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Mini-review of plant-based protein gel source material and gelation induction

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ABSTRACT

People in low- and middle-income countries view plant protein as a cost-effective alternative dietary source. Because of their practical qualities, plant proteins are beneficial for functional food applications. One of the functional characteristics of plant protein that may be further enhanced is the capacity to produce plant-based gel, which can be utilized as a meal textural modification for particular populations like older adults, dysphagia patients, and vegetarians/vegans. However, the features of the plant protein source, which heavily relies on gel induction technology, provide a major obstacle to the creation of food gel from plant-based materials. For a plant-based gel product, four plant groups: legume, cereal, pseudocereal, and vegetable tuber are recognized as possible protein sources. Denaturation, aggregation, and cross-linking are the three main processes by which this protein source creates gel. Aggregation is crucial in determining the gel's physicochemical characteristics. To guarantee the appropriate aggregation for the creation of the desired protein gel formation, induction technology is crucial. In order to denature plant protein for appropriate aggregation, this technology primarily uses physical techniques that either operate without heat (non-thermal technology) or employ heat (thermal technology). For improved plant-based gel quality, the chemical method of pH shifting and ionic strength treatment can be used with the physical method to address the problem of plant protein solubility. A high-quality plant-based gel is a viable food texture modification product that can be produced using an appropriate plant protein source and efficient induction technique.

Keywords: cereal; gelation; legume; plant protein; pseudocereal

INTRODUCTION

A plant-based diet has recently become a worldwide trend in food preference choices (Hargreaves et al., 2023). People choose a plant-based diet for its positive health benefits (Szabo et al., 2021; Triandini et al., 2022). The plant-based diet has a beneficial effect on combating several diseases and metabolic disorders, including cardiovascular disease (Salehin et al., 2023), stroke (T. Campbell, 2017), type II diabetes (T. M. Campbell et al., 2023), dyslipidemia (Lee et al., 2021), hypertension (Alexander et al., 2017), disabling diseases (Greger, 2015), overweight and obesity (Turner-McGrievy et al., 2017). A plant-based diet is also considered a choice when people are concerned about ethical issues with animal-based food (Klapp et al., 2022). Furthermore, plant-based products promote sustainability and have little environmental impact

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(Perignon et al., 2017). Sensory evaluation also confirms that this product is well accepted and promising to be further developed (Triandini et al., 2024).

Protein is the major compound in plant-based food that is valuable for its positive health benefits (Ahnen et al., 2019). Plant protein is considered a sustainable alternative nutrient source that is economically affordable for the populations in low and middle-income countries (Gradl et al., 2024). The diversity of plant sources and characteristics makes plant protein a valuable ingredient to develop a variety of food products (Q. Fu et al., 2023; Wangiyana et al., 2024). Moreover, the functional properties of plant protein give a positive value to provide functional uses in food applications through processes such as solubilization, emulsification, foaming, and dough formation (Tan et al., 2023).

One of the functional properties of plant protein that has the potential to be further developed is the gelation capacity (Hettiarachchy et al., 2013). Food gel based on the gelation capacity of plant protein is a promising food product that has various applications (Wangiyana & Triandini, 2023; Zha et al., 2021). This product is soft and tender, which makes it easy to chew for the older adult population with mastication problems (Aguilera & Park, 2016). The cohesiveness of food gel makes it safe to be swallowed by dysphagia patients who have difficulty swallowing (Cichero et al., 2017). This ingredient also has a suitable texture to be processed into meat analogue product for vegetarian and vegan (H.-G. Zhu et al., 2021).

Food gel production from plant-based materials have several challenges for improving product quality. The characteristic of gel depends on the gelling capacity of the plant source material, especially its main protein storage (Hettiarachchy et al., 2013). Most plants contain Globulins as the main protein storage, which need induction to form a gel when it is suspended in aqueous solution (Nicolai & Chassenieux, 2019). The purpose of this study is to elaborate on the potential plant source material of plant-based gel and its gelation induction technology for product improvement.

MECHANISM OF PROTEIN GEL FORMATION

The gelation of a protein molecule is a transformation of its molecule from a sol state into a gel-like structure through physical or chemical processes. In terms of rheological measurement, the gel can be defined as a viscoelastic material for which G' (storage modulus) is greater than G" (loss modulus) and for which both G' and G" are almost independent of frequency. In terms of non-rheological measurement, gel properties include protein crosslinking, denaturation, extended protein chains, gel networks, opacity, and thermal reversibility (Hettiarachchy et al., 2013).

Protein gel formation generally involves 3 primary steps: denaturation, aggregation, and cross-linking. Applying physical or chemical treatment can disrupt the tertiary and secondary structure of a protein, causing its unfolding, which is called "denaturation". Unfold proteins can then interact with each other to form aggregates. The aggregates form a 3-dimensional cross-linking network leading to gel formation (Ma & Chen, 2023).

Aggregation is the essential step in protein gel formation that determines the physicochemical properties of the gel (Cao & Mezzenga, 2020). There are four major aggregation-derived factors in protein gel, including hydrophobic interactions, electrostatic interactions, disulfide bond formation, and hydrogen bond (**Table 1**).

Table 1.
Major aggregation factor for several plant proteins

Plant protein	Major aggregation factor for gel formation	Reference
Maize protein	Disulfide bond for gel stiffness and hydrogen bond for gel structure	(X. D. Sun et al., 2015)
Potato protein	Disulfide bond linkage, which forms a higher molecular weight polymer	(Z. K. Zhao et al., 2018)
Barley protein	Disulfide bond crosslinking and hydrophobic interaction	(J. Zhao et al., 2011)
Sweet potato protein	The disulfide bond, which is significantly higher than the hydrophobic and hydrogen bonds	(Arogundade et al., 2012)
Rice protein	Exposing the free sulfhydryl group into a disulfide bond, followed by hydrophobic interaction and hydrogen bonding	(Lian et al., 2024)
Lentil protein	Fibrillar aggregates with hydrophobic interaction and disulfide bond influence the strong gel formation.	(Jo et al., 2020)
Chickpea protein	Electrostatic interaction, hydrophobic interaction, and hydrogen bond are the main drivers of protein aggregation to form a gel network.	(Lin et al., 2024)
Pea protein	Electrostatic and hydrophobic interactions are involved in protein aggregation and initial gel formation, while the hydrogen bond is responsible for gel stiffness.	(X. D. Sun & Arntfield, 2012)
Mung bean protein	Hydrophobic interactions and disulfide bonds are the main forces for gel formation.	(Wang et al., 2023)

PLANT MATERIAL AND THE GELATION CAPACITY

Protein gel from plant-based material has been recently developed and has promising potency as a food textural modification product (Floret et al., 2023; Wangiyana et al., 2025). There are several advantages of using plant-based materials as a source of protein gel. Firstly, plant-based materials have better environmental sustainability due to a low carbon footprint and low resource demand (Kesumajayadi et al., 2025; Xu et al., 2021). Secondly, plant-based materials have certain health benefits, including low cholesterol, low allergy risk, and high fibre content (P. Zhang, 2023). Thirdly, plant-based materials are considered to have an advantage in economic value due to low production costs (Aschemann-Witzel et al., 2021). Lastly, plant-based materials are considered a better choice when people are concerned about ethical issues with animal-based materials (Klapp et al., 2022).

Plant-based materials have diverse protein sources, offering protein gel with various flavours, textures, and nutritional profiles. This diversity makes protein gel from plant-based materials versatile and promising for development. Plants with high protein content can generally become the source of protein gel (Sim et al., 2021). However, several studies used plant-based materials only from 4 groups, including legume, cereal, pseudocereal, and vegetable tuber (**Table 2**).

Table 2.

Plant-based materials as the protein gel source

Class	Plant	Main storage protein	Gelation potency	Reference
Legume	Soybean (*Glycine max*)	Glycinin (11S Globulin)	Gelation properties can be improved by ultrasound, microwave, and high-pressure.	(Zheng et al., 2022)
	Pea (*Pisum sativum*)	Legumin (11S Globulin)	Protein gelation can be improved by applying ionic strength at low pH.	(Tanger et al., 2022)
	Lupin (*Lupinus* sp.)	Conglutin (7S Globulin)	Gelation property can be improved by low heat and chemical-free novel protein modification.	(Al-Ali et al., 2021)
	Red bean (*Phaseolus angularis*)	Phaseolin (7S Globulin)	It has a suitable gelation property, which can be improved by heat and salt induction.	(Meng & Ma, 2002)
	Broad bean (*Vicia faba*)	Vicilin (7S Globulin)	It has the potency to be applied in acidic food, where the gel strength can be maintained.	(Freitas et al., 2000)
	Chickpea (*Cicer adiantum*)	Legumin (11S Globulin)	It has an excellent gelling property, which can be improved by adjusting pH, sodium, and calcium chloride.	(T. Zhang et al., 2007)
	Pigeon pea (*Cajanus cajan*)	Legumin (11S Globulin)	Have an excellent thermal gelation affected by pH and ionic strength	(Fernández Sosa et al., 2023)
	Cowpea (*Vigna unguiculata*)	Vicilin (7S Globulin)	Good gelation potency, which can be improved by pH and salt concentration	(Ragab et al., 2004)
	Lentil (*Lens culinaris*)	Legumin (11S Globulin)	Protein gel improvement for food texturization by heating and adjusting pH	(Jo et al., 2020)
	Peanut (*Arachis hypogaea*)	Arachin (11S Globulin)	Good potency of protein gelation, which is improved by ionic strength and enzymatic pre-treatment	(Basse et al., 2020)
	Black bean (*Phaseolus vulgaris*)	Phaseolin (7S Globulin)	Suitable protein gelation properties that can be improved by ultrasound treatment	(L. Li et al., 2020)
	Mung bean (*Vigna radiata*)	Phaseolin (7S Globulin)	It has a suitable gelation property, which can be improved by ultrasound treatment.	((Wang et al., 2023)
	Alfalfa (*Medicago sativa*)	Convicilin (7S Globulin)	Protein gelation improves by heat treatment (60 °C – 77 °C) at pH 7	(P. Lamsal et al., 2005)
	Hyacinth bean (*Lablab purpureus*)	Vicilin (7S Globulin)	Protein gelation improves with heating treatment	(Purwanti et al., 2024; Subagio, 2006)
Cereal	Rice (Oryza sativa)	Glutelin	Gel formation in rice protein depends on base concentration and heating, 50 – 80	(Lian et al., 2024)

	Maize (*Zea mays*)	Zein	Protein gelation involving molecular forces, which were determined by various reagents	(X. D. Sun et al., 2015)
	Sorghum (*Sorghum bicolor*)	Kafirin	Protein gelling capacity in Kafirin film formation using a mixture of glycerol, PEG 400, and lactic acid.	(L. S. da Silva & Taylor, 2005)
	Oat (*Avena sativa*)	Avenins	Heating (90 °C), alkaline conditions (pH 8), and enzymatic modification induce gel formation, which improves protein aggregation.	(Brückner-Gühmann et al., 2021)
	Rye (*Secale cereale*)	Secalins	Gel formation occurs in high alkaline conditions (pH 12) with a minimum of 3–4 freeze-thaw cycles.	(Lim et al., 2013)
	Barley (*Hordeum vulgare*)	Prolamins and Glutelins	Ultrasound treatment, pH shifting, and deamidation can improve barley protein's colloidal stability and aggregation.	(Silventoinen & Sozer, 2020)
Pseudocereal	Amaranth (*Amaranth* Sp.)	Albumin	Protein gel water holding capacity increases by heating at 80-90 °C and decreases with acid treatment. The ideal protein concentration is >7%, w/v.	(Bejarano-Luján et al., 2010)
	Quinoa (*Chenopodium quinoa*)	Globulin	Protein gelling capacity improved by acid (pH 3.5), heating (70 – 90 °C), and addition of divalent ions (Ca^{2+} and Mg^{2+})	(Kaspchak et al., 2017)
	Buckwheat (*Fagopyrum tataricum*)	Albumin and Globulin	Mild protease hydrolysis and ultrafiltration induced natural buckwheat self-assembly peptides, which affect the hydrogel-forming ability	(Yu et al., 2022)
	Chia seed (*Salvia hispanica*)	Globulin	Alkaline extraction (pH 10 – 12) and temperature improve protein aggregation ability, foam stability, and water absorption capacity.	(López et al., 2018; Timilsena et al., 2016)
Vegetable tuber	Potato (*Solanum tuberosum*)	Patatin (glycoprotein)	Protein gelling capacity improved by temperature (minimum 45-50 °C), high pressure (300-500 MPa), and acidic conditions (pH 3)	(Y. Fu et al., 2020; Katzav et al., 2020)
	Sweet potato (*Ipomoea batatas*)	Sporamin (lectin)	Protein gelling capacity improved by heat (76 – 79 °C), high pressure (400 MPa), and alkali conditions (pH 9.0)	(Arogundade et al., 2012; Z. K. Zhao et al., 2018)

Legumes have excellent plant protein quality, making this group the priority source of protein gel (Tiong et al., 2025). Protein content in legumes varies depending on the species but is expected on average, with a range of 20% - 30% per 100 grams (Jha et al., 2022). With this high protein content, various plant species in the legume group can be chosen as sources of protein gel with excellent gelling capacity (Ge et al., 2023). Legumes are also considered a sustainable protein source, but have become underutilized, so the exploration of protein gel using this material should be increased (Semba et al., 2021). Further appropriate food processing in legume protein sources can potentially increase the protein intake and its digestibility (King et al., 2024).

Cereals have considerably lower protein content compared to legumes. However, this group has higher fibre content, which can provide digestive benefits (Serna Saldívar & Hernández, 2020). Allergy considerations should be noted when using cereal as a source material for protein gel, especially wheat. This issue occurs because older adults tend to have an increased risk of gluten allergy, which can cause coeliac disease (Bathrellou et al., 2018). The challenge of finding a processing method to lower the risk of gluten allergy issues might be promising for future research when wheat protein is used as a protein gel source material (Dong et al., 2021).

Pseudocereals are plant-based materials that resemble grains (like cereal) but are classified differently based on taxonomy studies. Several plants in this group have high protein content, making them excellent protein gel sources, including amaranth, quinoa, buckwheat, and chia seeds (Henrion et al., 2020). However, some studies explore the mucilage potency of pseudocereals more than their potency as a gel protein source (Ribes et al., 2022; Solanki et al., 2024).

Potato and sweet potato are the two plants in the tuber group that have been widely used as protein gel source material (Arogundade et al., 2012; Y. Fu et al., 2020). Potato tuber contains higher crude protein than sweet potato, which shows a higher potency as a protein gel source (Senanayake et al., 2013; Wichrowska & Szczepanek, 2020). High-pressure treatment can improve potato and sweet potato protein gelling capacity (Katzav et al., 2020).

PROTEIN GELATION INDUCTION

The most common physical method for protein gelation is thermal technology (**Figure 1**). The basic principle of this technology is transferring heat from the instrument to the food sample, which affects its protein molecular structure (Singh et al., 2017). Applying a temperature range mostly from 70 °C to 90 °C can disrupt the tertiary and secondary structure of the protein, causing its unfolding, which is called "denaturation." Unfold proteins can then interact to form aggregates (Ma & Chen, 2023). The aggregates form a 3-dimensional network leading to gel formation (Hettiarachchy et al., 2013).

Heat treatment is commonly used to induce plant globulin gelation, the primary storage protein in legumes (Amagliani & Schmitt, 2017). The temperature level in the gelation process affects the protein aggregation and stabilisation, which becomes the main parameter of gel strength (Nicolai & Chassenieux, 2019). Several legume species can be classified into high, medium, and low gel strength based on the gelation ability under heat treatment (Ge et al., 2023). Mixing different species of legumes under heat treatment can also be a good option for adjusting the techno-functional properties and nutritional characteristics of protein gel (Guidi et al., 2022).

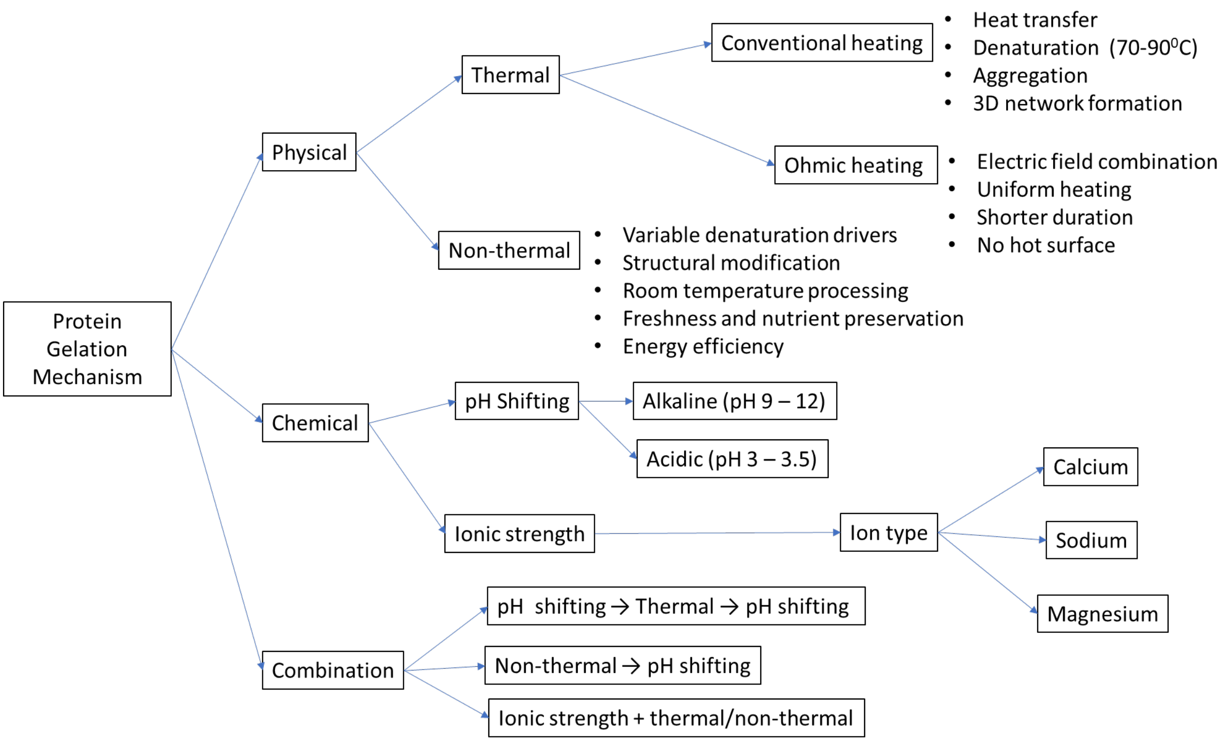

Figure 1. The summary of technology to enhance the gelation of plant-based material

Advanced heating has been developed to increase the efficiency of heating treatment. One of the advanced heating technologies that combines heating and an electric field used for plant-based protein modification is ohmic heating (dos Santos et al., 2024). This processing method has improved certain parameters compared to conventional heating methods, including shorter heating duration, avoiding hot surfaces, reducing temperature gradients, and achieving uniform heating (Jaeger et al., 2016). The efficiency of ohmic heating on food textural modification depends on optimizing pre-heating temperature, processing time, and electric field application (Gavahian et al., 2019).

Food processing technology that does not use direct heating to the sample is later called "non-thermal" technology (Chacha et al., 2021). This technology has emerged recently as an alternative method for food processing and preservation (F. V. M. Silva & Oey, 2023). In non-thermal technology, food is processed near room temperature, which can decrease the damage risk of heat-sensitive nutrients in food material (Jadhav et al., 2021). Food processing using non-thermal technology requires a short treatment duration, keeping it fresh and less change compared with traditional heating treatment, which requires a longer treatment duration (Z. H. Zhang et al., 2019). Non-thermal technology in food processing is also considered environmentally friendly in terms of energy efficiency, water savings, and low emissions (Pereira & Vicente, 2010). These advantages show the promise of non-thermal technology applications in food processing (Safwa et al., 2023).

Non-thermal technologies can modify the structure and functionality of proteins, including gelation (Barbhuiya et al., 2021). Non-thermal technology has various protein gelation mechanisms compared to thermal technology, which does not involve high temperature as the main driver for denaturing the native form of protein (Venkateswara Rao et al., 2023). Different non-thermal technologies have different denaturation mechanisms responsible for unique plant-based protein gel structure and functionality (Dash et al., 2024).

Physical treatment (thermal and non-thermal) can be combined with chemical treatment for plant-based protein gelation (Ma & Chen, 2023). Chemical treatment can improve protein gelation when using plant-based materials, especially because plant protein isolate commonly has insoluble particles that affect gel quality (Janssen et al., 2024). Two chemical treatments commonly conducted in plant-based protein gelation are pH sifting and ionic strength (Tanger et al., 2022).

The main principle of the pH shifting process is to treat protein isolate under extremely alkaline or acidic conditions, followed by adjusting pH to an isoelectric point or to neutral pH (Z.-X. Tang et al., 2021). Exposing protein to extreme pH conditions far below or above the isoelectric point (pi) can promote charge repulsions. Neutralisation after extreme pH treatment can produce aggregates with excellent emulsifying and foaming properties, which is considered a good gel quality (J. Jiang et al., 2018).

Plant-based proteins commonly have a particular pH value for pH-shifting treatment. Several plant proteins from the legume group can improve their gel property quality by alkaline pH shifting treatment at pH 12, including mung bean protein (Jeong & Cho, 2024), soy protein (P. Sun et al., 2023), and pea protein (P. Zhu et al., 2021). Other legumes can be treated with alkaline pH shifting at different effective pH levels, including peanut protein at pH 10 (J. Li et al., 2020) and chickpea protein at pH 9 (Q. Tang et al., 2024). Acid pH shifting treatment can also be conducted in several plant-based protein gelations, including quinoa protein at pH 3.5 (Kaspchak et al., 2017) and potato protein at pH 3 (Katzav et al., 2020).

The main principle of ionic strength treatment for protein gelation is adjusting the concentration of ions (salt) in protein solution, which affects the electrostatic interaction between protein molecules (L. Jiang et al., 2015). Calcium is an ion that has been widely used to improve protein gelation from plant-based materials, including cowpea protein (Peyrano et al., 2022), potato protein (Wannasin et al., 2024), soy protein (Peng et al., 2022), pea protein (Ren et al., 2024), amaranth protein (Marinacci et al., 2024), and mung bean protein (Israkarn et al., 2022). Other ions commonly used to improve plant-based protein gelation are sodium (Chen et al., 2018) and magnesium (Q. Zhu et al., 2017).

CONCLUSION

Through the four main stages of the gel formation mechanism (denaturation, aggregation, and cross-linking), legumes, cereals, pseudocereals, and vegetable tubers can be utilized as a protein source for plant-based gel due to their exceptional gelation ability. Plant proteins are often denatured for appropriate aggregation using physical techniques that either employ heat (thermal technology) or do not (non-thermal technology). To improve the quality of plant-based gel, the physical method can be combined with the chemical method through pH shifting and ionic strength treatment.

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