitable for large-scale field application. Future efforts should focus on quantifying the relationships between diverse plasma source parameters, crop species, and growth stages to facilitate the standardization and intelligent implementation of stress-resilient cultivation.

Despite these advantages, large-scale field implementation remains constrained by several practical bottlenecks. First, the initial cost of plasma generators, discharge electrodes, power-control modules, and gas-supply systems may limit adoption by small- and medium-scale producers. Second, uniform treatment of bulk seed batches is difficult because seed size, coat thickness, surface morphology, moisture content, packing density, and motion trajectory can generate heterogeneous plasma-dose distributions. Third, medicinal and edible plants such as ginseng, red dates, and lotus seeds differ markedly in dormancy traits, seed-coat structure, moisture sensitivity, and endogenous antioxidant capacity; species-specific parameter windows are therefore required. Future field-oriented systems should combine conveyor or fluidized-bed plasma devices with online monitoring, response-surface modeling, and AI-assisted parameter adjustment to improve exposure uniformity and operational reproducibility.

2.2 Green agricultural inputs and microbiome modulation

2.2.1 Plasma-activated fertilizers

LTP, driven by different gas sources (air, nitrogen, oxygen, argon, or their mixtures), directly interacts with solutions containing phosphates, potassium salts, calcium salts, iron salts, magnesium salts, and nitrogenous compounds^[7-10]. This interaction drives chemical transformations and changes in complexation states, can significantly enhance the bioavailability of essential elements such as phosphorus, potassium, calcium, nitrogen, and magnesium. Specific effects include phosphate ion activation, improved ferrous ion stability, modulation of the ammonium-to-nitrate ratio, and enhanced solubility of trace elements. The resulting plasma-activated nutrient solutions, applied *via* irrigation or foliar spray, facilitate efficient mineral absorption and transport within the plant, allowing for a substantial reduction in conventional fertilizer use while maintaining or even improving crop yield and quality. This approach substantially mitigates the risk of agricultural non-point source pollution, introduces no persistent chemical byproducts, and is compatible with existing fertigation systems. Future research should elucidate the mechanisms governing reactive species generation and nutrient element transformation under different gas-solution-plasma parameter combinations, leading to standardized application protocols for specific plant species and growth stages.

2.2.2 Plant protection and pest control

Considering the specific growth characteristics of different plant crops (plant architecture, leaf surface structure, cuticle thickness,

stomatal density) and their phenological stages, customized plasma devices (dielectric barrier discharge, jet discharge, corona discharge) can be employed for periodic, tailored interventions. This technology directly inactivates pathogenic bacteria, fungi, and insect pests through a multifaceted mechanism involving the disruption of pathogen cell membranes by reactive species, oxidation of proteins and nucleic acids, and synergistic antimicrobial effects from the electric field and UV radiation^[11-13]. Unlike conventional chemical pesticides, the multi-target physicochemical action of LTP makes it difficult for pathogens to develop specific resistance mutations, enabling complete lethality at low doses without inducing long-term resistance. Simultaneously, plasma activation can beneficially modify the plant surface micro-environment and induce local defense responses, achieving a dual effect of disinfection and immune priming. This strategy permits a substantial reduction in the frequency and concentration of chemical pesticide applications, decreasing the toxic burden on soil microbial communities, non-target organisms, and agricultural workers, while also significantly lowering the risk of pesticide residues in the final product.

2.2.3 Soil microbiome engineering

Rising global temperatures, increased frequency of soil drying-rewetting cycles, and more extreme precipitation events are profoundly impacting the biotransformation capacity, nutrient transport efficiency, and plant-root interactions of soil microbial communities. These changes impair the plant's ability to utilize fertilizers and humic substances, leading to disruptions in secondary metabolic pathways and a marked decline in the diversity and concentration of natural active components (flavonoids, phenolic acids, polysaccharides, terpenoids) in plant-derived food and medicine homology resources. In response to this climate-soil-plant cascade of stress, LTP offers a unique strategy for microbiome engineering. By applying gradient intensities and periodic pulsed plasma treatment, a selective pressure is exerted on complex soil microbial communities. Functionally robust microorganisms, such as efficient phosphate-solubilizing bacteria, nitrogen-fixing bacteria, organic matter decomposers, and plant growth-promoting rhizobacteria, are enriched over successive screening rounds, while metabolically inefficient strains are progressively eliminated^[14-17]. The resulting synthetic microbial consortia, characterized by enhanced environmental resilience (tolerance to heat, drought, acidification) and high resource utilization efficiency, can be reintroduced to the soil of authentic producing areas. This approach helps restore and maintain the yield and quality basis of plant-derived products while reinforcing the genuine characteristics of the producing area, namely the stable expression of a distinctive profile of active metabolites linked to geographical indication attributes. This dual technological and cultural strategy ensures the sustainable supply of plant-derived food and medicine homology resources.

2.3 Post-harvest quality regulation

2.3.1 Preservation and maintenance of bioactivity

LTP can effectively inhibit the infection, colonization, and proliferation of pathogenic microorganisms, such as viruses, bacteria, and fungi, during post-harvest handling and storage, significantly reducing nutrient losses and quality deterioration. The mechanism involves oxidative damage to pathogen nucleic acids and proteins, disruption of envelope structures, and

irreversible inactivation of intracellular metabolic pathways by reactive species^[18]. Concurrently, the moderate oxidative stress induced by plasma actively modulates plant stress metabolism networks, notably activating the phenylpropanoid pathway. Upregulation of key enzymes like phenylalanine ammonia-lyase enhances the synthesis of antioxidant secondary metabolites, including phenolic acids, flavonoids, and lignin, thereby maintaining high levels of natural active components^[19]. To counteract the potential non-selective oxidative damage to plant tissues from plasma's inherent oxidizing nature, synergistic strategies can be employed, namely ultrasonic treatment to increase the penetration depth of reactive species, magnetic fields to control the trajectory and energy distribution of charged particles, and functional coating materials such as chitosan- or sodium alginate-based films as selective barriers^[20]. These combined physical and chemical approaches allow for the targeted suppression of undesirable oxidative effects while amplifying the beneficial outcomes of sterilization, immune induction, and metabolic promotion.

The synergistic mechanisms of ultrasound, coating, and LTP are complementary rather than redundant. Ultrasound can induce cavitation, microstreaming, and local loosening of tissue surface structures, thereby improving mass transfer and facilitating the penetration of plasma-generated reactive species. LTP provides the primary non-thermal antimicrobial and regulatory factors, including ROS, RNS, charged particles, electric fields, and UV photons, which contribute to microbial inactivation, enzyme modulation, and moderate activation of stress-metabolism pathways. Chitosan- or sodium alginate-based coatings act as selective barriers that reduce water loss, limit excessive oxidative attack, provide additional antimicrobial effects, and prolong the local residence of beneficial reactive species near the tissue surface. Therefore, the sequence and intensity of the combined process should be optimized to balance microbial control, tissue integrity, reactive-species penetration, and preservation of bioactive compounds.

2.3.2 Detoxification

Reactive species generated by LTP can induce controlled chemical modifications of certain natural active components within plant-derived products. This process can precisely alter the functional groups or conformation of molecules such as specific alkaloids, glycosides, or terpenoids, neutralizing their inherent hepatorenal toxicity while preserving or modestly optimizing their therapeutic efficacy. This molecular-level modification can broaden the therapeutic window per unit dose and reduce the burden of long-term medication. Furthermore, concerning mycotoxins (aflatoxins, ochratoxin A, persistent organic pollutant, endocrine disruption chemicals, micropollutants) and pesticide residues that may contaminate plants during cultivation, processing, or storage, LTP treatment efficiently degrades these toxic substances^[21-24]. The mechanism involves reactive species attacking sensitive structures within toxin molecules, such as unsaturated double bonds, lactone rings, and aromatic rings, breaking them down into low-toxicity or non-toxic fragments without introducing additional chemical reagents or generating persistent harmful byproducts. By appropriately controlling treatment parameters, effective degradation of toxins and pesticide residues can be achieved while largely preserving the overall functionality of the natural active components, thereby harmonizing the safety and efficacy of plant-derived food and medicine homology resources.

2.3.3 Enhancing efficacy

LTP treatment can alter the hydrophilic-lipophilic balance on the surface of plant-derived food and medicine homology resources. The introduction of oxygen- or nitrogen-containing polar functional groups enhances interaction with aqueous media, significantly increasing the dissolution rate of intracellular active components such as flavonoids, saponins, alkaloids, and polysaccharides^[25,26]. This consequently can further improve bioavailability and therapeutic effect at the same dosage. Moreover, the reactive species and electric field effects can selectively target macromolecules like proteins and polysaccharides^[27,28]. By inducing controlled scission of glycosidic or peptide bonds, crosslinking, or conformational rearrangements, plasma enables controllable changes in molecular weight and higher-order structure. Without compromising the core biological function of these macromolecules, a dual regulatory potential can be achieved. On one hand, moderate reduction in molecular weight can enhance gastrointestinal dissolution, diffusion, and trans-membrane transport, promoting bioavailability and efficacy^[29]. On the other hand, special populations requiring restricted nutrient intake (individuals with diabetes or metabolic syndrome), plasma treatment can induce the formation of more complex polymeric networks or anti-digestive structures. This inhibits the rate and extent of digestion and absorption of specific carbohydrates or amino acids, enabling the development of functional foods and pharmaceuticals with targeted nutritional intervention capabilities. This approach introduces no exogenous additives or chemical residues and offers mild, controllable processing conditions, providing a novel physical platform for the precise and personalized deep processing of food and medicine homology resources.

2.4 Sensory attributes improvement

LTP treatment can ameliorate undesirable taste characteristics in plant-derived products, specifically bitterness, astringency, and persistent off-tastes. Reactive species within the plasma selectively interact with bitter compounds (alkaloids like matrine and synephrine), astringent polyphenol-protein complexes, and off-taste components (terpenoid lactones or bitter peptides)^[30-34]. Through oxidative degradation or molecular modification, these undesirable taste-active molecules are converted into derivatives with reduced or no taste, while the overall flavor profile and aroma characteristics of the plant material remain largely intact. Unlike traditional methods such as encapsulation, masking, or the addition of sweeteners or flavorings, LTP directly alters the chemical structure of the taste-active molecules themselves, modifying their binding affinity to taste receptors without introducing any exogenous additives. This aligns with the growing consumer preference for clean labels and natural products. While improving palatability, careful control of plasma treatment parameters is essential to avoid excessive damage to the primary active components of the product. Systematic optimization of critical variables, including gas composition, discharge voltage and frequency, treatment duration, and sample moisture content, enables a precise process balance between selectively degrading/modifying undesirable taste substances and effectively retaining target bioactive compounds. Under appropriately optimized plasma conditions, major active components such as flavonoid glycosides, saponins, polysaccharides, and phenolic acids can be well-preserved, and the core therapeutic efficacy indicators, such as anti-inflammatory, antioxidant, or immunomodulatory

activities, remain largely unchanged. This strategy offers a novel, safe, and effective non-thermal physical processing route for improving the palatability and patient compliance of plant-derived food and medicine homology resources.

At the molecular level, bitterness reduction is not limited to the direct degradation of bitter substances. Alkaloids, terpenoid lactones, bitter peptides, and some polyphenol-derived complexes interact with bitter taste receptors through hydrophobic interactions, hydrogen bonding, electrostatic interactions, and steric complementarity. LTP-induced oxidation, hydroxylation, carbonylation, bond cleavage, or conformational rearrangement can change molecular polarity, spatial configuration, and electron distribution, thereby weakening receptor-binding affinity and reducing bitterness perception. However, excessive exposure may oxidize or degrade beneficial flavonoids, saponins, phenolic acids, and polysaccharides. A multi-objective optimization strategy is therefore required, in which gas composition, discharge voltage, pulse frequency, treatment duration, sample moisture, and post-treatment storage conditions are jointly optimized against bitterness reduction, retention of marker active compounds, antioxidant capacity, and sensory acceptability.

2.5 Waste valorization and novel drug discovery

Large quantities of waste generated during the processing of plant-derived products, such as pomace, seed meal, root and stem residues, and extraction residues, still remain rich in underutilized functional active components, including polysaccharides, dietary fiber, polyphenols, flavonoids, alkaloids, and terpenoids. LTP, in synergy with other physical (ultrasound, magnetic and electric field), chemical, and biotechnological (enzymatic treatment, supercritical fluid extraction) methods, can efficiently release and extract these bound or trace active components from the waste matrix, significantly reducing resource waste while improving the economic and ecological efficiency of the entire value chain^[35-37]. Specific plant organs like root bark, seed coats, calyces, leaf veins, and phloem often accumulate unique secondary metabolites, yet low-abundance components within waste streams are difficult to release and identify under conventional extraction conditions. Plasma's penetrating ability and surface modification capacity disrupt cell wall and cellulose physical barriers, releasing potentially novel compounds such as polyphenols, flavonoid glycosides, and oligosaccharides covalently bound to cell wall polysaccharides or lignin. This approach holds promise for identifying previously unrecognized natural products, including potentially novel and highly potent functional agents, thereby offering new opportunities for discovering lead compounds in drug development. Furthermore, plasma-modified waste residues can be utilized to produce functional bio-based materials, such as porous adsorbents for heavy metal or dye removal, and biodegradable active packaging films for the preservation and controlled release of plant-derived products, thereby achieving high-value, cascaded utilization and closing the loop in a circular economy^[38-40].

3 Animal-derived food and medicine homology resources

Animal-derived resources require a fundamentally different plasma application logic from plant systems, because product quality is shaped not only by microbial safety and post-harvest preservation, but also by the physiological state, rearing environment, feed conversion pathway, and tissue-specific

accumulation of functional components. In this domain, LTP offers a prospective whole chain strategy that links environmental biosecurity, precision feeding, *in vivo* quality formation, and low-loss preservation. Rather than relying on antibiotics, chemical disinfectants, synthetic additives, or intensive thermal processing, plasma-based interventions can provide controllable physicochemical regulation of rearing atmospheres, feed molecular structures, microbial load, color stability, and functional nutrient retention. The strategic significance of this domain lies in moving animal-derived products from “end-point safety control” toward “front-end ecological regulation and process-integrated quality design”. Future progress will depend on defining safe exposure thresholds, animal-specific plasma response mechanisms, and intelligent treatment systems that balance pathogen suppression, animal welfare, metabolic efficiency, product efficacy, and consumer safety (Fig. 2).

3.1 Environment sanitization and controlled-atmosphere rearing

LTP devices driven by different gas sources can produce tailored mixtures of reactive oxygen and nitrogen species that selectively inactivate bacteria, viruses, fungi, and other environmental microorganisms, thereby reducing the microbial burden in animal-derived food and medicine homology production systems^[41-43]. However, LTP-assisted environmental regulation should be implemented within species-specific exposure limits and animal-welfare requirements, rather than assuming universal tolerance to ozone, nitrogen oxides, or other reactive species. Practical systems must therefore integrate real-time monitoring of ozone, nitrogen oxides, oxidation-reduction potential, humidity, temperature, ventilation rate, and

microbial load. For terrestrial livestock and poultry houses, plasma-treated air can be coupled with ventilation ducts, negative-pressure exhaust, ozone decomposition units, UV-assisted disinfection, and biofilters to control aerosols, ammonia/odor accumulation, and airborne microorganisms while avoiding direct overexposure of animals. For aquaculture, equipment selection should prioritize plasma-activated water, dissolved-oxygen regulation, oxidation-reduction potential control, dissolved ozone decay, circulating-water microbial load, and compatibility with recirculating aquaculture systems and biological filtration. Such differentiated turnkey designs are essential for translating LTP from laboratory disinfection to stable industrial biosecurity management.

3.2 Dynamic functional feeds

Recognizing the varying nutritional demands and metabolic patterns of animals at different growth, finishing, reproductive, and pharmaceutical-metabolic stages, LTP can be used to pre-treat or post-modify feed ingredients. This enables the development of functional feeds with dynamically adjustable nutrient composition and content. Plasma treatment, through reactive species interacting with proteins, lipids, carbohydrates, and micronutrients in the feed, alters their molecular structure, solubility, and digestive characteristics^[44,45]. This allows for the precise matching of the animal's nutrient absorption capacity and anabolic requirements at different rearing stages. Appropriately designed plasma-treated feed can improve meat quality parameters, such as muscle fiber tenderness and water holding capacity, enhancing marbling scores and the accumulation of flavor precursors. For the quality control of byproducts like horn, hide, bone, and foot tissue, plasma treatment can also optimize the crosslinking state of keratin and collagen, as well as the efficiency

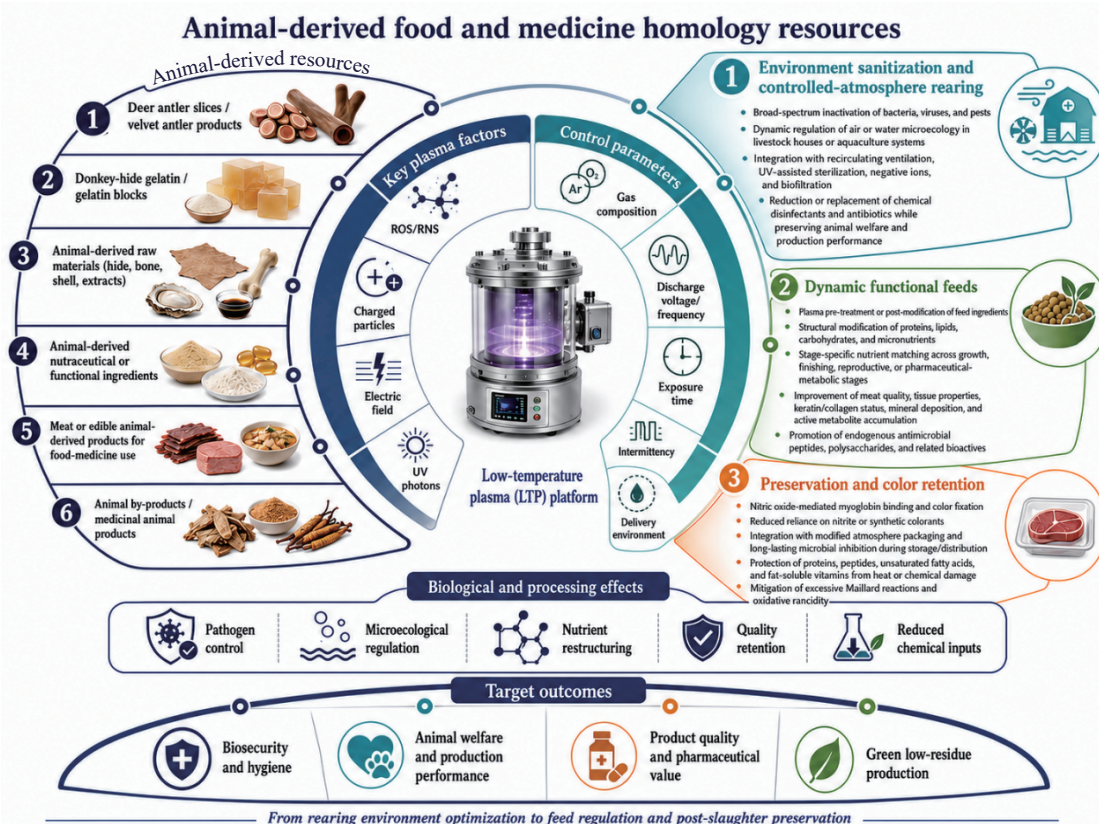


Figure 2 Conceptual schematic diagram of LTP application logic in animal-derived food and medicine homology resources.

of mineral deposition, improving the density and mechanical properties of these structures. For animals specifically reared for pharmaceutical purposes, like producing specific active metabolites, plasma-assisted feed can modulate the conversion pathways and accumulation rates of drug intermediates *in vivo*, significantly increasing the concentration and efficacy of target metabolites. Concurrently, this technology can reduce the animal's digestive and metabolic burden, promoting the biosynthesis and tissue accumulation of endogenous active substances like antimicrobial peptides, polysaccharides, and flavonoid glycosides, thereby achieving a synergistic improvement in both animal health and product quality.

3.3 Preservation and color retention

Nitrogen-containing reactive species, particularly nitric oxide generated during LTP discharge, possess unique color-fixing and color-enhancing properties. These can replace conventional synthetic color enhancers or nitrite additives in the processing of animal-derived products. By controlling plasma parameters, nitric oxide selectively binds to myoglobin in meat products, forming stable nitrosyl myoglobin which imparts an attractive, stable rose-red color, while avoiding the health risks and residue issues associated with exogenous chemical colorants. During storage and distribution, the integration of plasma technology with modified atmosphere packaging, through continuous or intermittent plasma generation that modulates the gas composition within the package, can achieve long-lasting microbial inhibition in cold stores, temperature-controlled warehouses, or shipping containers. This significantly extends the microbiological safety period^[46-48]. Furthermore, this strategy protects heat-sensitive bioactive components such as proteins, peptides, unsaturated fatty acids, and fat-soluble vitamins from degradation and loss typically

caused by traditional high-temperature cooking, chemical fumigation, or preservative treatments. It effectively mitigates issues like protein denaturation, amino acid loss due to excessive Maillard reactions, and oxidative rancidity of functional lipids. This approach enables safe, green, low-loss preservation and quality maintenance of animal-derived products while maintaining or even enhancing their pharmaceutical value.

4 Microbial-derived food and medicine homology resources

Microbial-derived resources provide a particularly promising frontier for LTP because microorganisms are both highly responsive to physicochemical stress and highly amenable to directed functional reconstruction. Compared with plant- and animal-derived resources, microbial systems allow plasma effects to be translated more directly into strain improvement, community selection, metabolic flux redistribution, biomacromolecule modification, and industrial biomanufacturing efficiency. In this domain, the core value of plasma technology lies in its ability to generate controllable biological variation and structural modification without introducing foreign genes or persistent chemical residues. It can therefore serve as a bridge between physical mutagenesis, synthetic microbial ecology, fermentation engineering, and functional product development. The future direction should shift from empirical strain screening toward mechanism-guided and data-driven plasma bioprocessing, in which discharge parameters, microbial stress responses, omics-level metabolic networks, and final product bioavailability are systematically coupled to create high-yield, safe, green, and function-oriented microbial food and medicine homology products (Fig. 3).

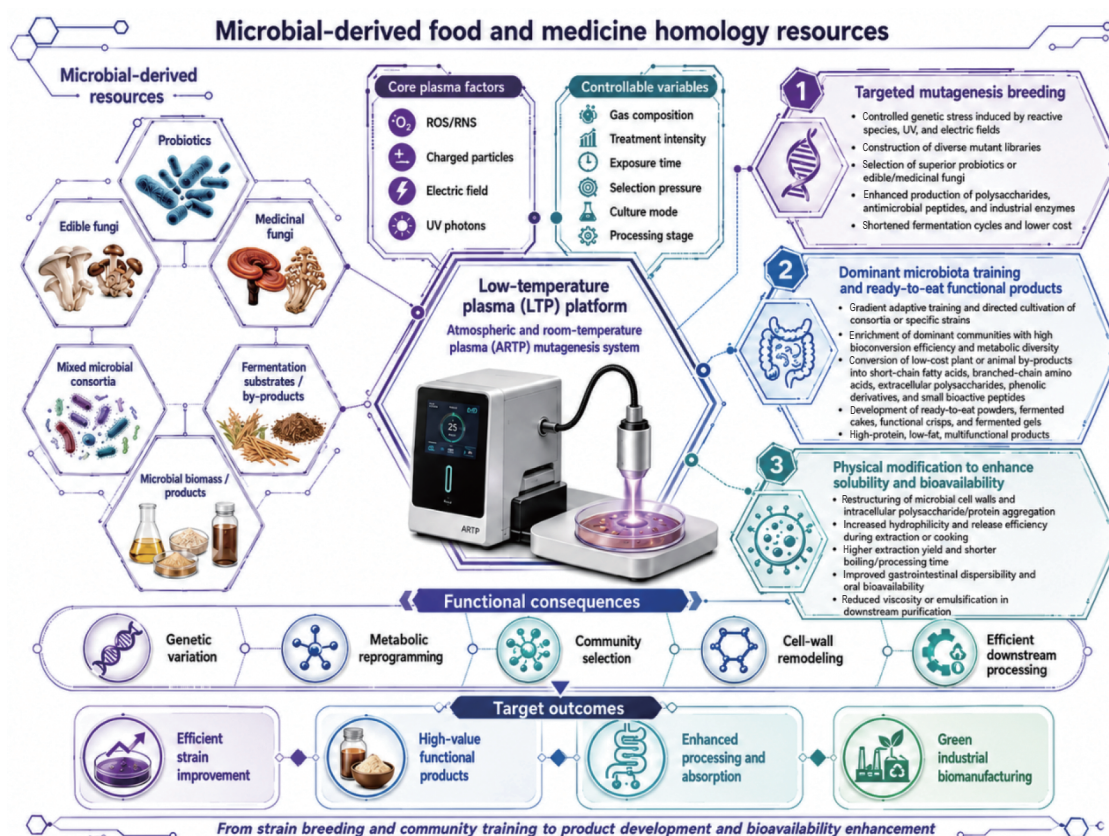


Figure 3 Conceptual schematic diagram of LTP application logic in microbial-derived food and medicine homology resources.

4.1 Targeted mutagenesis breeding

The reactive species, UV radiation, and electric field effects generated by LTP impose controlled genetic damage and repair stress on microbial cells, such as probiotics and edible fungi. This induces genetic variations, including point mutations, deletions, and genomic rearrangements, thereby enabling targeted mutagenesis breeding without the introduction of foreign genes^[49-52]. By modulating treatment intensity, gas composition, and exposure time, a diverse library of mutant phenotypes can be established. According to this library, superior mutant strains exhibiting significantly enhanced capacity for synthesizing target functional compounds can be selected. Within microbial-derived food and medicine homology resources, this strategy can effectively increase both the diversity and yield of functional substances. Examples include polysaccharides (β -glucans, mannans), antimicrobial peptides, and industrial enzymes (proteases, cellulases). Following plasma mutagenesis, target strains representing probiotics (*Lactobacillus*, *Bacillus*) and medicinal fungi (*Ganoderma*, *Hericium*) undergo metabolic reprogramming, redirecting metabolic flux from byproduct pathways toward target product synthesis. Compared to traditional chemical mutagens or UV mutagenesis, LTP offers higher mutation efficiency, safer and more controllable operation, and introduces no residual external mutagens. At the industrial level, this technology can significantly shorten fermentation cycles, reduce raw material consumption per unit of product, decrease production costs and energy use, while maintaining or even improving the specific activity and bioavailability of functional substances in the final product. This provides a novel pathway for the breeding and process optimization necessary for the efficient industrial utilization of microbial-derived products.

4.2 Dominant microbiota training and ready-to-eat functional products

LTP can be used for gradient adaptive training and directed cultivation of mixed microbial consortia or specific functional strains. The screening process for gradient stress-induced domestication should follow a stepwise workflow: Mild initial LTP exposure to generate selective pressure, recovery culture to permit survival and adaptation, serial subculturing under gradually increased plasma intensity or environmental stress, functional screening based on substrate utilization, metabolite yield, acid/bile tolerance, antioxidant capacity, and antimicrobial activity, and final validation by community profiling, metabolomics, and fermentation-performance assessment^[53,54]. During this process, community structure may be reshaped through competitive exclusion, cross-feeding, quorum sensing, organic-acid accumulation, bacteriocin production, extracellular-polysaccharide-mediated protection, and activation of shared stress-response networks. These interactions provide a mechanistic basis for enriching stable dominant consortia rather than selecting single strains only. The engineered microbial systems developed through this strategy can be further employed to produce ready-to-eat microbial-based foods and pharmaceuticals^[55,56].

For ready-to-eat fermented products, the retention of viable probiotics and functional metabolites during storage is a critical boundary condition. Shelf-life stability depends on water activity, oxygen exposure, packaging atmosphere, storage temperature, matrix composition, and protective agents used during drying or formulation. Freeze-dried microbial powders, fermented cakes, functional crisps, and fermented gels should therefore be evaluated

through viable cell counts, reactivation capacity, metabolite stability, sensory quality, and microbial safety over storage. Cryoprotectants, microencapsulation, oxygen-barrier packaging, low-moisture matrices, and cold-chain storage may be required to maintain probiotic activity and product functionality. This technological pathway integrates microbial breeding, fermentation engineering, and functional food design, representing an innovative platform extending the concept of food and medicine homology resources into the microbial domain, with the potential to develop a new generation of green, ready-to-eat bioproducts offering both nutritional support and disease prevention benefits.

4.3 Physical modification to enhance solubility and bioavailability

LTP physical modification can controllably reconstitute the cell wall structure and the aggregation state of intracellular polysaccharides and proteins in microbial-derived products. This significantly enhances their solubility and release efficiency during cooking, boiling, and high-temperature extraction processes^[57,58]. Plasma treatment increases the surface hydrophilicity and moderately reduces the rigidity of microbial cell walls. Consequently, intracellular active components, such as polysaccharide-peptidoglycan complexes, extracellular polysaccharides, and antimicrobial peptides, are more easily released into the aqueous phase. This substantially reduces the loss of active components typically caused by cell wall barriers during conventional thermal processing. In the preparation of products like decoctions, fluid extracts, and functional beverages, plasma pre-treatment can improve the extraction yield of active components per unit of raw material, while simultaneously shortening the cooking or boiling time and reducing the degradation of heat-sensitive functional compounds. At the digestive absorption level, the modified microbial components possess a smaller average particle size and improved gastrointestinal dispersibility. This allows them to more fully interact with digestive enzymes and be taken up by intestinal brush border epithelial cells, significantly enhancing the bioavailability of orally administered preparations. Furthermore, for subsequent purification processes utilizing crude microbial extracts as starting materials, plasma treatment can reduce the viscosity and degree of emulsification of the feed solution. This improves solid-liquid separation efficiency and the throughput of chromatographic media, thereby reducing the consumption of solvents and column packing materials. This physical modification strategy introduces no chemical solvents or enzymes, offers a clean and controllable process, and provides a green solution for enhancing efficiency across the entire value chain of microbial-derived products, from raw material processing to final absorption.

5 Discussion and future perspectives

The effects of LTP differ substantially among plant-, animal-, and microbial-derived food and medicine homology resources because their dominant response units are different. In plant systems, LTP primarily functions as a physical signal and surface-regulatory tool across the growth and post-harvest cycle, affecting seed vigor, stress adaptation, secondary metabolism, plant-surface microbiota, active-component retention, and waste valorization. In animal-derived systems, the major targets shift toward environmental biosecurity, feed protein/lipid modification, heme-related color chemistry, preservation of heat-sensitive nutrients,

and exposure control compatible with animal welfare. In microbial systems, LTP more directly affects genomic variation, cell-wall remodeling, membrane permeability, community succession, metabolic-flux redistribution, and fermentation efficiency.

Several common bottlenecks still restrict industrial translation. First, a unified parameter database is lacking, and species-, substrate-, and process-specific parameter windows remain incomplete. Second, microscopic interaction mechanisms between reactive particles and biomacromolecules are not fully resolved, particularly the dynamic binding, oxidation, cleavage, crosslinking, and conformational pathways involving proteins, polysaccharides, lipids, pigments, and secondary metabolites. Third, large-scale continuous equipment is insufficiently developed, making laboratory-scale results difficult to reproduce under industrial throughput. Fourth, safety and toxicological evaluation systems for LTP-processed foods and traditional Chinese medicinal materials remain incomplete. Fifth, online control technologies that connect LTP devices with smart agriculture, digital monitoring, and AI-based decision systems are still immature.

Future research should proceed along three implementation pathways. The first is to establish standardized LTP parameter systems and shared databases for food and medicine homology resources, including plasma source type, gas composition, discharge power or voltage, exposure time, sample geometry, moisture content, microbial load, active-component retention, and target functional outcomes. The second is to clarify microscopic interaction mechanisms by integrating metabolomics, transcriptomics, proteomics, microbial community sequencing, molecular simulation, and in situ detection of reactive species. The third is to build interdisciplinary platforms that couple LTP with smart agriculture, precision nutrition, circular economy, digital twins, and AI-driven online parameter optimization, thereby enabling adaptive, controllable, scalable, and safety-oriented industrial application.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be requested from the corresponding author upon request.

Conflicts of interest

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

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Author contribution statement

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Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

During the preparation of this work, the authors used ChatGPT 5.1 version in order to generate Figure 1, 2, 3 and graphical abstract. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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