附表 植物蛋白凝胶常见的分类方式及其特点

Supplementary table The common classification methods and characteristics of plant protein gels

分类依据 **Basis for classification**	**凝胶类型** **Gel type**	**主要诱导条件/机制** **Main induction condition/Mechanism**	**关键作用力** **Key interactions**	**典型实例、蛋白来源与核心特点** **Typical examples, protein sources and core characteristics**
形成诱因 Formation inducement	热诱导凝胶 Heat-induced gel	加热使蛋白质变性、伸展并聚集 Heat induces protein denaturation, unfolding and aggregation	疏水作用、氢键、二硫键 Hydrophobic interaction, hydrogen bond, disulfide bond	最常见。如大豆蛋白制作的传统热凝豆腐，通常为热不可逆凝胶，质构受温度、浓度影响大[1] Most common type. Traditional heat-set tofu made from soybean protein, usually thermo-irreversible gel; texture greatly affected by temperature and protein concentration[1]
	酶诱导凝胶 Enzyme-induced gel	酶（如 MTGase）催化蛋白质间形成共价交联 Enzymes (*e.g.*, MTGase) catalyze covalent cross-linking between proteins	共价键（异肽键）、非共价力辅助 Covalent bond (isopeptide bond), assisted by non-covalent forces	凝胶强度高、热稳定好。可通过酶与热处理的组合精密调控质构，用于高端植物肉。如芸豆、红豆、绿豆和大豆类分离蛋白[2] High gel strength and excellent thermal stability. Texture can be precisely controlled by combining enzyme and heat treatment, applied in high-end plant-based meat. Examples include isolated proteins from kidney bean, adzuki bean, mung bean and soybean[2]
	离子诱导凝胶 Ion-induced gel	二价阳离子（如 Ca^{2+} 、Mg^{2+} ）与带负电基团“架桥” Divalent cations (*e.g.*, Ca^{2+} , Mg^{2+}) act as “bridges” with negatively charged groups	离子键（“盐桥”）、疏水作用 Ionic bond (salt bridge), hydrophobic interaction	如大豆蛋白制作的卤水/石膏豆腐。凝胶速度较快，结构可能较粗糙，热不可逆[2] Such as brine/gypsum tofu made from soybean protein. Fast gelation rate, relatively coarse structure, thermo-irreversible[2]
	酸诱导凝胶 Acid-induced gel	酸化（如 GDL）使 pH 降至蛋白等电点附近 Acidification (*e.g.*, GDL) reduces pH close	静电作用（减弱）、疏水作用、氢键 Reduced electrostatic interaction, hydrophobic interaction, hydrogen bond.	凝胶质地通常较柔软[2]，如大豆蛋白制作的内酯豆腐、植物基酸奶 Generally soft gel texture[2], *e.g.*, silken tofu and

		to the isoelectric point of proteins.		plant-based yogurt made from soybean protein
质地与外观 Texture and appearance	透明/半透明凝胶 Translucent/Semi-translucent gel	蛋白质均匀有序自组装（如形成纳米纤维），结构均一，光散射弱 Protein undergoes uniform and ordered self-assembly (*e.g.*, formation of nanofibers), resulting in homogeneous structure with weak light scattering	氢键、静电作用等分子间有序作用 Ordered intermolecular interactions such as hydrogen bonds and electrostatic interactions	特定条件下形成：如某些芸豆蛋白在低 pH、低离子强度下长时间加热，可通过自组装形成纳米纤维，最终形成结构均匀的透明凝胶[2, 3] Formed under specific conditions: for example, certain kidney bean proteins can self-assemble into nanofibers upon prolonged heating at low pH and low ionic strength, eventually forming transparent gels with uniform structure[2, 3]
	不透明凝胶 Opaque gel	蛋白质快速、无序聚集，形成不均一网络，光散射强 Rapid and disordered aggregation of proteins forms a heterogeneous network with strong light scattering	疏水作用、二硫键等导致随机聚集 Random aggregation driven by hydrophobic interactions, disulfide bonds, *etc*	最常见的状态。多数热诱导、离子诱导凝胶属此类，如常见的大豆蛋白制作的豆腐、热凝固蛋白块 The most common state. Most heat-induced and ion-induced gels fall into this category, such as conventional tofu and heat-set protein gels prepared from soybean protein
组成与结构 Composition and structure	单一蛋白凝胶 Single protein gel	单一来源植物蛋白形成的凝胶网络 Gel network formed by plant protein from a single source	取决于诱导方式和蛋白本身 Depends on the induction method and the protein itself	基础形式，性能受限于该蛋白的特性（如大豆、豌豆、小麦面筋凝胶） Basic form, whose properties are limited by the characteristics of the protein (*e.g.*, gels from soybean, pea, wheat gluten)
	复合凝胶 Composite gel	蛋白质与多糖/油脂等通过分子间作用力共同构成 Co-constructed by proteins and polysaccharides/lipids via intermolecular forces	静电相互作用、氢键、缠绕等 Electrostatic interactions, hydrogen bonds, chain entanglement, *etc*	可显著改善性能：如增强强度、持水性或提供环境响应性（智能递送）。如大豆、玉米醇溶蛋白与油脂制备的乳液凝胶[4] It can significantly improve functional properties, such as enhancing gel strength and water-holding capacity, or providing environmental responsiveness (intelligent delivery). Such as emulsion gels prepared from soybean protein, zein with lipids[4]

分散介质 Dispersion medium	水凝胶 Hydrogel	以水为连续相的凝胶网络，水被束缚在网络中 Gel network with water as the continuous phase, in which water is immobilized within the network	氢键、静电作用、离子键等，主要在水相中作用 Hydrogen bonds, electrostatic interactions, ionic bonds, *etc*., mainly acting in the aqueous phase	最普遍的类型。几乎所有传统蛋白凝胶（如大豆蛋白制作的豆腐）都属于水凝胶，其性能高度依赖网络的持水能力 The most common type. Almost all traditional protein gels (*e.g.*, tofu made from soybean protein) are hydrogels, whose properties highly depend on the water-holding capacity of the network
	油凝胶 Oleogel	以液态油为连续相，由蛋白质形成的三维网络将油结构化 A three-dimensional network formed by proteins with liquid oil as the continuous phase, which structures the oil	蛋白质在油相中的自组装、疏水相互作用，或蛋白质与凝胶剂的协同 Self-assembly and hydrophobic interactions of proteins in the oil phase, or synergy between proteins and gelling agents	用于构建低饱和脂肪的固态脂质[5]，如植物基黄油、减脂涂抹酱。能提供良好的口感和热稳定性。如马铃薯、大豆、豌豆蛋白等 Used to construct solid lipids with low saturated fat content[5], such as plant-based butter and low-fat spreads. It provides good mouthfeel and thermal stability. Examples include potato, soybean and pea proteins
	气凝胶 Aerogel	通过特殊干燥（如超临界干燥）去除水凝胶中的液体，保留其多孔网络结构的固体材料 Solid material obtained by removing liquid from hydrogels via special drying methods (*e.g.*, supercritical drying) while retaining the porous network structure	凝胶干燥前网络的机械强度决定其最终结构完整性 The mechanical strength of the network before gel drying determines the final structural integrity	具有极高的孔隙率、极低的密度和优异的比表面积。主要用于非食品领域，如吸附剂、隔热材料或作为生物活性物质的超高负载载体，如大豆、小麦、豌豆、甜菜蛋白等[5-7] Characterized by extremely high porosity, ultra-low density and excellent specific surface area. Mainly applied in non-food fields, such as adsorbents, thermal insulation materials, or ultra-high loading carriers for bioactive substances. Examples include soybean, wheat, pea and sugar beet proteins[5-7]
界面性质 Interfacial properties	界面凝胶 Interfacial gel	蛋白质在油-水或气-水界面吸附、交联形成的稳定薄膜或网络 Stable films or networks formed by protein adsorption and cross-linking at oil-water or	核心驱动力为疏水相互作用、静电、界面二硫键、氢键、离子键等共同调节、强化界面膜结构及连续相中的网络交联	乳液凝胶、泡沫凝胶。用于稳定高内相乳液、制作轻质多孔食品及结构化脂肪替代物，如大豆、小麦、豌豆蛋白等，具备可调控的质构和润滑感；是脂溶性、疏水性活性物（如β-胡萝卜素）的优良载体[2, 4]

		air-water interfaces	The core driving forces are synergistically regulated by hydrophobic interactions, electrostatic interactions, interfacial disulfide bonds, hydrogen bonds and ionic bonds, which strengthen the interfacial membrane structure and network cross-linking in the continuous phase	Including emulsion gels and foam gels. Used for stabilizing high internal phase emulsions, preparing lightweight porous foods and structured fat substitutes. Examples include soybean, wheat and pea proteins, with tunable texture and lubricity. It is an excellent carrier for lipophilic and hydrophobic bioactive compounds (*e.g.*, β-carotene)[2, 4]
动力学特性 Kinetic properties	快速凝胶 Rapid gelation	条件剧烈/瞬时变化或蛋白对环境变化相应迅速。通过添加高浓度盐、强酸或骤然改变温度等强烈扰动，使蛋白质迅速、大规模地发生非特异性聚集 Caused by drastic/instant changes in conditions or rapid response of proteins to environmental alterations. Strong disturbances such as addition of high-concentration salts, strong acids, or abrupt temperature changes induce rapid and non-specific aggregation of proteins on a large scale	离子键、疏水相互作用（在变性后快速主导） Ionic bonds, hydrophobic interactions (rapidly dominant after denaturation)	在秒/分钟级内快速形成，网络结构可能不均匀。如卤水点豆腐（大豆蛋白），适用于快速定型的生产工艺 Gel forms rapidly within seconds to minutes, with a potentially heterogeneous network structure. *e.g.*, brine-induced tofu (soybean protein), suitable for production processes requiring rapid setting
	慢速/自组装凝胶 Slow/Self-assembled gelation	条件缓慢/可控变化。通过缓慢酸化、酶解或温和热处理，使蛋白质有充分时间进行部分展开、重排和有序聚集，形成更精细的结构 Caused by slow/controllable changes in conditions. Mild acidification, enzymatic hydrolysis, or gentle heat treatment allows sufficient time for partial protein unfolding,	氢键、静电作用、疏水相互作用（在长时间尺度下有序进行） Hydrogen bonds, electrostatic interactions, and hydrophobic interactions (occurring in an ordered manner over a long timescale)	凝胶速度慢，结构均一有序，通过控制条件变化速率（如 pH 下降速度），可精准调控最终凝胶的质地与功能[8]。如 GDL 内酯豆腐（大豆蛋白）、某些透明纳米纤维凝胶（如小麦、玉米醇溶蛋白） Slow gelation rate, with uniform and ordered structure. The texture and functionality of the final gel can be precisely regulated by controlling the rate of condition changes (*e.g.*, pH reduction rate)[8]. Such as,

		rearrangement, and ordered aggregation, leading to finer structures		GDL-induced silken tofu (soybean protein), certain transparent nanofiber gels (*e.g*., wheat protein, zein)
网络作用力本质（对应环境稳定性） Nature of network interactions (Corresponding to environmental stability)	物理交联凝胶/可逆凝胶 Physically cross-linked gel/Reversible gel	由温度、pH、离子强度等物理化学条件变化诱导 Induced by changes in physicochemical conditions such as temperature, pH, and ionic strength	非共价力：静电、疏水、氢键、范德华力 Non-covalent interactions: electrostatic, hydrophobic, hydrogen bonds, van der Waals forces	作用力较弱、可逆。凝胶性质易受环境变化影响。多数酸、热诱导凝胶含此类作用。如大豆分离蛋白、豌豆、绿豆、米糠蛋白等 Weak and reversible interactions. Gel properties are susceptible to environmental changes. Most acid-induced and heat-induced gels involve such interactions. Examples include soybean protein isolate, pea, mung bean, rice bran protein, *etc*
	化学交联凝胶/不可逆凝胶 Chemically cross-linked gel/Irreversible gel	涉及不可逆的共价键形成。 Involves the formation of irreversible covalent bonds	共价键：二硫键、酶促异肽键、美拉德后期交联等。 Covalent bonds: disulfide bonds, enzyme-catalyzed isopeptide bonds, advanced Maillard cross-linking, *etc*	网络稳定、强度高。如酶诱导凝胶、面团中的二硫网络。如小麦面筋蛋白、大豆分离蛋白等 Stable network with high strength. Examples include enzyme-induced gels and disulfide networks in dough. Representative proteins: wheat gluten, soybean protein isolate, *etc*

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