



The use of soy protein isolate (SPI) in the development of analogue meat products and their derivatives as a protein source for vegetarians: A systematic literature review

Fatimah Karim¹, Nani Ratnaningsih^{1,2}

¹Department of Family Welfare Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Jalan Colombo No 1, Yogyakarta, 55281, Indonesia

²Department of Industrial Engineering, Faculty of Engineering, Universitas Negeri Yogyakarta, Jalan Colombo No 1, Yogyakarta, 55281, Indonesia

*Correspondence: fatimahkarim.2024@student.uny.ac.id

ABSTRAK

Latar Belakang: Peningkatan kesadaran kesehatan dan keberlanjutan lingkungan mendorong minat terhadap diet berbasis nabati, yang selaras dengan tujuan pembangunan berkelanjutan (SDG) 3, 12, dan 13. Bagi vegetarian, pemenuhan protein menjadi kendala, sehingga dibutuhkan sumber protein nabati berkualitas tinggi. Kedelai dengan kandungan protein 35–40% menghasilkan Isolat Protein Kedelai (IPK) sebagai produk termurni dengan kadar protein melebihi 90% dan daya cerna yang tinggi.

Tujuan: Penelitian ini bertujuan untuk mengkaji pemanfaatan IPK dalam pembuatan produk daging analog nabati melalui systematic literature review (SLR) terhadap 29 artikel ilmiah pada periode 2014–2025.

Metode: Fokus kajian mencakup karakteristik fungsional IPK (daya ikat air, emulsifikasi, pembentukan gel), kandungan gizi, serta perannya dalam membentuk struktur, tekstur, dan rasa produk daging analog beserta turunannya seperti sosis dan patty.

Hasil: Hasil kajian menunjukkan bahwa IPK memiliki kemampuan yang kuat untuk membentuk gel, berfungsi sebagai pengikat, serta berperan dalam membentuk struktur ber serat, terutama pada proses ekstrusi. IPK berkontribusi dalam menahan air di matriks gel, yang memengaruhi tingkat kebasahan produk. Penambahan IPK secara optimal meningkatkan elastisitas, kekuatan gel, kapasitas menahan air, kekerasan, kekoherenan, kekenyalan, serta keseragaman struktur internal. Kandungan asam glutamat dan asam aspartat yang tinggi turut memperkuat rasa umami, sekaligus meningkatkan kandungan protein, setara dengan produk daging konvensional. Kendati demikian, penambahan berlebih dapat menurunkan kualitas gel dan elastisitasnya.

Kesimpulan: IPK efektif meningkatkan nilai gizi, sifat fungsional, dan kualitas tekstur daging analog pada konsentrasi optimal.

KATA KUNCI: daging analogue; kedelai; pangan; protein

ABSTRACT

Background: Increased health and environmental awareness has driven interest in plant-based diets, aligning with SDGs 3, 12, and 13. For vegetarians, meeting protein needs remains challenging and requires high-quality plant-based protein. Soybeans, containing 35–40% protein, yield soy protein isolate (SPI), the purest product, with >90% protein content and high digestibility.

Objectives: This study examines the use of SPI in plant-based meat analogue production through a systematic literature review (SLR) of 29 articles from 2014–2025.

Methods: The review covers SPI's functional characteristics (water-binding, emulsification, gelation), nutritional content, and its role in shaping the structure, texture, and flavor of meat analogues and derivatives like sausages and patties.

Results: The results indicate that SPI exhibits strong gelation capacity, acts as a binder, and forms fibrous structures, particularly during extrusion. SPI facilitates water retention in the gel matrix, influencing juiciness. Optimal SPI incorporation enhances elasticity, gel strength, water-holding capacity, hardness, cohesiveness, springiness, and internal structural uniformity. High glutamic and aspartic acid contents enhance umami taste, while significantly increasing protein levels comparable to conventional meat. However, excessive addition can reduce gel quality and elasticity.

Conclusions: SPI effectively improves nutritional value, functional properties, and textural quality of meat analogues at optimal concentrations.

KEYWORDS: food; meat analogue; protein; soybean

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INTRODUCTION

This study examines the role of soy protein isolate (SPI) in developing plant-based meat analogues to support sustainable protein consumption aligned with SDGs 3, 12, and 13 (1). Vegetarianism encompassing categories from ovo-vegetarians to vegans is rapidly expanding worldwide, with over 122 million adherents globally and significant growth in Indonesia (2–4). While plant-based diets promote healthier lifestyles and reduce environmental impacts, meeting daily protein requirements remains a key focus for consumers through legumes, grains, and soy products (1,5). This rising demand has fueled rapid growth in the plant-based food industry, with an annual demand increasing by 7.9% and major market expansions projected across Asia-Pacific and Europe (6,7). Consequently, demand for meat analogues, plant-based items mimicking animal meat characteristics, has risen sharply (4). To achieve a meat-like texture, formulations commonly incorporate soy-based ingredients, binders like methylcellulose or carrageenan, and various plant oils that provide freshness, tenderness, and flavor (8,9). As members of the Fabaceae family, soybeans are widely utilized across diverse food applications, with dried seeds

containing 35–40% high-quality protein comparable to meat and milk (10,11). Among commercial derivatives, soy protein isolate (SPI) represents the purest form, featuring over 90% protein content and high digestibility (12).

SPI enhances product value and organoleptic acceptance, serving as an effective raw material for meat alternatives such as sausages, nuggets, and meatballs (13,14,15). Research demonstrates SPI's proven capacity to increase protein content in burgers, replace chicken meat in tempeh sausages, and comply with national SNI 3820:2015 standards for analogue meat (13,16,17,18). Furthermore, SPI's functional advantages lie in its ability to form a fibrous texture resembling meat while supporting sustainable vegetarian dietary patterns (13). Although the literature confirms that well-planned vegetarian diets meet protein and essential amino acid needs (5), limited research specifically examines the functional role of SPI in shaping the structure, texture, and nutritional profile of ready-to-eat meat analogues (8). Addressing this gap, the present study aims to evaluate the functional and nutritional roles of Soy Protein Isolate (SPI) in the development of plant-based meat analogues and

their derivatives. The analysis focuses specifically on the influence of SPI on structural formation, textural attributes, and sensory profiles of plant-based sausages and patties.

MATERIALS AND METHODS

This study employs a Systematic Literature Review (SLR) methodology adhering to the PRISMA 2020 guidelines and the framework outlined by Moher et al. (19). A systematic search across databases such as Scopus, ScienceDirect, and Google Scholar was conducted using keywords including "Soy Protein Isolate," "Meat analogue," and "Functional Properties" to identify peer-reviewed research articles published between 2014 and 2025. Through a qualitative synthesis and thematic analysis, the findings were systematically categorized and interpreted to evaluate the functional properties, nutritional profiles, and resulting structural and textural attributes of plant-based sausages and patties.

Keyword Identification and Discovery

The literature search used two main inclusion criteria: literature discussing ISP (characteristics, applications, or its effects on food products), and sources reviewing topics related to the development of plant-based meat analogues as a substitute for animal protein, specifically for vegetarians. The main keywords used were "Isolated Soy Protein," "Soy Protein Isolate," "meat analogue," and "vegetarian."

Literature Search

The literature search was conducted using Scopus AI with predefined keywords, limited to publications between 2014 and 2025. The initial search yielded 456 articles. Subsequently, 55 articles were screened and evaluated. A total of 26 articles were excluded for not meeting the inclusion criteria, leaving 29 articles for analysis. Literature Search Strategy: A comprehensive literature search was conducted across multiple electronic databases, including Scopus, ScienceDirect, and Google Scholar, to ensure data completeness.

The search strategy employed Boolean operators (AND/OR) with an expanded set of keywords: ("Soy Protein Isolate" OR "Isolated Soy Protein" OR "SPI") AND ("Meat analogue*" OR "Plant-based Meat" OR "Meat Substitute") AND ("Sausage" OR "Patty" OR "Texture"). The publication period was limited to the last decade (2014–2025). Study Selection and Inclusion Criteria: The study selection followed a transparent three-stage screening process adhering to PRISMA guidelines, initially identifying 456 articles across databases. After removing duplicates and irrelevant non-food or non-SPI studies through title, abstract, and full-text eligibility assessments based on specific inclusion criteria, 29 articles were ultimately synthesized for this review (**Figure 1**).

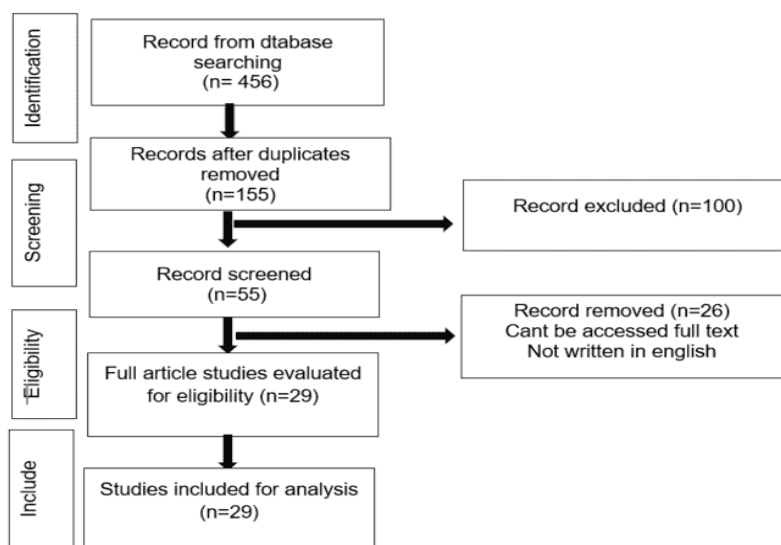


Figure 1. Schematic representation (PRISMA Flow Chart) of the literature review process

Description of the Study Selection Process (PRISMA)

The selection process was conducted in four distinct phases to ensure a systematic and transparent review: Identification: A total of 456 records were initially identified through comprehensive database searches, consisting of 150 articles from Scopus, 200 from ScienceDirect, and 106 from Google Scholar. Screening: After removing duplicates, 456 records underwent title and abstract screening. During this stage, 401 articles were excluded because they were either published outside the defined period (2014–2025) or were irrelevant to the specific field of food science and technology. This process left 55 articles for full-text assessment.

Eligibility: The 55 full-text articles were rigorously evaluated for eligibility. 26 reports were excluded based on specific criteria: 10 articles did not focus on soy protein isolate (SPI), 8 were not original primary research articles (e.g., reviews or book chapters), and 8 lacked essential data regarding texture or functional measurement. Included: After this rigorous screening and

evaluation process, a final total of 29 articles met all criteria and were included for qualitative and quantitative synthesis in this review.

RESULTS AND DISCUSSIONS

Inclusion articles 5

A total of 29 articles were included in this systematic review, spanning a publication period from 2017 to 2025. The geographic distribution of these studies reflects a diverse global interest in soy protein isolate (SPI)-based meat analogues, with representation from 15 countries across four continents. Asia emerged as the most dominant region, accounting for 20 studies (69%), followed by Europe with 8 studies (27.5%) and Oceania with 1 study (3.5%). In contrast, no studies from Africa met the selected inclusion criteria. Regarding economic classification, studies were balanced between income levels, with 14 articles from high-income countries (48.3%) and 15 from Low- and Middle-Income Countries (LMICs) (51.7%), highlighting a strong global commitment to sustainable food innovation across different economic landscapes.

Table 1. Articles that met the inclusion criteria

Author	Title	Research Purposes	DOI
(20)	Fabrication and characterization of double-network meat analogues based on camellia oleosomes and soy protein-wheat gluten induced by transglutaminase and calcium alginate	Developing and characterizing plant-based analogue meat with a double-network structure, using a combination of soy protein, wheat gluten, and oleosomes from camellia seeds, induced by transglutaminase enzyme and calcium alginate.	https://doi.org/10.1016/j.ijbiomac.2025.143322
(21)	Enhancing variability in fibrous structures via geometric modifications of breaker plates in high-moisture extrusion of meat analogues	Evaluating the effect of variations in breaker plate geometry during extrusion under high humidity conditions on the fiber structure and mechanical properties of soy protein isolate-based meat analogue.	https://doi.org/10.1016/j.foodeng.2025.112602
(22)	Development of emulsion gels as animal fat analogues: The impact of soybean and coconut oil concentration on rheological and microstructural properties	Evaluating the effect of the type and concentration of vegetable oils (soybean oil and coconut oil) on the rheological properties and microstructure of soy protein isolate (SPI)-based gel emulsions, agar, and alginate as animal fat analogues.	https://doi.org/10.1016/j.foodchem.2025.102439
(23)	Gallic acid enhanced fiber formation in soy protein isolate-based meat analogues	Analyzing the effect of gallic acid addition on fiber formation (fibrous structure) in soy protein isolate (SPI)-based analogue meat produced through high-moisture extrusion	https://doi.org/10.1016/j.foodchem.2025.143329
(24)	Meat analogues: The relationship between mechanical anisotropy, macrostructure, and microstructure	Investigating the relationship between macro, micro, and anisotropic mechanical properties in analogue meat to improve texture and similarity to real meat.	https://doi.org/10.1016/j.crfs.2025.100980
(15)	Physical, chemical, and organoleptic properties of oyster mushroom	Developing and analyzing the physical, chemical, and organoleptic characteristics of analogue meat-based nuggets formulated with	https://doi.org/10.47836/ifrj.32.1.11

Table 1. Cont.

Author	Title	Research Purposes	DOI
	(Pleurotus ostreatus) meat analogue nuggets	oyster mushroom (Pleurotus ostreatus) substitution.	
(25)	Emulsion gels with chia flour enhance quality of plant-based meat analogues by reducing fat and improving texture	Developing olive oil-based emulsion gels (EGs) combined with oat bran, chia flour, and soy protein isolate (SPI) to improve the lipid profile, texture, and overall quality of plant-based patties (PPs).	https://doi:10.1016/j.lwt.2024.117140
(26)	Structure and flavor properties of meat analogues from yeast and soy protein prepared via high-moisture extrusion	Developing and evaluating meat analogues (MA) made from a blend of yeast protein and soy protein isolate using high-moisture extrusion technology	https://doi:10.1016/j.lwt.2024.117013
(27)	Influence of cellulose and pectin on anisotropic texture of high-moisture meat analogue from soy protein isolate	Understanding the effect of adding dietary fiber in the form of cellulose (insoluble fiber) and pectin (soluble fiber), either separately or in combination (in the form of artificial and natural mixtures), on the anisotropic structure and texture of high-moisture meat analogues (HMMA) based on soy protein isolate (SPI).	https://doi:10.1111/jifs.17549
(28)	Ingredient Functionality of Soy, Chickpea, and Pea Protein before and after Dry Heat Pretreatment and Low Moisture Extrusion	To investigate the effect of dry heat pretreatment on the functionality of plant-based protein raw materials, namely soy protein, chickpea protein, and pea protein, in the production of texturized vegetable protein (TVP) using low-moisture extrusion.	https://doi:10.3390/foods13142168
(29)	Optimizing Screw Speed and Barrel Temperature for Textural and Nutritional Improvement of Soy-Based High-Moisture Extrudates	Evaluating the effect of screw speed and barrel temperature on the high-moisture extrusion process on the texture characteristics and nutritional value of extruded products based on soy protein isolate and concentrate.	https://doi:10.3390/foods13111748
(30)	Soluble and insoluble fractions of soy protein isolate affect the properties of its high-moisture extrudates	Understanding how the soluble and insoluble fractions of soy protein isolate (SPI) affect the rheological properties, structure, and texture characteristics of SPI-based high-moisture extruded products.	https://doi:10.1016/j.fbio.2024.103850
(31)	Textured soy protein with meat odor as an ingredient for improving the sensory quality of meat analogue and soy burger	Evaluating the use of textured soy protein (TSP) supplemented with thiamine (as a precursor for meat aroma) in improving the sensory quality of meat analogue products and soy burgers.	https://doi:10.1007/s13197-023-05875-0
(11)	Physical and sensory characteristics of soybean and glucomannan-based meat analogue for obesity intervention	Developing soy protein isolate and glucomannan-based meat substitutes for obesity intervention, and determining the physical characteristics (such as cooking shrinkage and water-holding capacity) and sensory characteristics (appearance, texture, taste, aftertaste, and acceptability) of the product.	https://doi:10.20473/amnt.v8i1.2024.67-73
(32)	Conformational changes and product quality of high-moisture extrudates produced from soy, rice, and pea proteins	Understanding how proteins from soybeans, peas, and rice behave during high-moisture extrusion (HME), with a focus on the formation of meat-like fibrous structures as well as changes in the conformation and textural properties of the resulting products.	https://doi:10.1016/j.foodhvd.2023.109341
(33)	Type of pectin determines the structuring potential of soy proteins into meat analog applications.	Understanding how different types of pectin (from soybeans, sugar beets, and oranges with high and low methylation degrees) affect the ability of soy protein isolate (SPI) to form fibrous structures using shear cell technology, which is a method for producing meat analogues.	https://doi:10.1016/j.foodhvd.2023.109262
(7)	High-moisture soy protein-mushroom-based meat analogue: physicochemical, structural properties and its application	Developing soy-based and king oyster mushroom-based meat analogues using high-moisture twin-screw extrusion, and evaluating their physicochemical properties, structure, and	https://doi:10.1111/jifs.16595

Table 1. Continue

Author	Title	Research Purposes	DOI
(34)	Influence of extrudate to SPI-gel-binder ratios and transglutaminase crosslinking on texture of a plant-based salami analogue	application as meat substitutes in Thai-style sausage products (Sai-aua). Understanding the effect of the extrusion ratio on soy protein isolate (SPI)-based binders, as well as the role of transglutaminase (TG) enzymes in forming the texture of plant-based salami analogues.	https://doi:10.1016/j.fufo.2023.100235
(35)	Impact of interactions between soy and pea proteins on quality characteristics of high-moisture meat analogues prepared via extrusion cooking process	Understanding how mixing soy protein isolate (SPI) and pea protein isolate (PPI) in various ratios affects the quality characteristics of high-moisture meat analogue (HMMA) processed using extrusion technology.	https://doi:10.1016/j.foodhvd.2023.108567
(36)	Textural, Sensory and Volatile Compounds Analyses in Formulations of Sausage Analogues Elaborated with Edible Mushrooms and Soy Protein Isolate as Meat Substitute	Developing mushroom-based and soy protein isolate-based sausage analogues as meat substitutes, and evaluating the texture, taste, and aroma compounds produced to resemble authentic meat sausages.	https://doi:10.3390/foods1010052
(37)	Mapping the texture of plant protein blends for meat analogues	Mapping the rheological properties of plant-based protein blends (soybean, pea, and wheat gluten) used in meat analogue production, using texture maps and color schemes, to understand the relationship between composition, processing conditions, and texture characteristics.	https://doi:10.1016/j.foodhvd.2021.106753
(38)	Blending Proteins in High Moisture Extrusion to Design Meat analogues: Rheological Properties, Morphology Development and Product Properties	Determining the effect of mixing soy protein isolate (SPI) with whey protein concentrate (WPC) in the high-moisture extrusion process on the rheological properties, morphological development, and texture of meat analogue products.	https://doi:10.3390/foods10071509
(39)	High Moisture Extrusion of Soy Protein: Investigations on the Formation of Anisotropic Product Structure	Understanding the mechanism of water release (juiciness) from soy protein gel and plant-based meat analogues using the confined compression method, as well as examining the influence of internal structure (such as water-filled cavities) on the rate of water release.	https://doi:10.3390/foods10010102
(40)	Water release kinetics from soy protein gels and meat analogues as studied with confined compression	Understanding the mechanism of anisotropic structure formation in soy protein isolate-based meat analogue products through high moisture extrusion, particularly by observing changes in protein interactions and the microstructure of multiple phases	https://doi:10.1016/j.ifset.2020.102528
(41)	Development of High-Moisture Meat analogues with Hemp and Soy Protein Using Extrusion Cooking	To determine the potential substitution of soy protein isolate (SPI) with hemp protein concentrate (HPC) in the production of high-moisture meat analogues using extrusion techniques, and to assess its impact on product texture and color.	https://doi:10.3390/foods9060772
(42)	Evaluation of the Physicochemical and Structural Properties and the Sensory Characteristics of Meat Analogues Prepared with Various Non-Animal-Based Liquid Additives	To determine the effect of various types of non-animal liquid ingredients (such as water, canola oil, emulsions, SPI, and lecithin) on the physicochemical properties, structure, and sensory characteristics of meat analogue products.	https://doi:10.3390/foods9040461
(43)	Functional and instrumental textural properties of reduced-salt meat emulsions with konjac gel: Combined effects of transglutaminase, isolate soy protein, and alginate	To determine the effect of the combination of konjac gel, transglutaminase (TG), soy protein isolate (SPI), and alginate on the functional properties and texture of low-salt emulsion meat, to produce a product with a quality similar to normal emulsion meat.	https://doi:10.1080/10942912.2020.1797784

Table 1. Cont.

Author	Title	Research Purposes	DOI
(44)	Gelling properties of myofibrillar protein-soy protein and k-carrageenan composite as affected by various salt levels	To determine the effect of different salt concentrations on the gel properties of a composite system of myofibrillar soy protein isolate (SPI) and kappa carrageenan, to improve the quality of low-salt meat products containing plant-based protein.	https://doi:10.1080/10942912.2019.1705482
(45)	Improving the quality of meat-free sausages using j-carrageenan, konjac mannan and xanthan gum	To determine and compare the effects of adding j-carrageenan, konjac mannan, and xanthan gum (0–1.5%) on the physical and sensory characteristics of meat-free sausages based on soy protein isolate.	https://doi:10.1111/ijfs.13394

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In terms of publication trends, research is concentrated in recent years, with the most dominant period occurring between 2024 and 2025, which accounts for 16 studies (55.2% of the total). This is followed by publications in 2020–2021 (7 studies, 24.1%), while the remaining 6 studies (20.7%) were published between 2017 and 2023. This upward trend indicates a rapidly accelerating academic interest in SPI applications for meat analogues, particularly in the last two years, likely driven by increasing consumer demand for sustainable and healthy plant-based protein alternatives.

Nutritional Content of Soy Protein

Soy protein is of high quality, comparable to animal proteins such as meat and milk, with dried soybeans containing approximately 35–40% protein, 20% lipids, 9% dietary fiber, and 8.9% water (11). The three main commercial soybean products include soybean flour, soybean protein

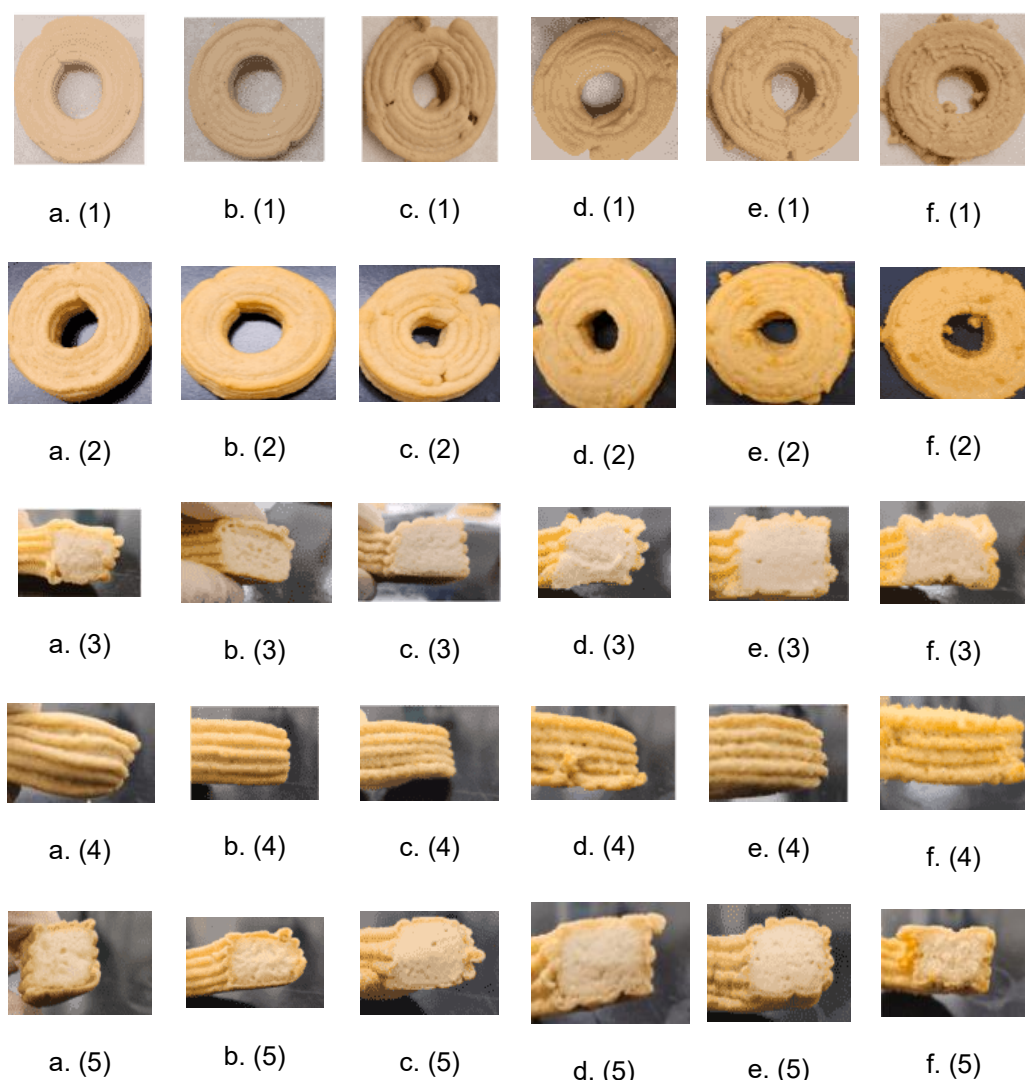
concentrate, and soybean protein isolate (SPI) (46). SPI is the purest form of soy protein, obtained through fat and carbohydrate extraction, yielding a higher protein content, a neutral taste, and a light color that suits various food formulations like meat analogues (46,47). Containing roughly 90% protein primarily composed of beta-conglycinin (7S globulin) and glycinin (11S globulin) (32,42,48), SPI exhibits a high digestibility of 95%–98% and a PDCAAS score of 1.00, which is comparable to meat, egg, and milk proteins (12,26,49,50). The amino acid profile of soy protein isolate (SPI) demonstrates a rich composition of essential and non-essential amino acids expressed in mg/g protein (35). Specifically, the essential amino acids include leucine at 60.3 ± 1.8 mg/g protein, lysine at 47.6 ± 1.3 mg/g protein, phenylalanine at 41.0 ± 0.8 mg/g protein, valine at 31.9 ± 0.9 mg/g protein, threonine at 29.8 ± 0.7 mg/g protein, isoleucine at 29.6 ± 0.8 mg/g protein, histidine at 20.2 ± 0.8 mg/g protein, methionine at 9.2 ± 0.3 mg/g protein, and tryptophan at 9.0 mg/g protein (36). Furthermore, SPI contains significant amounts of non-essential and functional amino acids, with glutamic acid having the highest concentration at 151.6 ± 4.1 mg/g protein, followed by aspartic acid at 91.3 ± 2.6 mg/g protein, arginine at 58.5 ± 1.0 mg/g protein, serine at 43.9 ± 1.1 mg/g protein, proline at 37.5 ± 0.9 mg/g protein, glycine at 32.1 ± 0.8 mg/g protein, alanine at 30.7 ± 0.9 mg/g protein, tyrosine at 25.0 ± 1.0 mg/g protein, and cysteine at 1.5 mg/g protein (35). Glutamic acid is typically used as monosodium glutamate (MSG), which imparts a unique flavor commonly referred to as umami when added to food (51). Several peptides have been confirmed to possess a flavor profile similar to monosodium glutamate (MSG) and, alongside glutamic acid, aspartic acid, and ribonucleotides,

significantly influence the perception of umami flavor, indicating that aspartic acid plays a crucial role in the complexity and intensity of umami taste (52). Conversely, the lowest amino acid content in SPI is tryptophan, measured at 0.15 g/100 g, which is significantly lower compared to beef from male cattle aged 12–18 months at 0.41 ± 0.01 g/100 g (53).

Functional Characteristics of Soy Protein Isolate

Soy protein isolate possesses several vital functional properties that make it an exceptional ingredient for plant-based meat analogues, including a strong capacity to form dense, uniform,

elastic, and break-resistant gels that function effectively as binders (40,54), alongside playing a critical role in developing fibrous or anisotropic structures during the extrusion process (29). These structural enhancements are supported by stable viscoelasticity and increased strength driven by disulfide bond formation without significantly altering the protein's secondary structure (32,42). While base- or acid-precipitated SPI exhibits high solubility, good emulsification, and robust gel-forming capabilities, additional heat treatments reduce solubility but enhance water-binding capacity while maintaining good gelation (8).



Note: (XG: xanthan gum, PE: pectin, HM: high methoxyl pectin, GG: gellan gum, LO: locust bean gum, CON: control) in raw condition, after frying, cross-section, layer section, and after freeze-drying.

Figure 2. Appearance of 3D analogue meat with various gelling agents

Overall, the functional attributes of SPI such as solubility, emulsification, and gel formation are heavily dictated by environmental and processing conditions, with hydrolysis and thermal treatments serving as critical parameters to optimize texture development in meat analogue applications. Methodological variations significantly alter these functional properties, as demonstrated through distinct processing techniques. Enzymatic hydrolysis can modify the molecular structure of SPI and consequently influence its functional properties. Methodological variations significantly alter these functional properties, as demonstrated through distinct processing techniques. Enzymatic hydrolysis can modify the molecular structure of SPI and consequently influence its functional properties

. Recent studies have demonstrated that enzymatic hydrolysis, particularly when combined with other processing treatments, can improve the emulsifying and foaming properties of SPI. However, the extent of these improvements depends on the degree of hydrolysis and processing conditions (55). Conversely, subcritical water treatments can significantly alter the conformational structure of SPI, where increasing treatment temperatures progressively improves the protein's emulsifying activity index (EAI). Furthermore, optimal subcritical thermal parameters have been shown to enhance both foam capacity (FC) and foam stability (FS) relative to untreated native soy proteins (56).

The Role of Soy Protein Isolate in the Formation of Structure, Texture, and Flavor of Analogue Meat

Soy protein isolate (SPI) is the primary component for forming gel networks and structures in analogue meat, where its water absorption and retention capabilities significantly enhance product juiciness (40,54,57). Optimal SPI incorporation improves elasticity, gel strength, water-holding capacity, hardness, cohesiveness, springiness, and internal structural homogeneity, although excessive amounts can diminish gel quality and reduce water-holding capacity (16,42,44). Beyond structural and textural contributions, SPI influences sensory profiles through volatile compounds like n-hexanal, 1-octen-3-ol, and 2-pentylfuran that produce a

characteristic beany aroma. At the same time, its glutamic acid content imparts an umami flavor (26,50,51,58). Furthermore, SPI's ability to form gels and fibers upon heating makes it a key ingredient for developing the fibrous tissue structures of meat analogs (56). **Figure 2** shows 3D-printed artificial meat with differences in surface structure.

The visualization in **Figure 2** shows that the structural and textural characteristics of soy protein isolate (SPI)-based analogue meat are heavily governed by strategic ingredient combinations, where incorporating hydrocolloids like pectin with xanthan gum or gellan gum yields smooth, dense surfaces and animal-like fiber matrices (56), while blending 5% SPI with 7% gelatin exceeds national protein standards by 8% (17). During high-moisture extrusion cooking (HMEC), SPI's high viscosity, moisture retention, and anisotropic structuring enhance extensibility, structural stability, and juiciness (5,11,40,59–61). Its high lightness and low redness and yellowness, driven by Maillard reactions, make it ideal for chicken-like alternatives despite the persistent beany-flavor hurdle (11,32,62). Optimizing product design also requires evaluating auxiliary ingredients, as substituting SPI with rice protein isolate decreases water absorption and porosity (63), whereas incorporating wheat gluten (WG) yields a compact ultrastructure with superior sliceability and chewiness (64,65). Multi-component blends combining 50% SPI, 40% WG, and 10% corn starch further generate a compact, fibrous, and meat-like structure with a higher nitrogen solubility index (65), enabling manufacturers to precisely regulate water binding and morphological properties for commercially viable alternatives.

The Role of Soy Protein Isolate in Forming Analogue Sausage and Meat Patties Analogue Sausage

Soy protein isolate (SPI) increases the protein content of analogue sausage formulations. SPI functions as a primary binder, mimicking the role of meat proteins by forming the structure and controlling the hardness, springiness, and cohesiveness of the analogue sausage (16,34). The prior study (7) reported that increasing the proportion of SPI in sausage production directly

correlates with improved textural values (hardness and chewiness), batter viscosity, and water-holding capacity. The resulting sausages exhibit a fibrous structure, formed through disulfide bonds during the extrusion process.

A study by (45) indicated that SPI contributes to forming the product's fundamental protein framework, which is essential for its texture. It also significantly contributes to nutritional value, with

protein content reaching 13.55%, comparable to meat sausages (12-14%). The prior study (36) reported that analogue sausages containing SPI had a texture and aroma that were not significantly different from commercial meat sausages, especially after dry fermentation, which enhanced the diversity and intensity of aromatic compounds. The role of SPI in forming analogue sausages can be further observed in **Figure 3**.

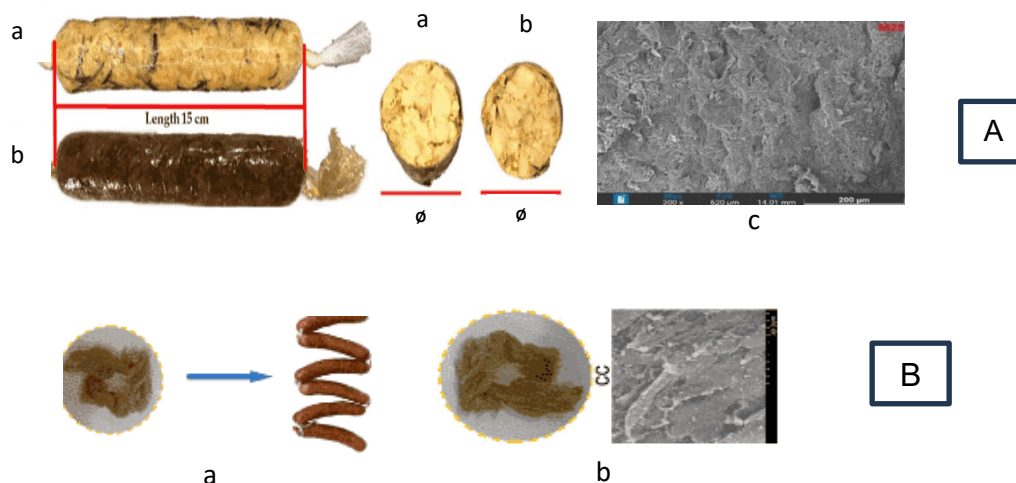


Figure 3. Visual appearance of uncooked analogue sausages

Note: A: (a), cooked (b), microstructure with magnification 300 x (c). Thai Northern-style sausage (Sai-ua) made from soy protein-mushroom based meat analogue M25 in cellulose casing (diameter 3.5 and 15 cm in length) and cross section of a and b. (7); B: (a) Appearance of analogue Sausage, (b) Microstructure of analogue Sausage (36)

Figure 3 a illustrates a Thai sausage (Sai-ua) product made with a mixture of soy protein isolate (SPI) and M25 mushroom powder (35:25), encased in cellulose. This product displayed a good structure after undergoing a high-moisture (61–64% wet weight) twin-screw extrusion process. The best formulation used 25% king oyster mushroom powder (M25), containing 15g of mushroom powder per 100g of total ingredients, which resulted in an optimal fibrous structure (7). Meanwhile, another analogue sausage was developed from three types of mushrooms (*Lentinus edodes*, *Coprinus comatus*, and *Pleurotus ostreatus*), with the best treatment being a combination of 15% *Coprinus comatus* (CC) mushroom and 100% SPI. Analysis showed that this analogue sausage had a microstructure and appearance most closely resembling beef,

especially internally, and yielded the best texture and physicochemical profile (36).

Meat Patties

Plant protein isolate acts as an effective gel-forming agent in emulsion gels, as soy protein isolate (SPI) possesses properties that enable it to emulsify oil and bind water. Formulating meat patties with SPI results in a dense texture, high viscoelasticity, and a more stable patty structure, while also contributing significantly to increasing the product's overall protein content (26). Furthermore, combining SPI with textured soy protein (TSP) in soy burger development not only elevates protein levels but also facilitates the formation of a stable protein network structure (32). Visual and microstructural evaluations further illustrate these dynamics, demonstrating that morphological and microstructural changes

occur in meat patties during processing. The visual appearance of the patties before and after cooking highlights excellent shape retention and textural evolution, while Scanning Electron Microscopy (SEM) images reveal the underlying configuration of the protein matrix (26). Specifically, raw patties exhibit a compact arrangement of SPI within the structure. In contrast, post-cooking images display a developed porous network and uniform fat globule distribution that directly correlate with the product's final juiciness and bite characteristics (26).

CONCLUSION AND RECOMMENDATION

This study confirms that Soy Protein Isolate (SPI) is not merely a nutritional filler but a fundamental structural element in the engineering of meat analogue matrices. The primary scientific contribution of this study is identifying SPI's synergistic mechanism for forming anisotropic protein networks through disulfide bonds, which functionally replicates animal muscle fibers in plant-based sausages and patties. Optimizing SPI levels has been shown to significantly enhance parameters such as viscoelasticity, gel strength, and water-holding capacity, which collectively determine the product's organoleptic acceptance. Nutritionally, SPI provides a concrete solution to protein deficiency challenges in vegetarian diets by offering an amino acid profile comparable to conventional meat. Furthermore, this study reveals a critical concentration threshold for SPI. Excessive SPI addition can trigger matrix stability degradation, which subsequently diminishes textural quality. These findings provide a robust framework for food scientists to balance functionality and palatability in developing next-generation plant-based meat products.

Based on these research findings, future studies should focus on several key areas to advance plant-based meat analogue development: optimizing multi-component formulations through synergistic combinations of soy protein isolate (SPI) with hydrocolloids or alternative plant proteins to reduce reliance on synthetic additives; evaluating emerging processing technologies like shear cell technology and advanced 3D printing for more realistic fiber structures; conducting *in vivo* studies or gastrointestinal simulations to verify optimal

nutritional bioavailability; and assessing oxidative stability and shelf-life within the SPI matrix during storage to guarantee long-term sensory quality and safety.

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