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Germination as a cost-effective processing strategy for enhancing industrial value of legume proteins

Yingjinzhu Wu , Weon-Sun Shin *

Department of Food and Nutrition, College of Human Ecology, Hanyang University, South Korea

A R T I C L E I N F O

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A B S T R A C T

Legumes are promising plant-based protein sources, yet their use is constrained by antinutritional factors, weak functionality, off-flavors, and allergenicity. Germination has gained attention as a low-cost, resource-efficient, and scalable method that enhances nutritional quality, functional properties, and safety compared with conventional physical, chemical, or biological treatments. This review synthesizes research from 2015 to 2025 on how germination modifies legume composition and protein properties, focusing on nutritional enhancement, functional improvements, sensory changes, allergenicity reduction, and industrial applicability. This focused review particularly emphasizes how germination-induced endogenous enzymatic activity restructures legume proteins and thereby improves techno-functional performance relevant to food processing. Germination improves protein digestibility, solubility, emulsification, antioxidant capacity, and bioactive compound content, while significantly reducing phytic acid, tannins, and IgE-binding proteins. It also offers advantages in energy efficiency, environmental sustainability, and accessibility. However, challenges remain in batch consistency, microbial safety, and sensory acceptance. With proper standardization and HACCP integration, germination represents a practical and sustainable strategy to enhance legume utilization, particularly for plant-based meat analogues requiring improved functionality and milder flavor profiles.

1. Introduction

The global food system faces urgent challenges in meeting protein demand sustainably. Animal-based proteins, although of high-quality, are resource-intensive, environmentally burdensome, and associated with health risks (Willett et al., 2019). The producing of 1 kg of animal protein requires up to 26 times more water and 17 times more land than of plant proteins production (Pimentel & Pimentel, 2003). Meanwhile, global meat consumption continues to rise, necessitating the diversification of protein sources.

Legumes encompass over 13,000 species in the Fabaceae family, provide 18–25% of protein along with dietary fiber, polyphenols, and other bioactive compounds. Commonly exploited legumes include soybeans, chickpeas, peas, lentils, and dry beans, whereas species such as lima beans, pigeon peas, and Bambara groundnut remain underutilized niche crops (X. Zhang, Zhang, et al., 2024). According to FAOSTAT data (2023), soybeans dominate global production, while underutilized legumes are largely confined to Africa and Asia (Fig. 1), reflecting disparities in production and consumption. Expanding the value of such crops through appropriate processing could address both nutrition gaps and regional protein equity. In addition to legumes, cereals, oilseeds, and pseudocereals have also been explored as plant protein sources, however, these materials are less frequently investigated in germination-based modification studies due to differences in protein composition and endogenous enzymatic activity (W. Zhang, Zhang, et al., 2024)

Despite their nutritional potential, legumes face constraints that limit application in high-value formulations. Antinutritional compounds (phytic acid, tannins, protease inhibitors), allergenic proteins, and off flavors reduce nutritional quality and consumer acceptance (Kuswaha et al., 2021). Techno-functional limitations—lower solubility, emulsification, foaming, and gelling compared to animal proteins—further restrict their adoption in applications such as dairy alternatives and plant-based meat analogues (Huamaní-Perales et al., 2024).

To overcome these challenges, multiple processing methods have been studied, including heating, soaking, enzymatic hydrolysis, and fermentation. While each provides specific benefits, they are often energy-intensive, costly, or difficult to scale. In contrast, germination, is a simple, additive-free, and cost-effective method that activates endogenous enzymes, improving digestibility, functional properties, and sensory quality while reducing antinutritional compounds and allergenicity

* Corresponding authorDepartment of Food and Nutrition, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 04763, South Korea.
E-mail address: hime@hanyang.ac.kr (W.-S. Shin).

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Abbreviations

ABTS	ABTS radical scavenging activity
DPPH	DPPH radical scavenging activity
EA	emulsifying activity
ES	emulsifying stability
EC	emulsifying capacity
FC	foaming capacity
FE	foaming efficiency
TI	trypsin inhibitor
ND	not detected
HACCP	hazard analysis and critical control points
SDF	soluble dietary fiber
ANFs	antinutritional factors

(Gaytán-Martínez et al., 2023). Importantly, germination also mitigates beany flavors, enhancing consumer acceptance of legume-based foods.

Beyond nutritional and functionality, germination offers sustainability advantages: it requires only water, time, and minimal infrastructure, making it particularly suitable for low- and middle-income countries (Mali & Kumar, 2025). This positions germination as not only a food processing technology but also a socio-technical innovation that bridges nutrition, food functionality, and sustainable development goals.

For this review, we compiled and analyzed studies published between 2015 and 2025 on the processing of both common and underutilized legumes. We first examine the technological, nutritional, and sensory challenges that limit the use of raw legumes in food systems. We then explore how physical, chemical, and biological treatments including soaking, heating, fermentation, enzymatic hydrolysis, and especially germination can enhance the value of legumes by improving protein composition, digestibility, functional traits, and overall product quality. Particular attention is given to germination's potential for plant-based meat analogues, where improved solubility, emulsification, and flavor directly support product development. We further discuss industrial feasibility, HACCP-based safety, and life-cycle assessment perspectives. To our knowledge, no prior review has systematically compared germination with other processing methods while integrating sustainability and industrial considerations. Accordingly, this review is designed as a focused review that critically examines germination as a processing strategy for enhancing the nutritional, functional, and industrial value of legume proteins. Legumes were selected as the focal plant protein category due to their dominant role in current plant-based meat and dairy alternatives, their distinctive 7S (vicilin) and 11S (legumin) storage protein structures that are highly responsive to germination-induced enzymatic remodeling, and the relatively extensive body of research available for systematic synthesis. In addition to widely commercialized legumes such as soybean and pea, this review also considers emerging and underutilized pulses—including cowpea, Bambara groundnut, and lima bean—whose nutritional richness and climate resilience highlight their potential for diversification of plant-protein supply chains through germination-based enhancement strategies.

2. Methodology

This review included peer-reviewed articles published between 2015 and 2025. Literature searches were conducted using Scopus, Web of Science, and Google Scholar with keyword combinations including "plant protein," "legumes," "germination," "sprouting," "functional properties," "antinutritional factors," "protein digestibility," and "allergenicity." Although broad plant-protein-related keywords were initially employed, the final literature selection prioritized legume-based studies due to the availability of germination research and the industrial relevance of legumes in plant-based food applications. Only English-language publications focusing on food-related applications of legumes were included. Studies unrelated to food systems or lacking

Fig. 1. Global production and human consumption of common and underutilized legumes in 2023. Source: Data from FAOSTAT (2022; 2023).
Bar charts present min-max-normalized production data (original unit: tonnes); normalized values are unitless and reflect the relative production scale of each legume; different colors indicate different legume types. In the map, the demand for legumes is graded on a blue color scale; the darker the color, the greater the demand (unit: 1000 tonnes).

original data were excluded.

For visualization of global legume production and consumption (Fig. 1), production data obtained from FAOSTAT (2022–2023) were min–max normalized to a unitless scale between 0 and 1. This normalization allowed cross-comparison of legumes with vastly different production volumes, without altering the relative distribution patterns.

3. Challenges of unprocessed legumes

Legumes are widely utilized in the food industry because they are rich in protein, dietary fiber, and bioactive compounds. With the accelerating development of plant-based diets, their relevance in sustainable nutrition has become increasingly evident. However, unprocessed legumes still face significant limitations in terms of techno-functional properties, nutritional composition, and sensory characteristics (Fig. 2), which restrict their incorporation into diverse food systems.

3.1. Techno-functional limitations

Legume proteins typically exhibit poor solubility, weak emulsification, and limited foaming, limiting their performance in dairy alternatives, baked goods, and aerated foods. Heat processing generally further reduce functionality through protein denaturation and aggregation (Stone et al., 2024). At the structural level, globulins form tightly packed quaternary assemblies stabilized by disulfide bonds and hydrophobic interactions, reducing their flexibility at air–water or oil–water interfaces, therefore, native legume proteins underperform in emulsions and foams compared to casein or whey proteins.

3.2. Nutritional concerns

Antinutritional factors such as phytic acid, tannins, and trypsin inhibitors limit protein and mineral bioavailability. Additionally, they limit the availability of sulfur-containing amino acids thereby lowering PDCAAS scores. Furthermore, soybeans, chickpeas, and lentils contain allergenic proteins (e.g., vicilin, legumin, Gly m 5/6), which resist thermal processing. The persistence of allergenic epitopes even after boiling or roasting highlights the resilience of legume allergens. These proteins often contain immunoglobulin (Ig)E-binding sites that remain intact after partial denaturation, explaining their clinical relevance in pediatric food allergies.

3.3. Sensory challenges: off-flavors and unappealing texture

Off-flavors (e.g., beany, grassy, and bitter) result from lipid oxidation catalyzed by lipoxygenase (Yang et al., 2023). Texture problems such as graininess and dark coloration reduce consumer acceptance, limiting applications in premium foods. Recent consumer studies have suggested that sensory rejection rather than nutrition is the main barrier to mainstream adoption of legume-based dairy or meat alternatives (Yang et al., 2023). Therefore, processing approaches must simultaneously address both nutritional and sensory quality.

4. Overview of processing methods

Amidst the global protein transition, enhancing the nutritional quality and processing adaptability of pulses through low-cost, sustainable methods has become a central challenge in food science. Antinutritional factors, limited functional properties, and allergenic proteins in pulses restrict their integration into plant-based food systems. To address these issues, various physical, chemical, and biological strategies have been explored to improve nutrient profiles, reduce antinutritional compounds, enhance techno-functional traits (e.g., solubility, emulsification, foaming), and modulate protein structure and allergenicity (Huamaní-Perales et al., 2024). Thes methods vary in efficacy, sustainability, and scalability, as summarized in Tables 1 and 2.

Physical, chemical, and biological methods each show distinct strengths and limitations. For example, ultrasound and pH-shift treatments can significantly improve solubility or foaming, but often require higher energy inputs, chemicals, or specialized infrastructure. Fermentation provides multifunctional benefits but depends strongly on strain selection and process control. These trade-offs underline the importance of selecting cost-effective and sustainable strategies depending on the target application. Among these strategies, germination has attracted growing attention. In what follows, we discuss the detailed mechanisms and advantages of the various approaches.

4.1. Physical processing methods

Physical processing, such as soaking and thermal treatment, is widely adopted because of its simplicity and low cost. Soaking softens the seed coat and facilitates leaching of compounds like phenolics and phytic acid. For instance, soaking decreased total polyphenols in black beans and cowpeas by approximately 50–60% after soaking. While slight increases in protein content or in vitro digestibility have been observed, improvements in solubility and emulsification are minimal (Giusti et al., 2019; Ouazib et al., 2015). Heat treatments (boiling, roasting) effectively inactivate trypsin inhibitors and lectins while enhancing flavor, but often result in protein denaturation, loss of phenolics (e.g., caffeic and ferulic acids), and reduced foaming and antioxidant capacity (Giusti et al., 2019) For example, Lentil foam capacity

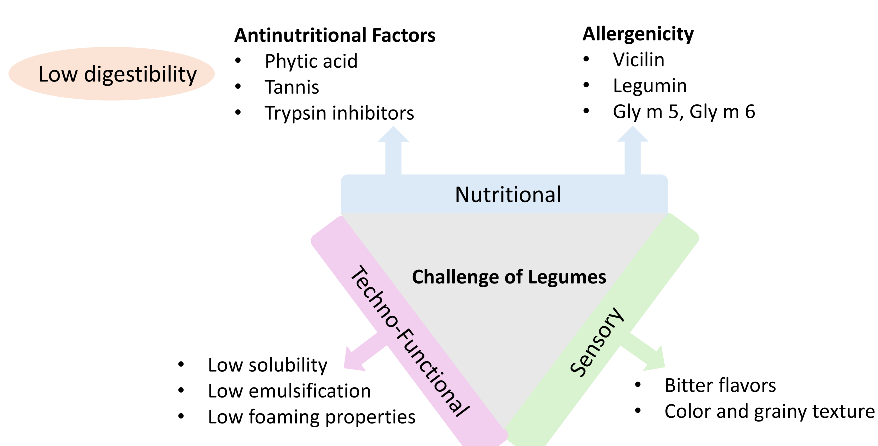

Fig. 2. Techno-functional, nutritional, and sensory challenges encountered with unprocessed legumes.

Table 1
Nutritional and antioxidant changes induces in legumes by different processing methods.

Legume	Processing method	Protein	Lipid	Fiber	Polyphenols/ phenolics	Flavonoids	Antioxidant activity (DPPH/ ABTS)	Notes	Ref.
Soybean	Soaking	↓	↑	—	—	—	—	—	(Agume et al., 2017; Cai et al., 2021; Guzmán-Ortiz et al., 2017; Warle et al., 2015)
	Roasting	↓	—	—	—	—	—	—	
	Germination	↑	—	↑	↑ (11.59 mg GAE/ g)	↑ (quercetin, catechin; glycosides → aglycones)	↑ ($ABTS^+$ 188%)	Isoflavones greatly ↑ after 6 days	
Chickpea	Soaking	—	—	—	↓ (free phenolic acids are leached)	—	—	—	(Giusti et al., 2019; Ouazib et al., 2015)
	Heating	—	—	—	—	—	—	—	
	Boiling	—	—	—	↓ (30–60%, particularly caffeic and ferulic acids)	↓	↓	Free and bound fractions are reduced	
	Germination	—	—	—	↑ (44 → 72 mg GAE/g)	↑ (ferulic acid, flavonoid glycosides)	↑	Enhanced liberation of bound phenolics	
	Fermentation	—	—	—	↑ (44 → 55 mg GAE/g)	—	↓	—	
Pea	Soaking	↑	—	↓	—	—	—	—	(Liu et al., 2020; Stone et al., 2021)
	Boiling	↓	—	↓	↓ (48–70%)	↓	↓	Large loss after soaking and boiling	
	Ultrasound	—	—	—	↑ (release of caffeic and ferulic acids)	—	↑	Better preservation	
	High pressure	—	—	—	↓	—	↓	Moderate reduction	
	Germination	↑	—	—	↑ (6.15 → 8.36 mg GAE/g)	—	↑ (21.6 → 48%)	—	
Lentil	Soaking	↓	—	—	↓ (2.6 → 2.2 mg GAE/g)	—	↓	—	(Duenas et al., 2016; Gandhi et al., 2022)
	Boiling	↑	—	—	↓ (2.6 → 1.0 mg GAE/g)	Partial loss	↓	More flavan-3-ols soluble in SDF	
	Germination	↑ (28 → 33)	—	↓	↑ (2.6 → 4.2 mg GAE/g)	—	↑ (43 → 50%)	—	
Cowpea	Soaking	↓	—	—	↓ (144 → 53–76 mg GAE/g)	—	—	—	(Ferreira et al., 2019; Gaytán-Martínez et al., 2023; Guzmán-Ortiz et al., 2017; Yadav et al., 2018)
	Boiling	↓	↓	—	↓ (144 → 91 mg GAE/g)	↓	↓	—	
	Roasting	—	—	—	↓ (−51%)	↓ (~30%)	↑	—	
	Germination	↑	—	↑	↑ (9 → 18 mg GAE/ g)	—	—	Syringic and benzoic acids ↑	
	Fermentation	—	—	—	↑	↓	↑	—	
Kidney bean	Soaking	↑	↓	—	—	—	—	—	(Mananga et al., 2022; Winarsi et al., 2020; Yeasmin et al., 2024)
	Boiling	↑	—	—	—	—	—	—	
	Ultrasound	—	—	—	↑ (5.7 mg GAE/g)	—	↑ (57%)	—	
	Germination	↑	—	—	↓ (7.76 → 5.26 mg GAE/g)	—	↑ (20.9 → 33.1%)	—	
	Fermentation	↑	—	—	—	—	—	—	
Mung bean	Soaking	↑	—	↑	—	—	—	—	(Ashraf et al., 2020; Chandrasiri et al., 2016; Guzmán-Ortiz et al., 2017; Liu et al., 2022)
	Boiling	↑	—	↓	↓ (6.03 → 5.17 mg GAE/g)	—	↓ (IC_{50} ↑)	—	
	Ultrasound	—	—	—	—	—	↑	—	
	Germination	↑	—	—	↓ (6.03 → 5.21 mg GAE/g)	—	↓ (IC_{50} ↑)	Benzoic and sinapic acids ↑	
	Fermentation	—	—	—	—	—	↑	—	
	Enzymatic hydrolysis	—	—	—	—	—	↑ ($ABTS^+$ 9.9%)	—	
Black bean	Soaking	—	—	—	↓ (26 → 12 mg GAE/100 g)	—	—	—	(Duenas et al., 2016; Guzmán-Ortiz et al., 2017; Le et al., 2021; Mali & Kumar, 2025)
	Roasting	—	↑	—	—	↑ (anthocyanin 791.6 mg/kg)	↓	—	
	Boiling	—	—	—	↓	↓	↓	—	
	Germination	↑	—	—	↑ (17–26 mg GAE/ g)	—	↑ (DPPH 28–37%; $ABTS^+$ 51–54%)	Benzoic and sinapic acids ↑	

Arrows indicate the direction of change compared with raw samples (↑ increase, ↓ decrease, — no significant change).
All phenolic contents were standardized to mg gallic acid equivalents per gram dry weight (mg GAE/g DW).
Abbreviations: ABTS: 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid; DPPH: 2,2-diphenyl-1-picrylhydrazil.

Table 2
Effect of various processing treatments on functional properties and antinutritional factors of different legume.

Legume	Processing method	Solubility	Emulsification	Foaming	Digestibility	Phytic acid	Tannins	Trypsin inhibitors	Notes	Ref.
Soybean	Soaking	—	—	—	↑ (2 → 44%)	—	—	—	Digestibility strongly improved	Ketnawa and Ogawa (2021) Yan et al. (2021)
	Boiling	—	—	—	↑ (3 → 49%)	—	—	—	—	
	Ultrasound	↑ (60 → 75–80%)	↑ (EA 0.5 → 0.9)	↑ (FS 0.38 → 0.7)	—	—	—	—	Improved emulsification & foam stability	
	Fermentation	—	—	—	↑ (18 → 50%)	—	—	—	—	
Chickpea	Soaking	↓	↓	—	—	↓	↓	—	Free phenolic acids leached	(Chandra-Hioe et al., 2016; Kang et al., 2022; Nadzri et al., 2021; Ouazib et al., 2015; Wang et al., 2022)
	Roasting	↓	↓	↓	—	↓	↓	—	—	
	Ultrasound	↑	↑ (EAI 33 → 44–53)	↑ (95 → 115%)	↓ (89 → 85%)	—	—	—	Foam capacity ↑ but digestibility slightly ↓	
	High pressure	↓	—	↑	—	—	—	—	—	
	pH-shift	↑ (6.7 → 9.1)	—	↑ (120 → 210–250%)	—	—	—	—	Strong foaming improvement	
	Germination	↑ (53 → 28–38%)	↓	↓	—	↓	↑	↓	Increased tannins, reduced phytic acid and TI	
	Fermentation	—	—	↓ (80 → 10%)	↑ (70 → 77%)	—	—	—	—	
	Enzymatic hydrolysis	↑	↑ (EC 53 → 57%)	↑ (82–120%)	—	—	—	—	Strong functional enhancement	
Pea	Soaking	—	—	—	—	↓	—	—	Minor reduction in phytic acid	(Ganzon-Naret, 2018; Hall & Moraru, 2021; Kravchenko et al., 2024; Setia et al., 2019; Sha et al., 2021)
	Heating	↓ (65 → 22%)	↓	↑ (FE 345 → 475%)	—	—	—	—	Foaming efficiency increased	
	Ultrasound	↑ (31 → 73–77%)	—	—	—	—	—	—	Solubility strongly improved	
	High pressure	↓ (65 → 25%)	↑	—	—	—	—	—	—	
	pH-shift	↓ (93.6 → 80.2%)	—	—	—	—	—	—	Slight solubility reduction	
	Germination	—	↑	↑ (114 → 124–151%)	↑ (78.6 → 79.9%)	—	—	—	Foaming capacity improved	
	Fermentation	↑	↑	↑ (1.8–4 ×)	—	—	—	—	Functional properties enhanced	
Lentil	Soaking	—	—	—	↑ (58.4 → 62.8%)	↓	↓	—	—	Gandhi et al. (2022)
	Boiling	—	↓	↓ (FC 95 → 23%)	↑ (58.4 → 79.1%)	↓	↓	—	Sharp loss of foam	Aryee and Boye (2017)
	pH-shift	↑ (60–80 → 90–95%)	—	—	—	—	—	↓	TIs reduced	Shi et al. (2024)
	Germination	↑	↑	↑ (94 → 103%)	↑ (58.4 → 76.7%)	↓	↓	—	Improved functionality	
	Fermentation	↑ (9.8 → 32–45%)	↑	↓	—	—	—	↓	TIs reduced	
Cowpea	Soaking	—	—	—	—	↓ (13.8 → 10.6–12.4)	↑	—	Phytic acid reduced, tannins increased	Wijatniko et al. (2023)
	Boiling	↑ (0.16 → 1.32 g/g)	—	—	—	↓ (44.9 → 22.3)	↓ (80.3 → 31.2)	—	Strong antinutrient reduction	Makinde and Abolarin (2020) Devi et al. (2015)
	Roasting	↑ (0.16 → 0.72 g/g)	—	—	—	↓	↓	—	—	
	Germination	—	—	—	↑ (59.8 → 65%)	↓ (308 → 19 mg)	—	—	Large reduction in phytic acid	
	Fermentation	↓ (63.3 → 52%)	—	—	—	—	—	—	Slight solubility reduction	
Kidney bean	Soaking	—	—	—	—	↓ (0.1 → 0.07)	↓ (0.28 → 0.03)	—	—	(Choe et al., 2022; Mananga et al., 2022; Winarsi et al., 2020; Yeasmin et al., 2024)
	Boiling	—	—	—	—	↓ (0.1 → 0.07–0.08)	↓	—	—	
	Ultrasound	↑ (88 → 99%)	↑ (EAI 14 → 18)	↑ (210 → 250%)	↑ (85–87%)	—	—	—	Strong functional improvement	

(*continued on next page*)

Table 2 (*continued*)

Legume	Processing method	Solubility	Emulsification	Foaming	Digestibility	Phytic acid	Tannins	Trypsin inhibitors	Notes	Ref.
	pH-shift	↑ (88 → 95%)	↑	↑	—	—	—	—	—	
	Germination	—	↑ (EC 171 → 176)	↑ (FC 6 → 25–67%)	—	↓ (2.18 → 1.6–1.97)	↓	—	Antinutrients reduced	
	Fermentation	—	—	—	—	↓ (342 → 317)	↓ (113 → 60)	↓ (15.5 → 0)	Complete TI elimination	
Mung bean	Soaking	—	—	—	—	↓ (1.28 → 0.71)	↓ (2.40 → 0.97)	↓ (15.5→ND)	Strong antinutrient reduction	(Du et al., 2018; Elobuike et al., 2021; Liang et al., 2022; Liu et al., 2022; Zhong & Xiong, 2020)
	Heating	—	—	—	—	↓	↓	↓	Same as soaking	
	Ultrasound	↑ (10.2%)	—	—	—	—	—	—	Improved solubility	
	pH-shift	—	↑	↑	—	—	—	—	Good emulsification	
	Germination	—	—	—	—	↓ (0.18 → 0.1–0.15)	↓	—	Reduced antinutrients	
	Fermentation	↑ (65–72%)	—	—	—	—	—	—	Solubility enhanced	
	Enzymatic hydrolysis	↑	↑	↑	—	—	—	—	Strong antioxidant and functional improvement	
Black bean	Soaking	—	↑(ES 70 → 80)	↑(FC 35 → 45)	↑(70 → 73)	↓	↓	↓	Foaming capacity decreased; digestibility improved; slight reduction in antinutrients	(Le et al., 2021) Li et al. (2020)
	Roasted	—	—	—	—	↓	↓	↓	Slight reduction in antinutrients	
	Ultrasound	↑	↑	↑	—	—	—	—	Improved solubility and interfacial properties	
	Germination	—	↑(ES 70 → 80)	↑(FC 35 → 50)	↑(70 → 80)	↓	↓	—	Digestibility improved; antinutrients reduced	

Arrows indicate the direction of change compared with raw samples (↑ increase, ↓ decrease, — no significant change).
Abbreviations: EA: emulsifying activity; ES: emulsifying stability; EC: emulsifying capacity; FC: foaming capacity; FE: foaming efficiency; TI: trypsin inhibitor; ND: not detected.

decreased from 95% to 23% after boiling, with similar declines in peas and chickpeas, highlighting the functional limitations of thermal processing.

Ultrasonic treatment has emerged as a green method for modifying protein structures and improving interfacial activity. Through cavitation, ultrasound enhances solubility and functionality by altering the protein tertiary structure and exposing hydrophobic groups. The solubility of pea, red kidney bean, and soy proteins increased by 30–50% (Sha et al., 2021; Yan et al., 2021; Yeasmin et al., 2024), while antioxidant capacity in red kidney beans rose by approximately 57% due to enhanced phenolic release (Yan et al., 2021). High-pressure processing induced inconsistent improvements in solubility and antioxidant activity in pulses, and its high equipment costs limit its industrial adoption.

4.2. Chemical processing methods

Chemical approaches, particularly pH-shifting and enzymatic hydrolysis, offer precise structural modification. pH-shifting involves alkaline extraction, acid precipitation, and neutralization, and significantly improve solubility and foaming. For example, chickpea foam capacity increased from 120% to 250% (Wang et al., 2022), and red kidney bean emulsification also improved (Choe et al., 2022). However, pH treatments may cause minor degradation or color changes. Enzymatic hydrolysis with papain or Alcalase further improves solubility, emulsification, and antioxidant capacity. Mung bean and chickpea proteins showed enhanced foaming and a more than 10% increase in 2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) radical scavenging activity after enzymatic treatment (Liu et al., 2022; Nadzri et al., 2021). Despite their effectiveness, chemical methods are often costly and involve complex processing, limiting their use in cost-sensitive applications.

4.3. Biological processing methods

Biological treatments combine sustainability with multi-functionality. Fermentation using lactic acid bacteria or yeast degrade phytic acid and tannins, generate vitamins and peptides, and improve functional properties (Shi et al., 2024). Fermented pea proteins exhibited two to four times higher foaming capacity, whereas trypsin inhibitor activity in red kidney beans was nearly eliminated. Fermentation also increased phenolic release and may reduce IgE-binding, suggesting its potential in lowering allergenicity (Chandra-Hioe et al., 2016). However, fermentation outcomes depend heavily on strain selection, substrate, and process conditions, posing challenges in terms of consistency and standardization. Besides fermentation and other bioprocessing techniques, germination represents a unique category of biological treatment approach. Owing to its simplicity and broad applicability, germination has been increasingly studied in recent years.

5. Germination as a cost-effective and sustainable method

Sprouting, a natural process initiated during seed germination, should be understood not merely as a simple biological event, but as a coordinated biochemical reprogramming process that fundamentally reshapes both nutritional composition and protein structure. Its primary advantages lie in its simplicity, lack of reliance on chemical additives or energy-intensive equipment, and broad applicability across pulse species. These multifaceted effects of germination are visually summarized in Fig. 3. In this context, germination represents a distinct modification pathway driven by endogenous enzymatic activation, which differentiates it from conventional physical or chemical treatments.

5.1. Nutritional enhancement

From a nutritional perspective (Table 1), germination can be interpreted as a coordinated metabolic transformation process rather than a series of isolated compositional changes. Germination induces the biosynthesis and release of proteins, soluble dietary fibers, polyphenols, and flavonoids. In soybeans, the isoflavone content increases significantly after six days of sprouting, particularly through the conversion of glycosidic forms into aglycones (Guzmán-Ortiz et al., 2017; Warle et al., 2015). Anthocyanin levels in black beans reached 791.6 mg/kg following sprouting (Le et al., 2021). In chickpeas and peas, the total polyphenol content increased by 30–50%, accompanied by notable improvements in 2,2-diphenyl-1-picrylhydrazil (DPPH) and ABTS radical-scavenging capacity (Setia et al., 2019). Sprouted lentils showed increased protein and phenolic content, and cowpeas and black beans also showed germination-driven improvements (Devi et al., 2015; Gandhi et al., 2022). These improvements have been attributed to the activation of β-glucosidases, phenolic esterases, and proteases, which liberate bound phenolic acids and cleave glycosidic isoflavones into more bioavailable aglycones. Taken together, we propose that germination-induced enzymatic activation not only enhances the quantity of bioactive compounds but also systematically improves their bioavailability, reflecting an integrated transformation of nutritional components rather than independent compositional shifts.

5.2. Functional improvement

Structurally, germination should be viewed as a protein remodeling process driven by controlled enzymatic hydrolysis, rather than a simple conformational modification (Table 2). Relaxation of the protein structure increases the exposure of hydrophobic groups, improving interfacial activity. For instance, the foaming capacity of sprouted chickpea

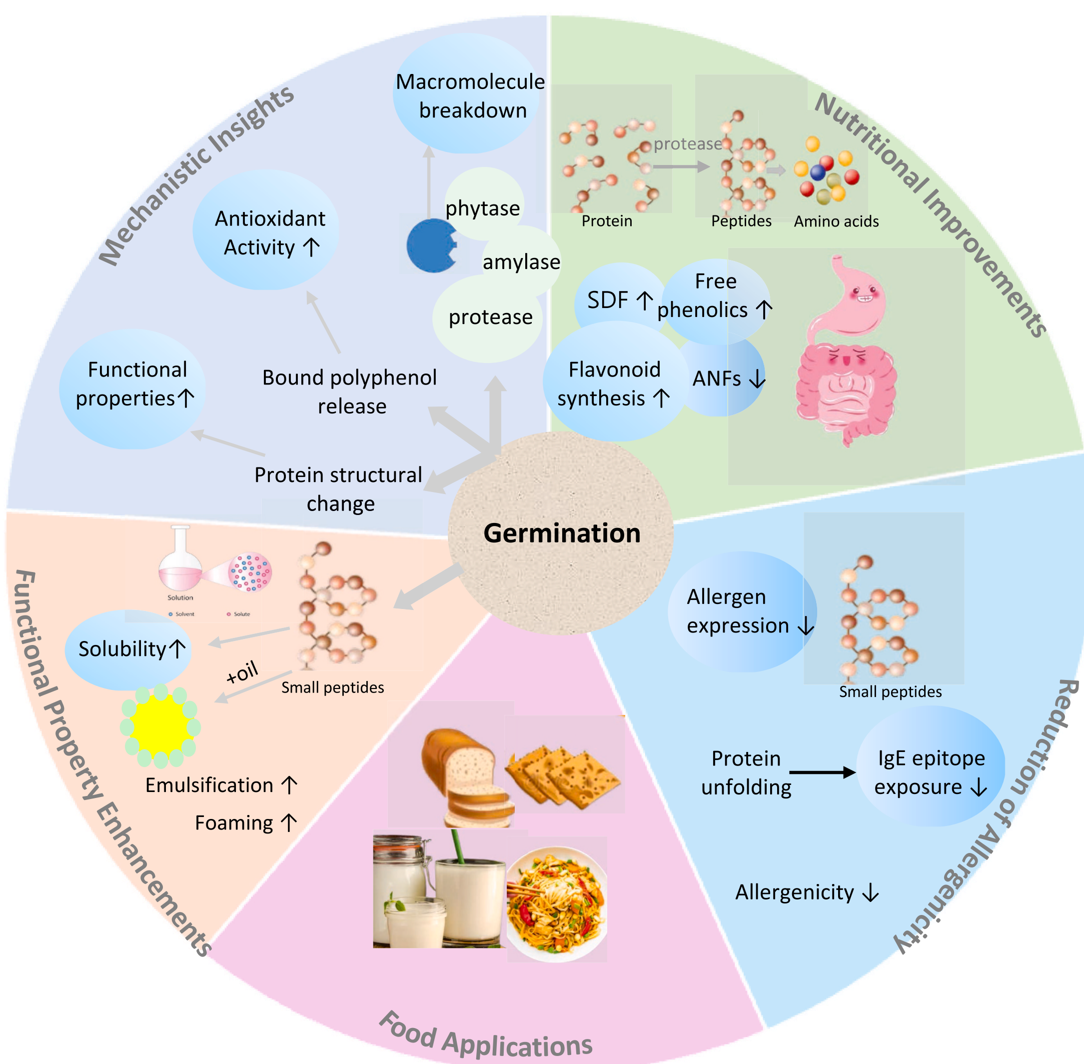

Fig. 3. Germination-induced changes in legume composition, functionality, allergenicity, and safety considerations (HACCP framework highlighted). Abbreviations: HACCP: hazard analysis and critical control points; SDF: soluble dietary fiber; ANFs: antinutritional factor.

proteins increased from 6% to 67%, and the emulsifying capacity of kidney beans proteins increases significantly (Winarsi et al., 2020). Germinated soybean protein digestibility improved markedly from 3% to 49% (Ketnawa & Ogawa, 2021), with similar trends observed in sprouted red lentils and black beans (Gandhi et al., 2022; Mali & Kumar, 2025), indicating better suitability for populations with elevated nutritional needs, such as infants and the elderly. Based on these observations, we propose that partial proteolysis and structural relaxation during germination are the primary drivers enhancing protein flexibility and interfacial behavior. From a structure–function perspective, we emphasize that this transformation fundamentally enhances the ability of legume proteins to adsorb and stabilize interfaces, thereby improving their performance in emulsified and aerated food systems.

5.3. Reduction of antinutritional factors and allergenicity

Germination can be interpreted as an intrinsic detoxification and structural modification process that markedly reduces anti-nutritional compounds (Table 2). In most legumes, the phytic acid content decreases by 30–90% within 48–72 h. In cowpeas, it decreased from 308 to 19 mg/100 g (Gaytán-Martínez et al., 2023; Guzmán-Ortiz et al., 2017). In kidney beans, the trypsin inhibitor content decreased from 2.18% to 1.6–1.97% (Winarsi et al., 2020). Lentils and mung beans showed similar reductions in phytic acid and tannins (Elobuike et al., 2021; Gandhi et al., 2022). These reductions are primarily driven by enzymatic activation, particularly endogenous phytase, which hydrolyzes phytic acid and releases bound minerals. This enzymatic pathway underpins the improved mineral bioavailability observed in germinated pulses.

Importantly, germination has been shown to attenuate the allergenicity of legumes (Table 3). Major storage proteins such as vicilin and legumin, including isoforms like Gly m 5 and Pis s 1, are reduced in abundance after sprouting, while conformational rearrangements decrease the accessibility of IgE-binding epitopes (Mastrorilli et al., 2024). Consequently, the IgE-binding capacity of chickpea, lentil, and soybean proteins is markedly lowered, which has been linked to partial proteolysis, peptide release, and relaxation of tertiary structures (Guzmán-Ortiz et al., 2017; Warle et al., 2015). We argue that allergenicity reduction during germination is fundamentally associated with structural reorganization of storage proteins, including proteolytic degradation and conformational rearrangement. Proteolytic cleavage of 7S and 11S globulins disrupts conformational epitopes, unfolding of protein structures masks or alters epitope presentation, and degradation into smaller peptides diminishes overall immunoreactivity. Nonetheless, the precise pathways underlying these transformations remain unclear. Advanced approaches such as proteomics, peptidomics, and structural immunoinformatic are needed to provide deeper insights into how germination reshapes allergenic potential at the molecular level. Taken together, the reduction of antinutritional factors and allergenicity is closely associated with enzymatic degradation and structural modification of storage proteins, highlighting germination as a dual-function strategy that improves both safety and nutritional quality.

5.4. Sensory quality and practical applications

Beyond nutritional and functional improvements, germination also plays a critical role in modulating sensory attributes, which is essential for improving consumer acceptance of legume-based foods. Germination reduces lipoxygenase activity and alters volatile profiles, thereby mitigating grassy and beany notes that limit consumer acceptance of legumes. These sensory improvements translate into enhanced palatability of germinated flours and protein isolates in various food systems.

In practical applications, sprouted legumes demonstrate strong potential as functional ingredients, supporting their integration into diverse plant-based food systems. Sprouted pea and faba bean flours have been blended with wheat flour, produce composite breads with improved texture and color (Setia et al., 2020). The incorporation of sprouted mung beans into cereal formulations enhances consumer acceptability (Barakat et al., 2025). Sprouted legumes have been combined with cereals for fermentation, yielding dairy-free probiotic beverages with enhanced microbial growth and flavor (Chavan et al., 2018). Furthermore, sprouted chickpea flour has been effectively applied in gluten-free noodle production, improving taste, elasticity, and overall consumer preference (Sofi et al., 2020). Emerging studies also indicate that sprouted underutilized legumes such as mung bean, cowpea, Bambara groundnut, and lima bean may further contribute to digestibility and bioactive release, though their use in food innovation pipelines remains limited.

These nutritional, functional, and sensory benefits highlight the relevance of germination not only for conventional food formulations but also for emerging applications such as plant-based meat analogues, which require improved solubility, emulsification, and flavor quality. Overall, we emphasize that germination provides a comprehensive and integrative enhancement of legume protein systems, simultaneously improving nutritional, functional, and sensory attributes. This multifunctional improvement is particularly critical for complex food applications, where multiple quality parameters must be optimized concurrently.

6. Application to plant-based meat analogues

The plant-based meat sector is experiencing rapid growth, with the global market projected to expand from USD 7.9 billion in 2022 to USD 15.7 billion by 2027 (Andreani et al., 2023). Consumer demand for sustainable, ethical, and nutritious protein products is driving innovation, while recent reviews highlight the need to diversify beyond soy and pea by incorporating novel legumes and processing technologies.

Raw legume proteins often suffer from low solubility, weak emulsification, and undesirable off-flavors, limiting their ability to mimic the texture and taste of meat. Sprouting activates endogenous enzymes, partially hydrolyzing storage proteins and enhancing solubility, emulsification, and foaming. It also reduces lipoxygenase activity and modifies volatile profiles, mitigating grassy or beany flavors (Lao et al., 2024). These changes align with the requirements of extrusion and shear structuring, where protein unfolding and alignment are critical for fibrous texture formation. Recent empirical evidence supports these

Table 3
Effect of germination on allergenicity of major pulses.

Legume	Major allergens	Protein type	Key allergenic characteristics	Impact of germination on allergenicity	Ref.
Soybean	Gly m 5, Gly m 6, Gly m 4, Gly m Bd 30K	7S/11S globulins, PR-10	Gly m 5/6 are heat-stable, digestion-resistant storage proteins; strong IgE-binding	Reduces IgE-binding of 7S/11S proteins and PR-10; partial hydrolysis and conformational changes	Wang et al. (2023)
Peanut	Ara h 1, Ara h 2, Ara h 3, Ara h 6, Ara h 8	7S, 2S, 11S globulins	Ara h 2 is the most potent, heat- and digestion-resistant allergen	Decreases Ara h 1 and Ara h 3 abundances; partial reduction in IgE-binding	Comstock et al. (2016)
Lentil	Len c 1	Vicilin-like (7S) storage protein	Structural homology with Ara h 1 and Gly m 5	Limited data; preliminary evidence suggests it decreases vicilin-like allergenicity	Valdelvira et al. (2022)
Chickpea	Ana o 1, Ana o 2	7S/11S globulins	Homologous to peanut allergens; possible IgE cross-reactivity	Decreases IgE-binding and enhances the breakdown of digestibility-resistant fractions	Boukid (2021a)

functional advantages in meat analogues. Knaapila et al. reported that demonstrated that high-moisture extruded meat analogues formulated with germinated faba bean flour showed improved texture and consumer liking compared with non-germinated controls (Knaapila et al., 2024). Similarly, Guo et al. reported that germination of pea and lentil flours enhanced fiber formation and mechanical strength in meat analogues, highlighting the role of endogenous enzymatic activation in structuring (Guo et al., 2024). These findings provide direct validation that sprouted legumes are not only beneficial in bakery or beverage systems but also in the design of fibrous meat analogues. However, applications of underutilized legumes such as lima bean, cowpea, and Bambara groundnut in this domain remain largely unexplored, representing a critical research gap. Their incorporation into plant-based meat could expand protein diversity, reduce reliance on single sources, and enhance regional value chains.

In summary, germination offers a cost-effective, sustainable, and consumer-oriented approach to improve plant proteins for plant-based meat. By simultaneously enhancing functionality, reducing off-flavors, and broadening raw material options, sprouted legumes can play a strategic role in the next generation of meat analogues, complementing extrusion, fermentation, and other structuring technologies.

7. Industrial feasibility and safety considerations of germinated legumes

Germination involves a relatively straightforward sequence of operations (i.e., washing, soaking, controlled temperature and humidity incubation, and drying) that does not require advanced or expensive equipment. This simplicity makes it applicable not only at the household or small-scale level but also highly adaptable to industrial-scale operations. By integrating basic automation and environmental controls, germination can be easily scaled and standardized for continuous production.

Despite its many benefits, germination is not without limitations (Fig. 3). The process is time-consuming it typically requiring 24 to 72 h, and is highly sensitive to environmental fluctuations, which can lead to inconsistency across production batches. Inappropriate handling or excessive moisture during soaking and incubation can promote mold growth, microbial contamination, or degradation of functional compounds. Additionally, water-soluble nutrients such as B vitamins and minerals may leach out during soaking, partially offsetting the nutritional gains achieved through sprouting.

To address these risks at an industrial scale, germination should be embedded within a hazard analysis and critical control points (HACCP) framework. This approach allows for systematic identification and monitoring of critical steps to ensure both product safety and consistency. Key CCPs include seed sanitation before soaking (e.g., UV treatment or chlorine rinsing), control of water quality and temperature during soaking (20–25 °C), and strict regulation of humidity (80–95%) and temperature during germination incubation (Gilbert et al., 2023; Symes et al., 2015). Post-germination handling, drying, and packaging also require microbial monitoring to prevent contamination. Several foodborne outbreaks associated with *E. coli* O157:H7 and Salmonella in improperly germinated sprouts highlight the importance of such preventive systems (Iacumin & Comi, 2019). Integrating HACCP checkpoints into germination operations can safeguard consumer safety while maintaining the functional and nutritional advantages of sprouted legumes.

In addition to pathogen risks, spoilage caused by yeasts and molds is a frequent challenge during large-scale sprouting, especially under high-moisture conditions. Such spoilage not only reduces shelf life but may also degrade flavor, texture, and nutritional quality. Preservation solutions shown to be effective include mild hot-water blanching, convective or freeze drying, vacuum sealing, and modified atmosphere packaging (MAP). For example, a recent study on bamboo sprouts found that MAP combined with cold storage at ~4 °C extended shelf life significantly compared to non-MAP conditions, preserving sensory and microbiological quality for over a week. Post-harvest treatment using hurdle technology (combining ozone or organic acid sanitizers with cold storage) has also been demonstrated to limit growth of spoilage organisms while retaining desirable sensory properties in mung bean and radish sprouts (Shomodder et al., 2022). Incorporating these safety and preservation measures within HACCP-based systems ensures that germination can be scaled reliably for industrial use. Importantly, stable and safe sprouted legume ingredients provide a secure raw material base for applications ranging from traditional foods to plant-based meat analogues, supporting both consumer safety and commercial feasibility.

8. Future directions and policy implications

Although extensive research has demonstrated the advantages of sprouting in enhancing the nutritional composition and functional properties of legumes while reducing antinutritional factors, several scientific and practical challenges remain. First, the effects of sprouting vary considerably across legume species and processing conditions, and systematic cross-species comparisons and standardized experimental designs are lacking to date (Gandhi et al., 2022; Mali & Kumar, 2025; Setia et al., 2019). This variability hampers the predictability of industrial applications.

Second, the allergenicity-reducing potential of germination is another area that requires deeper mechanistic study. While reductions in vicilin- and legumin-type proteins and IgE-binding capacity have been reported, the molecular pathways underlying these changes remain poorly understood. Omics-based approaches are beginning to reveal insights: proteomics has mapped remodeling of vicilin/legumin subunits and decline of protease inhibitors in chickpea (Di Francesco et al., 2024), while metabolomics consistently reports increases in phenolics, GABA, dipeptides, and micronutrients during sprouting. These findings suggest coordinated activation of proteolysis and phenylpropanoid pathways, but a more systematic integration of omics data across species is required.

Evidence on sensory outcomes and consumer acceptance is also limited. Emerging studies show that partial replacement with sprouted flours can improve bread handling, elasticity of gluten-free noodles, and overall liking scores (Bresciani et al., 2024). However, results are inconsistent, and standardized sensory protocols are lacking. Future work should systematically test how flavor, texture, and consumer perception vary by legume species and germination time, particularly in applications such as plant-based meat analogues where sensory quality is critical.

Emerging sensory and consumer studies suggest that short-term sprouting can improve acceptance when sprouted legume flours are partially blended into cereal matrices. In breads enriched with sprouted chickpea, dough handling and bread quality improved and formulations achieved acceptable or enhanced panel scores versus controls, while particle size moderated texture outcomes (Bresciani et al., 2024). In gluten-free traditional products, sprouted chickpea–based formulations attained the highest overall acceptability among test variants, underscoring sprouting's potential to mitigate off-flavors/texture penalties often associated with legume incorporation (Topaloğlu Günan et al., 2025). Broader reviews concur that germinated or fermented legume flours can raise consumer liking relative to 100% cereal controls, though standardized sensory protocols across species and germination times remain limited. Moreover, although germination is often proposed as environmentally preferable, comparative LCAs are rare; few studies have quantified the environmental impacts of germination versus alternative processing technologies (e.g., thermal or high-pressure treatments). To fill these gaps, future work should integrate proteomics/metabolomics with sensory panel trials and LCA analyses to fully evaluate germination's promise.

Environmental and industrial dimensions remain underexplored. Few comparative LCA have quantified the carbon and energy footprints of germination relative to thermal, high-pressure, or extrusion methods. At the same time, scaling up sprouting faces challenges of batch consistency, microbial control, and shelf stability. Promising solutions include combining germination with mild treatments such as ultrasound, low-temperature heating, or fermentation to improve safety and functional reliability. In parallel, accelerating research on underutilized pulses from diverse regions, including cowpea, Bambara groundnut, and lima bean, may broaden crop diversity and provide novel avenues for diversifying global protein supplies. From an industrial perspective, future research should prioritize the scalability of germination processes, batch to batch consistency, and compatibility of germinated legume ingredients with extrusion, shear structuring, and fermentation technologies used in plant-based food manufacturing (Boukid, 2021b).

From a broader perspective, sprouting represents a low-cost, energy-efficient, and environmentally friendly processing approach with profound implications for global food security and nutrition policies. Its simplicity and minimal reliance on sophisticated equipment or chemical reagents make it particularly suitable for low- and middle-income countries, where pulses are staple protein sources but protein and micronutrient deficiencies remain prevalent. Community-level adoption of sprouting techniques can substantially improve dietary quality and mitigate malnutrition, particularly among children and other vulnerable populations. Furthermore, integrating sprouted pulses into food aid programs or school meal initiatives may simultaneously improve nutritional outcomes and stimulate local pulse utilization and value-chain development.

Finally, future research should embed sprouting within broader LCA and techno-economic analytical frameworks. Compared with other processing techniques such as ultrasound, high pressure, or extrusion, sprouting likely offers distinct advantages in terms of energy use and carbon footprint; however, quantitative evidence is scarce. Only by systematically integrating nutritional enhancement, environmental performance, and economic feasibility can researchers, policymakers, and industry stakeholders establish a robust foundation for decision-making. In summary, sprouting is not merely a processing method for improving legume quality but also a strategic tool for advancing global dietary transitions, alleviating malnutrition, and promoting sustainable development.

9. Conclusion

As a sustainable source of dietary protein, pulses hold considerable potential to improve nutrition and drive global dietary transformation. However, their wider application is constrained by antinutritional factors, limited functionality, and allergenicity. Among the diverse processing strategies available, sprouting has emerged as particularly promising owing to its low cost, operational simplicity, and multifaceted benefits. Sprouting enhances protein digestibility, increases polyphenol and flavonoid contents, and improves techno-functional properties such as solubility, emulsification, and foaming capacity, while reducing antinutritional compounds and partially mitigating allergenicity. Collectively, these improvements suggest that germination-induced enzymatic modification plays a central role in restructuring legume protein functionality and enhancing their applicability in complex food systems. However, despite these advantages, several limitations remain, including variability in germination conditions, differences among legume species, and the lack of standardized processing protocols, which may lead to inconsistent functional outcomes and limit industrial scalability. In addition, microbial safety risks and potential nutrient losses during soaking and sprouting must be carefully controlled. From our perspective, future research should focus on integrating germination with complementary processing technologies, such as extrusion, fermentation, and mild physical treatments, as well as establishing standardized protocols and expanding research on underutilized legumes to improve consistency and diversify plant protein sources. Overall, germination offers a scalable and sustainable pathway to enhance the nutritional, functional, and safety profile of legumes, and with coordinated scientific, industrial, and policy efforts, may serve as a promising approach for advancing plant protein development and future food innovation.

CRediT authorship contribution statement

Yingjinzhu Wu: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Weon-Sun Shin:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Further reading

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