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Review article

RICE PROTEIN AS A FUNCTIONAL CARRIER: RECENT UPDATES ON MODIFICATION STRATEGIES AND ENCAPSULATION APPLICATIONS

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Abstract: Rice protein (RP), owing to its favorable nutritional profile, biodegradability, and biocompatibility, has emerged as a promising plant-based carrier for bioactive compound delivery. However, its poor water solubility, low emulsifying capacity, and rigid molecular structure limit its application in functional food systems. Recent advances have focused on physical, chemical, and enzymatic modification strategies to enhance RP's solubility and other functional properties. These improvements facilitate its incorporation into various encapsulation formats such as emulsions/nanoemulsions, micro/nanoparticles, edible films, and hydrogels. This review summarizes current progress in RP modification and its impact on encapsulation performance, including stability, bioactive protection, and controlled release. It also explores the interaction mechanisms between RP and bioactives and highlights challenges such as limited mechanistic insight. Future research should aim to develop food-grade, mild modification methods and investigate the digestive fate and bioavailability of RP-based delivery systems for functional food and nutraceutical applications.

Keywords: *rice protein, encapsulation, emulsion, solubility, bioactives*

INTRODUCTION

With the rapid growth of the global population and increasing concerns about the negative environmental impact of animal protein production, there has been a significant shift from animal-based protein toward plant-based protein sources (Kim, Wang & Selomulya, 2024). This transition is driven by the demand for sustainable, health-promoting, and ethically acceptable alternatives. Currently, the most consumed plant proteins include soy protein, pea protein, wheat protein (gluten), and rice protein. Compared to other plant proteins, rice protein has gained growing attention due to its favorable amino acid profile, hypoallergenic nature, and high digestibility (Jayaprakash, Bains, Chawla, Fogarasi, & Fogarasi, 2022). These characteristics make rice protein a promising ingredient for functional foods and nutraceutical applications, particularly in systems requiring clean-label and allergen-free formulations (Zheng, San, Xing, & Regenstein, 2024). Rice protein (RP) is the second most abundant com-

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ponent in rice (6-8%), following starch, which accounts for approximately 70-85%. Various extraction techniques have been reported, including alkaline extraction, solvent extraction, enzymatic extraction, and various physical-assisted methods (Jayaprakash et al., 2022; Zheng et al., 2024; Sun & Zhao, 2026). However, in industrial practice, rice protein is typically obtained as a byproduct of the enzymatic hydrolysis of starch. The resulting protein-rich residue undergoes further processing, including wet-milling, enzymatic treatment, washing, and drying, to reduce fat and sugar content, producing a final product with protein concentration exceeding 80%.

Despite its high protein content, the application of a protein-rich residue in the food industry remains limited due to its inherently poor solubility. This drawback negatively impacts other key functional properties, such as foaming, emulsification, gelation, and digestibility (Zhao Xiong, Chen, Zhu & Wang, 2020; Huang, Xia, Liu, & Wang, 2024). To overcome these limitations, various modification strategies, including physical, chemical, and enzymatic approaches, have been employed to improve the protein's structural and functional properties (Zheng et al., 2024).

Proteins possess amphiphilic structures, which allow them to interact with both hydrophobic and hydrophilic bioactive compounds, making them effective carriers for bioactive ingredients. Traditionally, animal-derived proteins, such as milk and egg proteins, are the most widely used encapsulation agents in the food industry (Zhao, Liang, & Li, 2023; Wang & Zhao, 2022; Zhang, Guo, Liu, & Luo, 2023). However, interest in plant-based proteins as encapsulation matrices has surged over the past decade due to their lower environmental impact, cost-effectiveness, and greater suitability for vegetarian, vegan, and allergen-sensitive populations (Kim et al., 2024). Nevertheless, plant proteins often face challenges such as poor solubility, structural heterogeneity, and limited functional performance (Jayaprakash et al., 2022).

Therefore, structural modifications and optimized processing techniques are essential to enhance the encapsulation efficiency of plant proteins. The interaction between plant proteins and bioactive compounds involves complex covalent and non-covalent bonding, influenced by factors such as pH, treatment conditions, and the molecular characteristics of both the protein and the target bioactive compounds.

Recent reviews (Yan et al., 2023; Kim et al., 2024) have comprehensively examined the binding mechanisms between plant proteins and polyphenols, highlighting methods to promote conjugate formation and their associated structure-function relationships. However, much of the research has concentrated on soy and pea proteins, with limited attention on rice protein. Given its hypoallergenic nature and well-balanced amino acid profile, rice protein remains an underexplored yet highly promising candidate for the encapsulation and delivery of bioactive compounds across the food, pharmaceutical, and nutraceutical sectors.

To date, most reviews have focused on rice protein extraction and modification, while its potential as a delivery vehicle for bioactive compounds has received limited attention. Therefore, the objective of this review is to summarize recent advancements in the structural modification of rice protein and its use in various encapsulation systems, including direct complexation (micro/nanoparticles), emulsions/nanoemulsions, hydrogels, and edible films. Furthermore, this review will discuss the interaction mechanisms, identify existing challenges, and propose future directions to promote the broader application of rice protein in food and pharmaceutical formulations.

MATERIALS AND METHODS

The present study was designed as a systematic review conducted in accordance with the PRISMA 2020 guidelines. Firstly, a systematic search of literature was performed in PubMed, Scopus, and Web of Science to identify relevant articles published up to 2025. A structured search strategy was developed using predefined terms related to rice proteins and polyphenols, combined with Boolean operators: ("rice protein" OR "rice bran protein") AND ("polyphenol" OR "phenolic compound" OR flavornoid"). Only peer-reviewed original research articles published in English were considered eligible. Conference abstracts, reviews, book chapters, and other non-original studies were excluded.

After removing duplicates, the titles and abstracts were screened by two reviewers independently to evaluate eligibility. Full-text articles were subsequently assessed according to predefined inclusion and exclusion criteria. All disagreements were resolved through discussion until a consensus was reached.

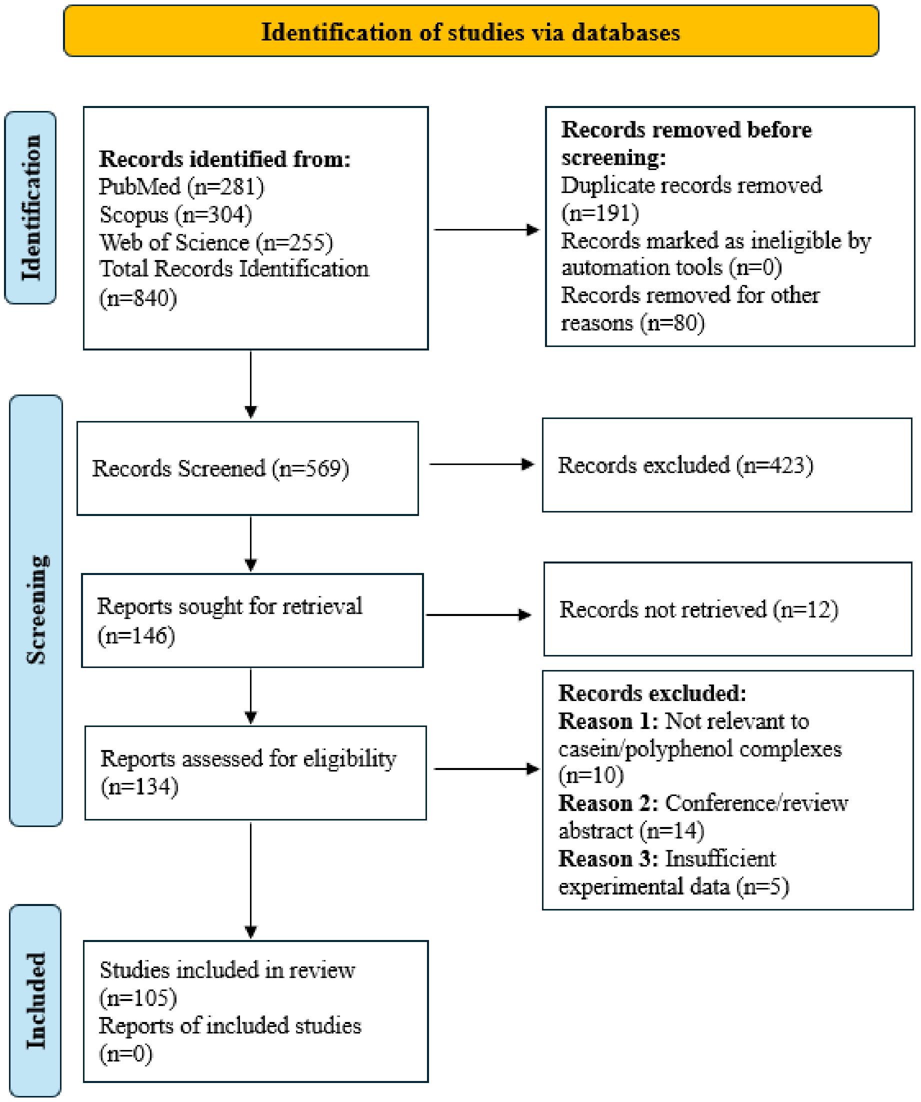

Figure 1. PRISMA 2020 flow diagram illustrating the study identification, screening, eligibility, and inclusion process

Table 1.

Categories of rice protein and their physicochemical properties

Protein fraction	Solubility	Abundance (% of total)	Molecular weight (kDa)	Isoelectric point (PI)	Key properties
Albumins	Water-soluble	5-10	30-45	4.1,6.4	High digestibility, rich in lysine, limited functional use due to low hydrophobicity
Globulins	Salt-soluble	7-17	20-66	4.3, 5.85-7.27, 7.9	Balanced amino acid profile, moderate solubility
Glutelins	Alkali-soluble	75-81	10-66	4.8, 5.7-6.8, 8.0-8.7	Good film-forming and gelation ability, low solubility in neutral pH, heat-stable
Prolamins	Alcohol-soluble	3-6	10-53	6.0-6.5	Rich in hydrophobic amino acids, useful for lipophilic compound encapsulation

The detailed selection process, including the number of records identified, screened, excluded, and included, is presented in a PRISMA 2020 flow diagram (Fig. 1).

STRUCTURAL AND FUNCTIONAL PROPERTIES OF RICE PROTEINS

Structural properties

Based on their solubility characteristics, rice proteins are classified into four major types: albumin (water-soluble), globulin (salt-soluble), glutelin (alkali-soluble), and prolamin (alcohol-soluble) (Zhao, Xiong, Chen, Zhu, & Wang, 2019). The composition and physicochemical properties of these protein fractions are summarized in Table 1.

Albumin is the only rice protein fraction soluble in water, attributed to its higher surface charge and limited disulfide crosslinking. It is composed of eight peptide subunits, is rich in lysine, and is readily digestible. Due to its porous structure, albumin is particularly suitable for bioactive delivery. However, it is heat-labile and undergoes irreversible denaturation and aggregation at temperatures above 73-75 °C. Albumin is currently the most widely used rice protein for stabilizing and delivering bioactives and pharmaceuticals (Jayaprakash et al., 2022).

Globulin is the second most abundant rice protein soluble in saline solutions. It possesses a random coil structure along with antiparallel β-sheet arrangements. Rice globulin is rich in sulfur-containing amino acids (cysteine and methionine) but contains comparatively lower levels of lysine. Upon reduction of disulfide bonds, globulin breaks down into smaller subunits, including a 16 kDa γ-globulin and a 21 kDa α-globulin (Jayaprakash et al., 2022).

Glutelin is the predominant storage protein in rice and plays a central role in determining the overall functional characteristics of rice proteins. It forms large, insoluble aggregates due to extensive disulfide bonding, glycosylation, and a compact structure, resulting in poor water solubility. However, its solubility significantly improves at extreme pH levels, either highly alkaline ($pH > 10$) or acidic ($pH < 3$) (Yu et al., 2022; Jayaprakash et al., 2022). Glutelin comprises two subunits: an acidic α-subunit (30-35 kDa) and a basic β-subunit (19-25 kDa), linked by disulfide bonds. The tendency to form large, water-insoluble aggregates is the primary reason for its limited functionality in food systems (Amagliani, O'Regan, Kelly & O'Mahony,, 2017).

Prolamin is primarily located within the protein bodies of the rice endosperm and is synthesized during seed development. It contains high levels of acidic amide residues and low levels of polar amino acids, resulting in poor solubility in water and salt solutions. However, it is soluble in 60-70% aqueous ethanol. Rice prolamin is rich in non-essential amino acids such as leucine, valine, and glutamine, but is deficient in lysine. Despite being present in relatively low amounts, prolamins play a key role in seed storage and structural integrity. They predominantly exist as low-molecular-weight polypeptides (10-16 kDa) and are considered relatively resistant to digestion (Yu et al., 2022).

Functional properties of rice protein

Like other cereal-derived proteins, rice protein exhibits various functional properties that make it valuable in food and nutraceutical applications. These include its inherent ability to bind hydrophobic bioactive compounds, enhancing their stability and bioavailability. Due to its amphiphilic nature, rice protein also possesses emulsifying capabilities, enabling it to stabilize oil-in-water emulsions/nanoemulsions, which is an essential function in processed foods and beverage formulations. Furthermore, rice protein can form cohesive films and coatings that act as effective barriers to moisture and oxygen, making it a promising material for edible packaging and shelf-life extension.

Numerous studies have reported that rice protein can interact with a wide range of bioactive compounds, such as curcumin (Xu, Qian, Wang, Chen & Wang, et al., 2022), chlorogenic acid (Pan et al., 2022), epigallo-catechin gallate (EGCG) (Zhao, Wei, Wu, Lin & Wu,, 2025), and β-carotene (Zhou, Wang, Li, Wu & Wu, 2023). Binding with certain polyphenols, such as catechins, induces conformational changes in rice protein, including an increase in β-turn and random coil content, which improves its functional characteristics (Li et al., 2020). Rice proteins also demonstrate notable emulsifying properties attributed to their amphiphilic structure, which enables them to reduce interfacial tension, stabilize interfacial layers, and generate small, uniform droplets. For instance, rice protein has been shown to form a robust interfacial layer in nanoemulsions, effectively protecting encapsulated compounds like β-carotene and quercetin from oxidative degradation by limiting their exposure to oxygen and moisture (Liu et al., 2021).

Despite these promising features, the application of rice protein as an emulsifier or bioactive carrier is often limited by several inherent drawbacks, including low solubility, weak interfacial activity, and a lack of reactive amino acid residues critical for strong protein-polyphenol interactions. Its rigid tertiary structure and suboptimal emulsifying efficiency further constrain its use in food and cosmetics. Therefore, functional improvements, such as enzymatic hydrolysis, physical processing, or chemical modifycation, are frequently necessary to enhance solubility and techno-functional properties. These modification strategies are essential to broaden the practical utility of rice protein in developing stable emulsions, controlled-release systems, and functional delivery vehicles.

MODIFICATION STRATEGIES FOR ENHANCING RICE PROTEIN FUNCTIONALITY

pH-shifting and physical treatments

The low solubility of glutelin is the main reason for the low functionality of rice protein. This poor solubility arises from extensive intra- and intermolecular hydrogen bonding, particularly involving small amino acid residues such as glycine and alanine, which interact with the amide groups of glutamine and asparagine (Yang, Meng, Wu, Chen, & Xue, 2023). These internal hydrogen bonds restrict interactions with water molecules, significantly reducing solubility. Additionally, the high content of disulfide bonds between glutelin subunits facilitates the formation of large protein aggregates, further impairing solubility and limiting functional performance (Li, Wang, Chen, Sun & Li, 2019).

Recent studies on RP-based delivery systems are summarized in Table 2. Traditional physical modification techniques, such as heating, high-pressure treatment, and sonication, have demonstrated limited ability to improve glutelin solubility. These are often combined with pH-shifting strategies to achieve more pronounced enhancements in solubility and functionality (Fig. 2). In a typical process, the rice protein dispersion is first adjusted to alkaline pH levels (pH > 9), causing the glutelin structure to unfold due to the disruption of disulfide bonds, hydrogen bonds, and hydrophobic interactions. Under these conditions, acidic amino acid residues (e.g., glutamic acid and aspartic acid) become deprotonated and negatively charged, increasing water accessibility to the protein's internal regions and thus enhancing solubility. Upon subsequent neutralization, the protein adopts a molten globule-like conformation, characterized by a disordered and partially unfolded state (Shen et al., 2023). Notably, Zhao et al. (2020) reported that treatment at 100 °C for 60 minutes at pH 12 significantly reduced disulfide bond content while increasing both surface net charge and hydrophobicity of glutelin. This treatment resulted in a threefold increase in solubility after neutralization to pH 7. Furthermore, combining pH-shifting with ultrasoniccation produced less com-pact and more dispersed protein aggregates, exhibiting both higher solubility and increased surface hydrophobicity. The modified rice proteins also demonstrated improved emulsifying capacity, forming nanoemulsions with smaller droplet sizes and enhanced stability (Igartúa, Dichano, Ferrari, Palazolo & Cabezas, 2024).

In another study, Li et al. (2025) integrated industrial-scale microfluidization with pH-shifting treatment, resulting in a substantial improvement in protein dispersibility, from 1.4% to 78.3%. Structural analysis revealed a decrease in disulfide bond content and molecular weight, an increase in surface hydrophobicity, and a secondary structure transition from β-sheet to α-helix, collectively contributing to the enhanced functional properties of rice protein.

Chemical modification

Different chemical modification strategies have been employed to enhance the solubility and functional properties of rice proteins, with glycation and deamidation being among the most extensively studied and effective approaches (Fig. 2). Mechanistically, the functional improvements observed upon chemical modification arise from specific structural alterations. Glycation, for instance, covalently attaches hydrophilic sugar moieties to the protein surface, which not only increases net solubility by enhancing water-protein interactions but also provides steric hindrance that prevents droplet coalescence in emulsions. Deamidation converts neutral amide groups into negatively charged carboxyl groups. This increase in net charge intensifies electrostatic repulsion between protein molecules, thereby reducing aggregation and improving solubility across a broader pH range. These structure-function relationships are critical for rationally designing rice protein with tailored encapsulation properties.

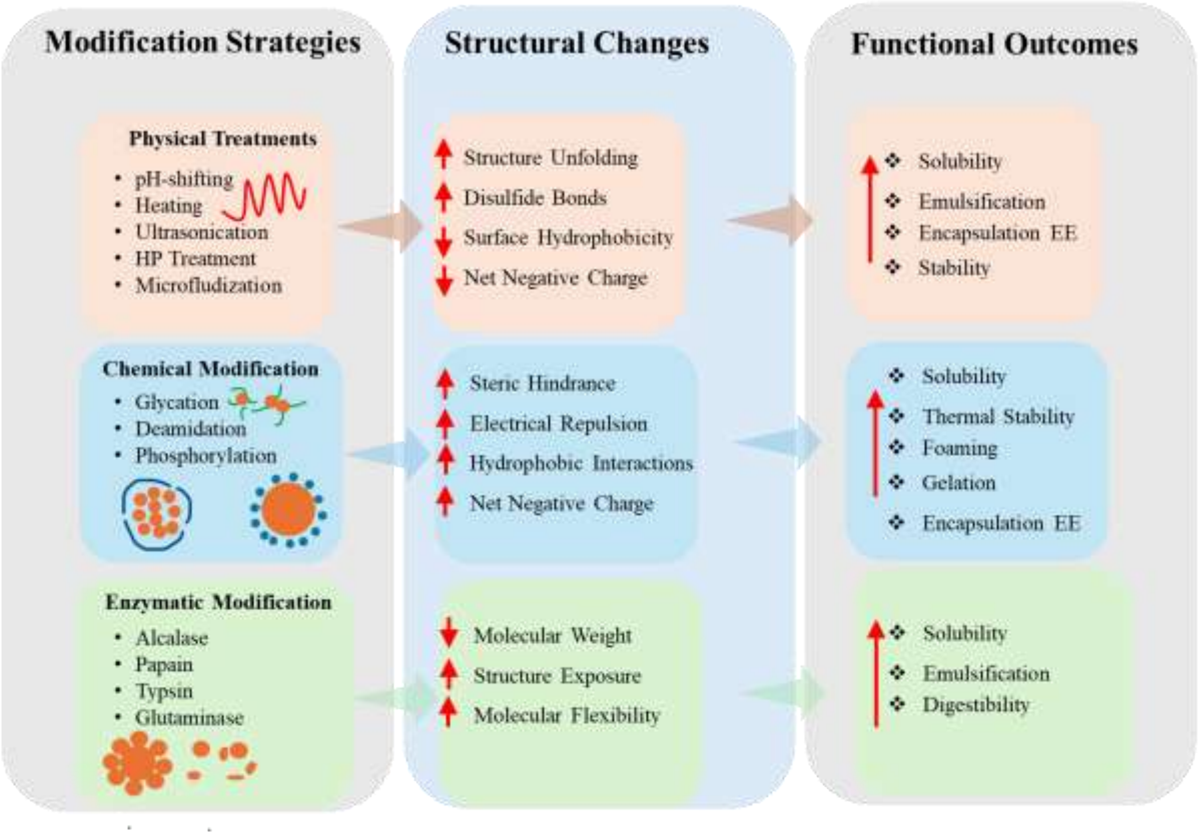

Figure 2. Modification strategies for rice protein (RP) and their functional outcomes

Table 2 .
Recent research using rice protein (RP)-based delivery systems for bioactive compounds

System Type	Bioactive Compound	Wall materials	Preparation method	Key findings	Reference
Nanoparticles	Curcumin	Rice bran protein/chitosan	Direct mixing	Increased EE Delayed degradation Increased bioavailability	Peng et al., 2017
Microparticles	Tea catechin	Rice bran isolate	Direct mixing	Modified secondary structure Increase bioavailability.	Shi et al., 2017
Microparticles	Doxorubicin	Gellan gum-sericin/rice bran albumin	Direct mixing	Increased EE Improved release profile	Arjama, Mehnath, Rajan & Jeyaraj, 2018
Nanoparticles	Curcumin	Rice bran albumin	Direct mixing	Increased EE Increased bioavailability	Liu et al., 2018
Microparticles	Vanillin	Flax seed gum/rice bran protein	Direct mixing	Increased EE Increased thermostability Increased shelf life	Hasanvand & Rafe, 2019
Microparticles	B-type procyanidin dimer (PB2)	Rice glutelin	Direct mixing	Modified secondary structure Reduced surface hydrophobicity Increased antioxidant properties	Dai et al., 2019a

Table 2. Continued

Microparticles	Anthocyanin	Rice proteins	Direct mixing	Increased EE Best functional properties at pH 3	Li et al., 2020
Microparticles	Lactobacillus acidophilus La-5	Rice bran protein/maltodextrin	Direct mixing and spray drying	High EE Increased viability during storage Increased thermal stability Increased digestion survival	Vaniski,da Silva, da Silva-Buzanello, Canan& Drunkler,, 2021
Microparticles	Ferulic acid	Rice bran protein hydrolysates	Direct mixing	Modified protein structure Improved emulsifying properties Improved antioxidant activities	Wang et al., 2021
Microparticles	β-carotene	Rice bran protein /Maltodextrin	Direct mixing	Increased EE Improved radical scavenging activity Improved digestion behaviour	Magnaye, Mopera & Flores, 2022
Nanoparticles	Catechin	Rice bran protein	Direct mixing	Improved complexation Produced smaller size Increased emulsification properties Increased oxidation resistance	Guo, Wang, Xing, Pan & Wang, 2023
Microparticles	Anthocyanin	Rice bran protein /maltodextrin	Direct mixing and spray drying	Increased anthocyanin retention Protected anthocyanin during spray drying of grape juice	Almeida, Gomes & Kurozawa, 2023
Microparticles	Anthocyanin	Hydrolyzed rice bran protein / maltodextrin	Direct mixing and spray drying	Increased surface activity Increased migration to the surface Increased EE	Almeida, Gomes & Kurozawa, 2024
Microparticles	Curcumin	Alkylated rice bran protein	Direct mixing	Alkylation increased EE Increased protection effect	Wang et al., 2024
Nanoparticles	Curcumin	Rice glutelin/rhamnolipid	Direct mixing	Increased EE Increased stability	Wu et al., 2025
Microparticles	Polyphenols	Rice protein	Direct mixing	Increased emulsion activity Covalent effect> non-covalent effect	Shi et al., 2024b
Emulsion	Fish oil	Rice glutelin / polysaccharides	Homogenization	Improved stability. Increased oxidative stability	Xu et al., 2017a,b
Emulsion	Resveratrol	Rice glutelin	Homogenization	Increased emulsifying capacity Produced smaller droplets	Dai et al., 2019b
Emulsion	Ferulic acid	Rice protein isolate	Homogenization	Increased antioxidation effect Decreased fat oxidation degradation	Jia et al., 2019
Nanoemulsion	Quercetin	Rice bran protein	Homogenization	Decreased size of emulsion droplet Increased stability Increased bioavailability	Chen et al. 2020

Table 2 Continued

Nanoemulsion	Chlorogenic acid	Rice protein/ dextran conjugates	Homoge-nization	Produced smaller particles Increased storage stability Increased oxidative stability	Liu et al., 2020
Emulsion	Ferulic acid	Rice bran protein hydrolysate	Ultraso-nication	Improved emulsifying capacity Reduced the droplet size Enhanced emulsion stability	Wang et al., 2022b
Emulsion	Fish oil	Rice bran protein fibrils /xanthan gum	Homogeni-zation and freeze drying	Increased EE Increased storage stability	Tang et al., 2022
Emulsion	Catechin	Rice bran protein	Homoge-nization	Improved emulsion stability Enhanced oxidation stability	Li et al., 2023
Emulsion	Orange essential oil	Rice protein hydrolysates /maltodextrin	Homoge-nization	Improved oil retention capacity Improved protein adsorption on surface	Gomes & Kurozawa, 2024
Emulsion	β-Carotene	Fibrillated rice protein hydrolysate	Homo-genization	Increased surface hydrophobicity Rapid adsorption to the interface Protecting β-carotene from degradation	Qi et al., 2024
Emulsion	Polyphenols	Rice protein	Homo-genization	Improved oxidative stability Inhibited lipid oxidation Enhanced interfacial structure	Shu et al., 2025
Edible films	Phenolic extract	Rice bran protein	Heat dry	Improved antioxidant properties Improved antibacterial properties Increased elasticity/tensile strength Increased water vapor permeability	Schmidt et al., 2015
Edible films	Curcumin	Rice hydrolysate/Chitosan		Increased antioxidant properties Increased antibacterial properties Increased thermal stability	Xie et al., 2022
Edible films	Curcumin	Rice protein hydrolysate / Chitosan	Heat dry	Increased DPPH scavenging activity Increased antimicrobial activity	Xie et al., 2023
Hydrogel	Curcumin	Rice protein/pectin	Heating	Increased viscoelasticity and stability Increased water holding capacity Improved EE Controlled release rate	Cheng et al., 2024
Emulsion gel	Free fatty acid	Rice bran protein aggregates	Homoge-nization/ GDL and Laccase	Increased water holding capacity Decreased release of free fatty acid	Luo et al., 2023
Emulsion gel	Curcumin	Rice bran protein	Homoge-nization and TGase	Increased EE Increased stability Promoted more compact structure	Liu et al., 2024

In glycation, the carbonyl groups of carbohydrates covalently react with the amino groups of proteins via the Maillard reaction, forming protein-carbohydrate conjugates with improved solubility and functional attributes (Yang et al., 2023). For instance, Xiao et al. (2021) reported that rice protein-glucose Maillard reaction products exhibited significantly enhanced solubility, thermal stability, and antioxidant activity. Rice protein has also been successfully conjugated with a group of carbohydrates, including arabinose, sodium alginate, maltodextrin, and lactose. Among these, conjugates with arabinose and maltodextrin demonstrated the highest degrees of glycation, with rice protein-arabinose conjugates showing the greatest improvement in solubility and emulsifying capacity (Liu et al., 2020). Similar enhancements have been observed in rice protein conjugates with dextran (Cheng et al., 2022; Chen et al., 2022) and exo-polysaccharides (Zhao, Ye, Wan, Zhang, & Sun, 2021).

Deamidation involves the conversion of amide groups in the side chains of amino acids-primarily asparagine and glutamine-into carboxylic acid groups, which decreases hydrogen bonding and molecular aggregation, thereby improving solubility and surface hydrophobicity (Yang et al., 2023). Deamidation can be achieved through acidic or alkaline hydrolysis or enzymatic catalysis. For example, Guan et al. (2017) demonstrated that alkaline deamidation at pH 12 and 120 °C for 15-30 minutes resulted in a maximum solubility of 90%, without altering the protein's secondary structure. In another study, Shi et al. (2024a) utilized citric acid-based natural deep eutectic solvents to perform deamidation, which significantly enhanced the solubility and emulsifying activity of rice protein, while maintaining pH stability.

Despite their effectiveness, chemical modifycation methods face several challenges that limit industrial application. These include process complexity, low reproducibility, and high cost, which may hinder their scalability and feasibility in commercial food and nutraceutical production

Enzymatic modification

Enzymatic modification enhances rice protein functionality primarily through proteolytic cleavage of peptide bonds. This controlled hydrolysis reduces the average molecular weight and disrupts the compact, aggregated structure of native glutelin. The resulting smaller peptides expose a higher proportion of exposed hydrophilic amino and carboxyl terminals, which significantly increases water solubility. Furthermore, the increased molecular flexibility allows for rapid conformational rearrangement at the oil-water interface, explaining the observed improvements in emulsifying activity and stability (Yang et al., 2023).

Several enzymes have been employed to partially hydrolyze rice proteins, including alcalase, papain, trypsin, and glutaminase (Fig. 2). Singh, Siddiqi, and Sogi (2021) reported that the hydrolysis of rice protein using papain significantly improved both solubility and digestibility in proportion to the degree of hydrolysis. Liu et al. (2022) found that alcalase exhibited higher hydrolysis efficiency than papain. Furthermore, combining alcalase treatment with high hydrostatic pressure (HHP) resulted in a significant decrease in α-helix content and an increase in random coil structures, which collectively enhanced solubility and emulsifying properties. At 300 MPa, treatment with an alkaline protease increased rice protein solubility by 1.7-fold, and enhanced emulsifying activity and stability by 2- and 3-folds, respectively. Microfluidization pretreatment has also been shown to improve enzymatic hydrolysis efficiency. Zhang et al. (2021) demonstrated that microfluidization not only facilitated enzymatic access to cleavage sites but also enhanced the final solubility and functional performance of the modified rice proteins.

Beyond conventional proteolysis, enzymatic approaches have also proven effective through deamidation. Protein-glutaminase, an enzyme that specifically deamidates glutamine residues without hydrolysis or transglutaminase activity, achieved a deamidation degree of 60.4%, leading to significant improvements in solubility, foaming capacity, emulsification, oil-holding capacity, antioxidant activity, and *in vitro* digestibility (Zhang et al., 2025). Yang et al. (2024) further demonstrated that combining disulfide bond reduction with deamidation improved rice protein solubility from 1.29% to 51.45%. In contrast, phosphorylation showed minimal impact on solubility enhancement. However, it has been proven to significantly increase the heat gelation properties of rice glutelin (Wang, Yang, Li-Sha & Chen, 2021).

Despite its effectiveness, enzymatic modifycation presents several challenges. Achieving uniform structural changes across all protein molecules is difficult due to the heterogeneous nature of protein substrates and enzyme specificity. Moreover, bitter peptides generated during hydrolysis can negatively affect sensory properties, posing a barrier to the use of enzymatically hydrolyzed rice protein in food systems. These limitations must be addressed through enzyme selection, process optimization, and potentially post-processing techniques to improve the sensory acceptability and functional consistency of rice protein hydrolysates.

METHODS OF USING RICE PROTEIN AS A CARRIER

Unlike synthetic polymers, rice protein is biodegradable, non-allergenic, and derived from a sustainable source, making it ideal for food, pharmaceutical, and nutraceutical applications. As summarized in Fig. 3, various methods, including pH-driven complexation, emulsion-based encapsulation, hydrogel entrapment, and film formation, have been employed to optimize its carrier efficiency. These techniques exploit rice protein's amphiphilic nature, amino acid flexibility, and ability to form covalent or non-covalent bonds with polyphenols, vitamins, and hydrophobic drugs.

Protein/bioactive compound complexes

Plant proteins can interact with bioactive compounds through direct mixing, leading to the formation of complexes stabilized by both covalent and non-covalent interactions, primarily hydrogen bonding and hydrophobic interactions. The pH of the environment plays a critical role in modulating the nature and strength of these interactions. Also, the formation of complexes can be promoted by physical treatments and chemical modifications.

Effect of pH

At neutral pH, non-covalent interactions are the predominant forces stabilizing the complexes between plant proteins and polyphenols. For in-

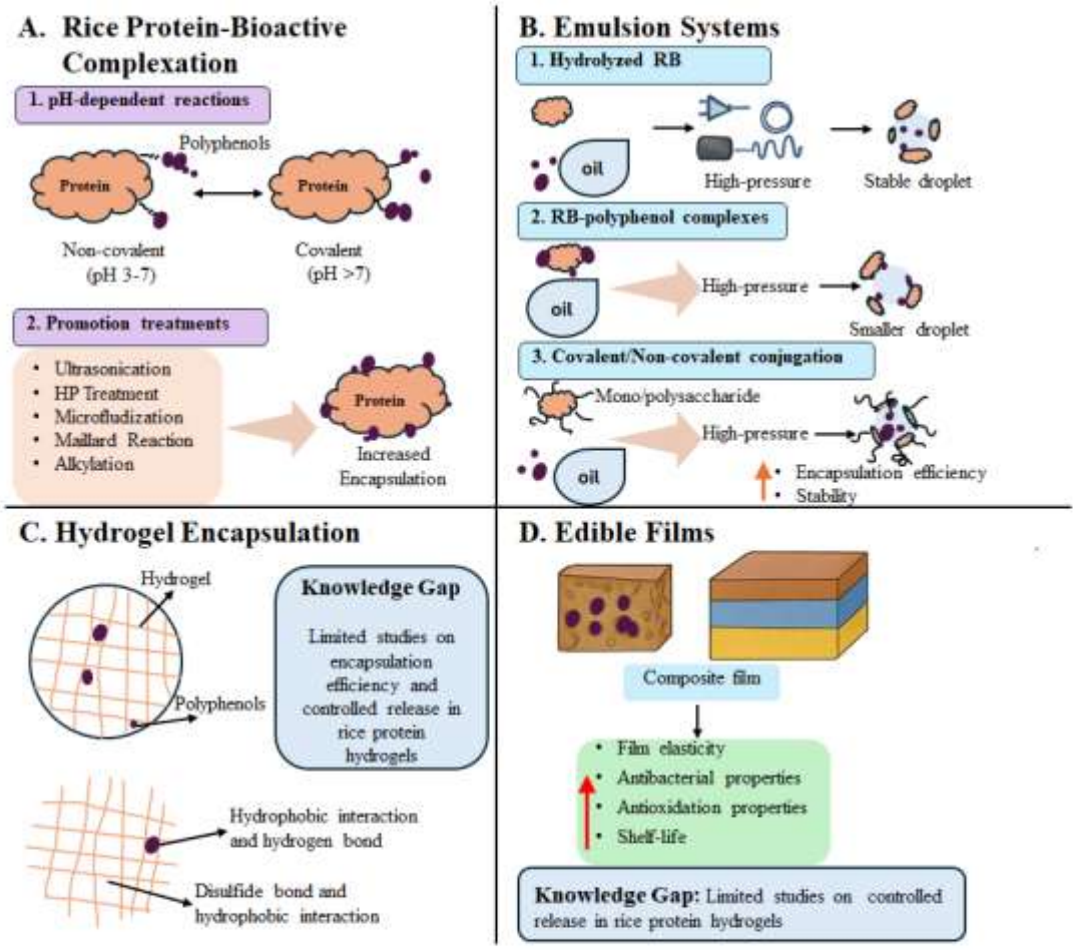

Figure 3. Rice protein as a versatile carrier for bioactive compounds: methods, mechanisms, and applications

stance, the interaction between rice glutelin and B-type procyanidin dimers (PB2) is primarily driven by hydrophobic forces. This binding results in structural changes in rice protein, including reductions in α-helix and random coil content, as well as decreased surface hydrophobicity (Dai et al., 2019a). The hydrophobic attraction between rice bran protein and β-carotene led to high efficiency and improved radical scavenging activity (Magnaye, Mopera & Flores, 2022). Rice bran albumin can achieve 96% encapsulation of curcumin by self-assembly into nanoparticles, which increases the stability and bioavailability of curcumin (Liu et al., 2018).

The adsorption of tea catechin with rice bran protein resulted in a great increase in the random coil and β-antiparallel, a minor increase in α-helix, and a reduction in large loop and turn. The recovery of tea catechin after *in vitro* intestinal digestion was significantly improved (Shi et al., 2017). Almeida et al. (2023) reported that complexation between rice protein and anthocyanin enhanced the stability of antho-cyanins against degradation. This protective effect was further amplified when the rice protein was partially hydrolyzed (Almeida, et al., 2024).

At alkaline pH, rice glutelin undergoes deploymerization and unfolding, promoting the formation of covalent bonds with bioactive compounds (Lian, Li, Lv, Wang & Xiong, 2024).

Compared with neutral conditions (pH 7.0), the conjugates formed at alkaline pH exhibited enhanced structural stability due to stronger covalent interactions, which intensify with increasing pH (Dai et al., 2023). Wu et al. (2025) demonstrated that rice protein-rhamnolipid complexes achieved a maximum curcumin encapsulation efficiency of 93.5%, with notable stability across a pH range of 6.0 to 9.0.

The dominant interactions involved hydro-phobic forces, hydrogen bonding, and electro-static attraction. At acidic pH, the conformation of plant proteins becomes more compact and ordered. Under these conditions, complexation with polyphenols primarily relies on non-covalent interactions, particularly hydro-phobic interactions and hydrogen bonding (Wang et al., 2021). Li, Wang, Chen, Zhang and Zhu (2020) found that at pH 3, rice proteins closely bind with anthocyanins to form rod-like nanostructures, primarily stabilized by hydrophobic interactions and hydrogen bonds.

Physicochemical methods to facilitate the complexation between rice protein and bioactive compounds

Physicochemical processing technologies have been widely employed to enhance the complexation between rice protein and bioactive compounds. These methods include high-pressure treatment, microwave treatment, and ultrasound treatment (Cheng, Mu, Jiao, Xu, & Chen, 2021). Such treatments not only disintegrate rice protein aggregates into smaller particles and alter the tertiary structure of protein molecules, but also expose hydrophobic residues, thereby promoting interactions with bioactive compounds (Zolqadri, Damani, Malekjani, Kharazmi & Jafari, 2023).

The mechanisms underlying enhanced conjugation depend on the specific technology applied. For example, ultrasound treatment has been shown to facilitate the formation of rice protein-catechin conjugates primarily through enhanced covalent bonding (Guo et al., 2023). Similarly, high-pressure pretreatment enables rice proteins to form covalent conjugates with ferulic acid under alkaline conditions, with hydrophobic interactions and hydrogen bonding also contributing significantly to complex formation (Wang et al., 2021). However, other studies have reported that high-pressure processing of plant proteins enhances interaction with tea polyphenols mainly via hydrogen bonding, hydrophobic interactions, and, to a lesser extent, van der Waals forces (Chen, Wang, Feng, Jiang & Miao, 2019).

Among chemical modification approaches, the Maillard reaction is the most employed method. This reaction occurs between the amine groups of amino acids and the carbonyl groups of reducing sugars (Arsa & Puechkamutr, 2022). The combination of rice bran protein and maltodextrin successfully encapsulated *Lactobacillus acidophilus* La-5 and increased its thermal stability and survival in a simulated gastric and intestinal fluid solution (Vaniski et al., 2021). Incorporation of reducing sugars improves both the stability and the functional properties of rice proteins, enhancing their performance as bioactive carriers. Gellan gum-sericin-rice bran albumin nanocomposite, which had a spherical shape with core protein-polysaccharide structures, showed high encapsulation efficiency of doxorubicin and better release profile during digestion (Arjama et al., 2018). Flax seed gum-rice bran protein complex had high encapsulation efficiency of vanillin and increased its heat stability and shelf life (Hasanvand & Rafe, 2019). Self-assembled chitosan/rice bran protein nanocomposite greatly enhanced the encapsulation of curcumin, which delayed its degradability during digestion and increased its bioavailability (Peng et al., 2017).

Furthermore, alkylation of rice protein with lauraldehyde has been reported to increase its self-assembly capability, thereby improving its curcumin encapsulation efficiency to as high as 83% (Wang et al., 2024).

Emulsion systems

An emulsion is a mixture of two or more immiscible liquids, where one liquid is dispersed in the form of small spherical droplets within the other. This dispersion is typically achieved through homogenization or ultrasonication in the presence of one or more emulsifiers. Based on droplet size, emulsions are categorized into microemulsions (0.1-100 μm) and nanoemulsions (≤100 nm) (Zolqadri et al., 2023). Among various delivery systems, protein-stabilized emulsions are widely employed to protect and control the release of targeted bioactive compounds (Li et al., 2020). For instance, at alkaline pH 9.0, rice bran protein stabilized nanoemulsion loaded with quercetin, which increased its stability and bioavailability (Chen et al., 2020).

However, compared with synthetic surfactants or animal-derived proteins (e.g., caseins, whey proteins), rice proteins show limited emulsifying performance due to their rigid molecular structure and poor solubility, which hinder their rearrangement and adsorption at the oil-water (O/W) interface. To overcome these limitations, several strategies have been investigated, including the formation of rice protein-polyphenol complexes (Huang et al., 2024), partial hydrolysis (Gomes & Kurozawa, 2021), and incorporation of mono-/polysaccharides (Xu, Luo, Liu & McClements, 2017a,b).

Enzymatic hydrolysis

Enzymatic hydrolysis reduces the molecular weight and increases the structural flexibility of rice proteins, allowing faster unfolding and adsorption at the oil-water interface. The resulting emulsifying capacity and stability are influenced by factors such as the type of protease, the protein source, and the degree of hydrolysis (Gomes & Kurozawa, 2021).

Pan et al. (2019) compared rice protein hydrolysates obtained using neutrase, trypsin, and alcalase, and found that trypsin-treated hydrolysates showed superior emulsifying stability, comparable to whey protein, due to their enhanced interfacial activity. Hydrolysates from rice albumin demonstrated weaker emulsifycation performance than those from globulin, attributed to stronger electrostatic repulsion and firmer interfacial film formation by globulin (Wang et al., 2022a).

Hydrolysis with flavourzyme improved both solubility and emulsifying properties, with enhancements increasing with the degree of hydrolysis. Emulsions with higher hydrolysis levels (6% and 10%) exhibited lower interfacial tension and better physical stability (Gomes & Kurozawa, 2023). Spray-dried emulsions with 10% hydrolysis showed high surface protein content and strong oil retention capability (Gomes & Kurozawa, 2024). Further fibrillation of hydrolysates improved interfacial adsorption and reduced interfacial tension, leading to enhanced protection of encapsulated β-carotene (Qi et al., 2024).

Rice protein-polyphenol complexes

Complexation with polyphenols not only improves rice protein solubility but also enhances its emulsifying properties. For instance, Dai et al. (2019a) observed spontaneous hydrophobic interactions between resveratrol and rice glutelin, producing emulsions with small, highly anionic droplets. However, particle aggregation during storage remained a challenge.

Complexes formed via non-covalent interacttions are reversible and generally less stable, while covalently bound complexes demonstrate better emulsifying stability (Santos, Okuro, Fonseca & Cunha, 2022). Covalently formed rice protein-catechin conjugates resulted in smaller droplet size, increased electrostatic repulsion, improved rheology, and oxidative stability of emulsions (Li et al., 2023).

Liu et al. (2020) used the Maillard reaction to form rice protein-chlorogenic acid-dextran conjugates, which produced smaller droplets and improved storage and oxidative stability. Shi et al. (2024b) compared emulsions formed by rice protein-polyphenol complexes through covalent vs. non-covalent bonds. Covalent bonding led to higher emulsifying activity and better digestion stability. In a later study, Shu et al. (2025) investigated conjugates between rice protein and three polyphenols (ferulic acid, gallic acid, tannic acid), showing that gallic acid significantly enhanced antioxidant properties and emulsion stability.

Additionally, Wang et al. (2021) used high hydrostatic pressure to promote covalent binding between rice bran protein hydrolysates and ferulic acid. This modification increased protein surface hydrophobicity and tertiary structural changes, with enhanced emulsifying properties observed at low ferulic acid concentrations (≤ 1.5 mg/mL). Similarly, rice bran protein hydrolysate covalently formed conjugate with ferulic acid, which was able to create stable emulsions at ultrasonication at 300 W (Wang et al., 2022b).

Incorporation of mono-/polysaccharides

Emulsions stabilized solely by rice proteins are prone to droplet aggregation due to high hydrophobic residue content and pH sensitivity. The addition of mono- or polysaccharides can introduce a secondary protective layer, providing steric stabilization through long hydrophilic chains and charged groups. These polysaccharides can form non-covalent or covalent complexes with rice proteins depending on the processing conditions (Kim et al., 2024).

At low pH (around 3.5), positively charged rice glutelin hydrolysates can interact with anionic polysaccharides via electrostatic attraction, improving emulsion stability (Xu et al., 2017a). Among various polysaccharides, pectin and xanthan gum provided superior stability compared to alginate and gum Arabic. Emulsions with xanthan gum exhibited better salt tolerance, while both pectin- and xanthan-stabilized emulsions were stable to thermal treatment (Xu et al., 2017b). Similarly, xanthan gum decreased the droplet size stabilized by rice bran protein and increased the encapsulation efficiency of fish oil. The freeze-dried capsules exhibited a lower oxidation rate during storage and more favorable controlled release of free fatty acid during simulated digestion (Tang et al., 2022). Rice protein isolate/ferulic acid conjugates-stabilized emulsion increased the antioxidation properties and decreased the fat oxidation degradation during storage (Jia et al., 2019). Du et al. (2012) formed κ-carrageenan/rice glutelin conjugates via the Maillard reaction. These conjugates showed excellent colloidal stability at low pH and under high ionic strength due to steric repulsion provided by κ-carrageenan extending into the aqueous phase. Additionally, glycation of rice protein with dextran, assisted by ultrasound, resulted in a looser, more flexible protein structure and improved emulsifying capacity by over 24-fold compared to untreated protein (Cheng et al., 2022). Igartúa et al. (2024) examined rice protein-gum Arabic interactions at different pH levels and mass ratios. Emulsions formed from coacervates at pH 3.0 and 5.0 showed smaller droplet sizes and significantly improved stability compared to those produced with rice protein alone.

Hydrogel encapsulation

Proteins are amphiphilic colloidal polymers capable of forming three-dimensional hydrogel networks upon absorbing substantial amounts of water (Kaur, Hamid, Choudhary, & Jaiswal, 2025). The presence of diverse functional groups within the polypeptide chains enables proteins to interact with bioactive compounds, facilitating their encapsulation within the gel matrix and allowing for controlled release during digestion.

Several types of protein-based hydrogels exist, including heat-set gels, cold-set gels, acid-induced gels, enzyme-induced gels, and protein-stabilized emulsion gels (Li & Zhao, 2019; Wang & Zhao, 2022). However, research on plant protein-based hydrogels as carriers for polyphenols remains limited. For instance, the incorporation of green tea polyphenols into pea protein gels disrupted hydrophobic interactions and hydrogen bonding, leading to weaker gel networks and the formation of larger protein aggregates (Chen et al., 2021). In contrast, alkaline conditions (pH 11) facilitated the cross-linking of soy protein isolate with tannic acid, forming more compact gel structures characterized by enhanced hardness and elasticity (Guo, Bao, Sun, Chang & Liu, 2021).

Due to their inherently poor water solubility, rice proteins have been infrequently studied for gelation applications. Felix, Romero & Guerrero (2016) reported that rice protein did not show proper gelation unless a low degree of hydrolysis was performed. Under strongly alkaline conditions (pH > 11), rice proteins adopt a molten globule conformation, which promotes gel formation. Stable rice protein gels can be formed at alkali concentrations above 0.075 M and protein concentrations of 10% (w/v), primarily through increased hydrophobic interacttions, disulfide bonds, and hydrogen bonding (Lian et al., 2024).

The rate of gel formation increases with temperature. Phosphorylation modification of rice glutelin significantly improved its heat-gelation properties, leading to increased viscoelasticity, gel strength, and water holding capacity, which is mainly due to the increased hydrophobic interactions and disulfide bonds (Wang et al., 2021).

Moreover, the mixture of rice protein with cod protein promoted gel formation through hydrogen bonding. The resulting dual protein gel had higher hardness, springiness, and a more compact structure than the single cod gel (Xie et al., 2024).

However, to date, few studies have reported the use of rice protein hydrogels as carriers for bioactive compounds. Cheng et al. (2024) used rice protein-pectin composite gel to encapsulate curcumin, where it was noticed that pectin interacted with rice protein mainly through hydrogen-bonding and attached to the surface of rice proteins, increasing the viscoelasticity and water holding capacity, resulting in a superior gel with excellent curcumin encapsulation efficiency. Luo et al. (2023) successfully prepared an emulsion gel using rice protein aggregates-stabilized emulsion crosslinked with GDL and laccase.

The prepared gel exhibited high gel strength, wa-ter holding capacity, and slow release of free fatty acid. Crosslinking of rice bran protein-stabilized emulsion using transgluta-minase promoted a more compact gel structure with increased encapsulation and protection effect of curcumin (Liu et al., 2024).

Further investigation is needed to understand how bioactive compound incorporation may influence the structural and functional properties of rice protein or composite gels.

Moreover, enhancing the gelation and encapsulation capabilities of rice protein through advanced cross-linking strategies, such as polysaccharide incurporation and enzyme-assisted gelation, presents a promising direction for future research (Kaur et al., 2025).

Edible films

Edible films are defined as thin, continuous layers composed of biodegradable polymers that serve as barriers to mass transfer between food and its surrounding environment. These films are increasingly used to enhance food presservation and to incorporate functional compounds.

Rice protein, due to its high nutritional value and good barrier properties, particularly its resistance to water vapor permeability, has drawn interest as a film-forming material. However, its poor solubility limits its film-forming performance, often resulting in films with rough surfaces and inferior mechanical properties (Wang et al., 2020).

To overcome these limitations, partial hydrolysis of rice protein using alkaline protease has been shown to improve its solubility and film-forming capability. When combined with chitosan and processed with ultrasound, the resulting composite films exhibited smooth morphology and enhanced mechanical strength (Wang et al., 2020).

Incorporation of phenolic compounds into rice protein-based films significantly affects their physicochemical properties. Phenolic-protein interactions have been reported to reduce film opacity and enhance elasticity (Schmidt et al., 2015). In a more recent study, Xie et al. (2023) demonstrated that genipin crosslinking of chitosan/rice protein hydrolysate films improved tensile strength and thermal stability.

Further enrichment with curcumin endowed the films with antioxidant and antibacterial properties, highlighting the potential of rice protein-based edible films as effective carriers for bioactive compounds and as active packaging materials to extend the shelf life of food products.

POTENTIAL INDUSTRIAL APPLICATIONS

Rice protein-bioactive compounds encapsulation systems offer diverse industrial applications across food, pharmaceuticals, nutraceuticals, and active packaging, due to their biocompatibility, functional versatility, and natural origin (Shi et al., 2024b; Li et al., 2021). Fig. 4 illustrates the potential application scenarios of rice protein-based encapsulation systems in food and pharmaceutical industries.

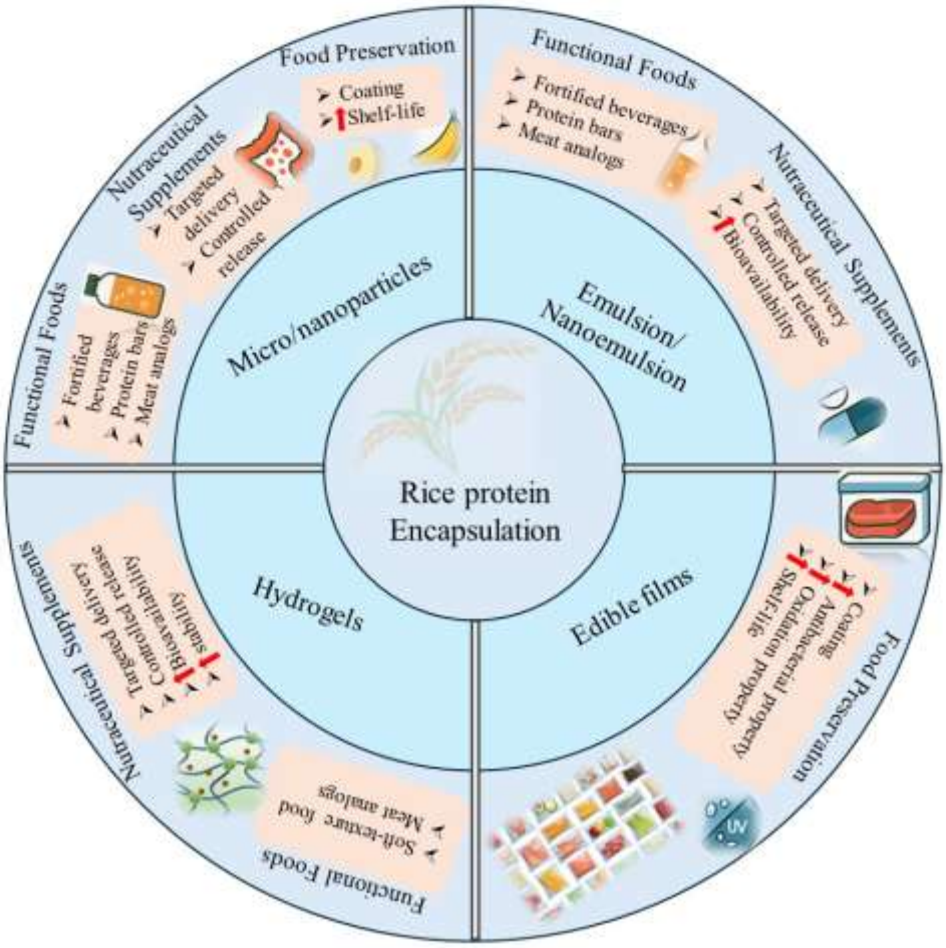

Figure 4. Applications of rice protein-bioactive encapsulation systems in food and pharmaceutical industries

Functional food and beverages

The encapsulation of bioactive compounds allows the stabilization and delivery of sensitive bioactive compounds such as polyphenols, vitamins, omega-3 fatty acids, and carotenoids in various food matrices. It can produce clear dispersions of fat-soluble nutrients in water-based drinks and prevents them from degradation, particularly in acidic environments like fruit juices (Hoskin, Plundrich, Vargochik & Lila, 2022).

In rice protein-fortified products such as bars, shakes, and plant-based dairy alternatives, these systems can improve health benefits while extending shelf life (Luo et al., 2025; Pan et al., 2019). These encapsulation strategies also facilitate innovative applications, such as bioactive-enriched meat analogs and soft-textured foods for elderly nutrition, demonstrating their versatility across product categories (Pu, Yao, Raghavan, Liu & Wang, 2025).

Nutraceuticals and dietary supplements

Rice protein-based encapsulation systems offer promising applications in the development of nutraceuticals and dietary supplements, particularly for targeted and functional delivery (Liu et al., 2024). For instance, anti-inflammatory polyphenols such as curcumin and carotenoids can be encapsulated using nanoparticles, emulsions, or hydrogels, for the treatment of inflamamatory bowel diseases (IBD), ensuring protection through the upper gastrointestinal tract and controlled release in the colon (Shah, Palakurthi, Khare, Khare & Palakurthi, 2020). Additionally, rice protein matrices can be used for probiotic encapsulation, enhancing the viability and stability of gut-health supplements (Vaniski et al., 2021). Emerging applications also include antioxidant and antimicrobial hydrogels for potential use in chronic wound care, leveraging the bioactive stability and controlled release properties of polyphenols (Liu et al., 2024). For the aging population, soft gel formats enriched with polyphenol can provide a convenient and palatable delivery system for essential nutrients, offering both therapeutic and preventive health benefits.

Food preservation

Rice protein-bioactive compound encapsulation systems are gaining attention for innovative food preservation applications, particularly in active and intelligent packaging and edible coatings (Xu et al., 2024; Schmidt et al., 2015; Xie et al., 2023). In packaging, rice protein-based films enriched with polyphenols exhibit strong antimicrobial properties, extending the shelf-life of fresh meat, seafood, and cheese by reducing microbial spoilage (Yan et al., 2022; Xie et al., 2023). The incorporation of Pickering emulsions containing various fatty acids has been shown to significantly enhance the mechanical strength and moisture barrier properties of rice protein/sodium alginate films, effectively reducing weight loss in bananas during storage (Luo, Li, Qin, Wang & Zhong, 2024).

As edible coatings, rice protein-based systems offer a natural, biodegradable solution to reduce post-harvest losses in fruits and vegetables by forming protective layers that limit oxidation and microbial growth. For instance, coating freshly cut apples with rice protein-curcumin nanoparticles significantly prolonged shelf life by boosting antimicrobial and antioxidant activities (Xu et al., 2024). Similarly, egg coating with rice protein/essential oil complexes improved internal quality and extended shelf life at room temperature (Pires et al., 2020). Moreover, these antimicrobial coatings serve as clean-label solutions for fresh produce such as berries and sliced fruits, helping to maintain quality and safety throughout distribution and storage (Vanaraj et al., 2024).

CONCLUSIONS AND FUTURE TRENDS

Rice protein has emerged as a promising plant-based carrier for bioactive compounds, owing to its hypoallergenic nature, sustainability, and compatibility with applications in functional foods, nutraceuticals, and pharmaceuticals. Its functional properties, such as solubility, emulsification, and encapsulation efficiency, can be significantly enhanced through structural modifications, including pH-shifting, physical treatments, enzymatic hydrolysis, glycation, and Maillard conjugation. Diverse delivery formats, including microparticles/nanoparticles, emulsions, hydrogels, and edible films, have demonstrated the ability to improve stability, bioavailability, and controlled release of polyphenols, vitamins, and other sensitive bioactives. These systems show strong potential in food fortification, targeted nutraceutical delivery, and active packaging applications.

Several critical challenges must be addressed to facilitate the wider application of rice protein-based encapsulation systems, including optimizing sensory characteristics, particularly the masking of undesirable flavors associated with polyphenols, and developing cost-effective, scalable manufacturing processes. Therefore, future research should be focusing on the following aspects: (1) developing advanced protein modification strategies to enhance functional attributes (2) designing stimuli-responsive delivery systems capable of controlled release in response to environmental triggers such as pH, enzymatic activity, or temperature (3) exploring multifunctional platforms that integrate bioactive delivery with roles in active or intelligent food packaging (4) in vivo studies to validate the bioavailability, efficacy, and safety of encapsulated compounds. Solving these research gaps can transition rice protein-based encapsulation technologies from laboratory to industrial-scale solutions, supporting the global trend for sustainable and health-promoting food and pharmaceutical innovations.

AUTHOR CONTRIBUTIONS

Conceptualization, Y. S.; Methodology, Y. S.; Investigation, formal analysis, validation, writing-original draft preparation, Y. S.; Writing-review and editing, Z.Z.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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PROTEINI IZ PIRINČA KAO FUNKCIONALNI NOSAČI: NAJNOVIJA DOSTIGNUĆA U STRATEGIJAMA MODIFIKACIJE I PRIMENI ENKAPSULACIJE

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Sažetak: Proteini iz pirinča (RP), zahvaljujući svom povoljnom nutritivnom profilu, biorazgradivosti i biokompatibilnosti, pojavili su se kao obećavajući biljni nosači za isporuku bioaktivnih jedinjenja. Međutim, njihova slaba rastvorljivost u vodi, niska sposobnost emulgovanja i kruta molekularna struktura ograničavaju primenu u funkcionalnim prehrambenim sistemima. Najnovija dostignuća fokusirana su na fizičke, hemijske i enzimske strategije modifikacije kako bi se poboljšala rastvorljivost i druge funkcionalne osobine RP-a. Ova poboljšanja olakšavaju njihovu inkorporaciju u različite formate enkapsulacije kao što su emulzije/nanoemulzije, mikro/nanočestice, jestivi filmovi i hidrogelovi. Ovaj pregled sumira trenutni napredak u modifikaciji RP-a i njegov uticaj na performanse enkapsulacije, uključujući stabilnost, zaštitu bioaktivnih jedinjenja i kontrolisano oslobađanje. Takođe istražuje mehanizme interakcije između RP-a i bioaktivnih jedinjenja i ističe izazove kao što je ograničeno razumevanje mehanizama delovanja. Buduća istraživanja treba da teže razvoju blagih metoda modifikacije pogodnih za prehrambenu industriju i da ispitaju strukturne promene tokom varenja i biodostupnost sistema isporuke zasnovanih na RP-u za funkcionalnu hranu i nutraceutsku primenu.

Ključne reči: *protein pirinča, enkapsulacija, emulzija, rastvorljivost, bioativne materije*

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