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Research Article

Development of low-glycemic egg noodles enriched with polyphosphate-modified jackfruit seed starch

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Abstract

Resistant starch enrichment is an effective strategy to improve the nutritional quality of cereal-based foods by reducing starch digestibility and glycemic response. In this study, jackfruit seed starch (JFSS) was chemically modified via polyphosphate cross-linking using sodium trimetaphosphate and sodium tripolyphosphate to produce resistant starch type IV. Polyphosphate modification significantly increased resistant starch content from 22.57% to 40.22%, accompanied by a marked reduction in rapidly digestible starch and starch hydrolysis rate. The modified starch exhibited improved water and oil absorption capacities and enhanced freeze-thaw stability. To evaluate its practical applicability, phosphorylated JFSS was incorporated into egg noodles as a partial wheat flour substitute. Noodles containing 10–30% modified starch showed increased resistant starch content, reduced estimated glycemic index, and acceptable cooking quality. These results demonstrate that polyphosphate-modified jackfruit seed starch is a promising functional ingredient for the development of low-glycemic noodle products, offering a value-added application for underutilized starch resources in food processing.

Keywords

agricultural by-products; phosphorylated jackfruit seed starch; egg noodles; glycaemic index

Abbreviations

CBR – cooking breakage rate; DML – dry matter loss rate; DMWA – dry matter water absorption rate; DS – degree of substitution; eGI – estimated glycaemic index; GOPOD – glucose oxidase–peroxidase; HI – hydrolysis index; JFSS – jackfruit seed starch; OAC – oil absorption capacity; OCT – optimal cooking time; P% – phosphorus content percentage; RDS – rapidly digestible starch; RS – resistant starch; SDS – slowly digestible starch; SP – swelling power; STMP – sodium trimetaphosphate; STPP – sodium tripolyphosphate; WAC – water absorption capacity; WSI – water solubility index.

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Introduction

Starch is the primary storage carbohydrate in plants and plays a crucial role in determining the appearance, structure, and overall quality of food products. From a nutritional perspective, starch is classified according to its digestibility in the gastrointestinal tract into rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) (Bojarczuk et al. 2022; Fuentes-Saragoza et al. 2011). Among these fractions, RS has attracted particular attention because it exhibits physiological functions similar to those of dietary fibre. The associated health benefits include attenuation of postprandial glucose responses and glycaemic index, reduction of plasma cholesterol levels, increased faecal bulk, enhanced production of short-chain fatty acids in the colon, and a protective effect against colon cancer (Song et al. 2011).

Resistant starch (RS) is categorised into five types: physically entrained starch (RS1), native starch granules with highly ordered crystalline structures (RS2), retrograded starches (RS3), chemically modified starches (RS4), and lipid-complexed amylose (RS5) (Bojarczuk et al. 2022). Among these categories, RS4 has attracted considerable attention because chemical modification enables precise alteration of starch molecular architecture, thereby allowing effective control over starch digestibility and functional performance (Ma et al. 2025; Bangar et al. 2024).

One of the most widely adopted approaches for RS4 production is polyphosphate cross-linking using sodium trimetaphosphate (STMP) and sodium tripolyphosphate (STPP) (Ma et al. 2025; Shi et al. 2013). This method introduces covalent phosphate bridges between starch chains, which restricts molecular mobility and enhances resistance to enzymatic hydrolysis (Shi et al. 2013; Sha et al. 2025; Vu et al. 2024).

In addition to increasing resistant starch content, polyphosphate cross-linking improves key physicochemical properties, including swelling behaviour, water and oil absorption capacities, and freeze-thaw stability (Ma et al. 2025; Zhao et al. 2024; Agvaandorj et al. 2025). Importantly, polyphosphate cross-linking using STMP/STPP is

approved for food applications, making it particularly suitable for the development of functional foods enriched with resistant starch (Agvaandorj et al. 2025).

Jackfruit (*Artocarpus heterophyllus* Lam.) seeds constitute approximately 8–15% of the total fruit weight in tropical regions and represent a promising yet underutilised source of starch, with reported starch contents ranging from 20 to 25% (Zhang et al. 2021; Suzihaque et al. 2022). Starch isolated from jackfruit seeds exhibits favourable native properties, such as relatively high gelatinisation temperatures, good thermal stability, and desirable adhesive characteristics (Zhang et al. 2021). Despite these advantages, the application of jackfruit seed starch as a functional biopolymer produced via controlled chemical cross-linking, particularly for RS4 development, remains largely unexplored.

Egg noodles, a widely consumed wheat-based product, are typically formulated using refined wheat flour, in which the starch is rapidly digested, leading to a quick rise in blood glucose levels (Di Pede et al. 2021; Li et al. 2023). This rapid digestibility is closely associated with the limited structural constraints of native wheat starch, contributing to the high glycemic index (GI > 70) commonly reported for commercial noodle products (Zhao et al. 2025). Partial substitution of wheat flour with modified starches enriched in resistant starch (RS) has been recognized as an effective approach to reduce noodle GI, thereby contributing to improved glycemic regulation and reduced metabolic risk (Zhao et al. 2025). However, the incorporation of modified starches may alter cooking behavior, sensory attributes, and textural properties of noodles. Therefore, formulation optimization is required to achieve a balance between enhanced nutritional functionality and consumer acceptability.

Therefore, this study aimed to develop egg noodles enriched with polyphosphate-modified jackfruit seed starch and to evaluate their starch digestibility, estimated glycemic index, and cooking quality. The relationships between phosphorylation degree, resistant starch formation, and noodle functional properties were investigated to identify an optimal substitution level for producing low-glycemic noodle products.

Materials and Methods

Materials. Fresh jackfruit seeds were collected from processing facilities that produce jackfruit products in Dong Nai, Vietnam. Sodium hydroxide (NaOH), sodium trimetaphosphate ($\text{Na}_3\text{P}_3\text{O}_9$, STMP), sodium tripolyphosphate ($\text{Na}_5\text{P}_3\text{O}_{10}$, STPP), sodium bisulfite (NaHSO_3), sodium sulfate (Na_2SO_4), and hydrochloric acid (HCl) were purchased from Sigma-Aldrich. The K-RSTAR test kit was obtained from Megazyme, Ireland. Vanadate-Molybdate reagent was purchased from Merck, Germany.

Jackfruit seeds extraction. Native jackfruit seed starch (JFSS) was prepared following the method of Dong et al. (2021). Jackfruit seeds were immersed in a 0.25% NaOH solution to completely remove the brown skin, then washed and ground in a 0.1% NaHSO_3 solution. The resulting starch slurry was decanted, filtered, and dissolved in distilled water. This procedure was repeated five times. The final starch product was dried at 50°C for 12 h.

Preparation of cross-linked starches. The phosphorylation with STMP/STPP was conducted in an aqueous slurry, according to the method of Woo et al. (2002). Starch from jackfruit seeds (50 g, dry basis) was mixed with 70.0 mL of water containing 5 g of sodium sulfate (10%, starch basis) at 25°C. Subsequently, a mixture of STMP and STPP (99:1 mass ratio, w/w) was added to the solution (6-12%, starch basis). The pH of the mixture was raised to 11.0 using 1.0 M sodium hydroxide, and the solution was stirred at 60°C for 1 h. Next, the pH was reduced to 6.5 with 1.0 M hydrochloric acid, after which centrifugation at 5000 rpm was performed for 10 minutes. The precipitated starch was recovered and washed seven times with distilled water. Finally, the product was dried at 40°C for 10 h.

Preparation of egg noodles. The noodles were made from 250 g of a mixture of wheat flour, phosphorylated jackfruit seeds starch, and 2.5 g of salt. The mixture was thoroughly blended with 25-30 g of egg to form a homogeneous dough. After resting for 30 min at room temperature, the dough was divided into small portions and processed into noodle strands using a Media-brand noodle-making machine. The noodles were then dried at 35°C for 6 h prior to storage.

Methods. Starch digestibility was determined according to AOAC Method 2002.02 using the K-RSTAR kit (Megazyme, Ireland). Samples were incubated with pancreatic α -amylase and amyloglucosidase (AMG) at 37°C for 16 h to hydrolyze non-resistant starch to D-glucose. The reaction was stopped with ethanol or industrial methylated spirits (IMS), and resistant starch (RS) was recovered by centrifugation and washed twice with 50% (v/v) aqueous ethanol. The RS pellet was dissolved in 2 M KOH under ice-cold conditions, neutralized with acetate buffer, and hydrolyzed to glucose using AMG. Glucose was quantified by GOPOD assay to determine RS content. Non-resistant starch was measured from pooled supernatants and washings, adjusted to 100 mL, and analyzed for glucose using GOPOD.

$$\text{RS (\%)} = (\Delta A \times F \times 90) / W \quad (1)$$

$$\text{RDS (\%)} = (\Delta A \times F \times 90) / W \quad (2)$$

$$\text{SDS (\%)} = 100 - (\text{RS} + \text{RDS}) \quad (3)$$

where,

ΔA is the optical absorbance of the analysed sample compared to the blank sample, is the conversion factor from absorbance to micrograms ($F = 100 \mu\text{g}$ D-glucose/ GOPOD absorbance corresponding to $100 \mu\text{g}$ of D-glucose), and

W is the dry weight of sample analysed, mg.

Phosphorus content was determined on a dry weight basis following Wongsagonsup et al. (2005). Briefly, 2.5 g of starch was dispersed in distilled water containing sodium carbonate, dried, and mineralized at 550°C for 12 h. The ash was dissolved in distilled water with 25% (w/v) HCl, filtered, and diluted to 250 mL.

An aliquot (10 mL) was reacted with vanadate-molybdate reagent for 45 min at room temperature, and absorbance was measured at 435 nm using a PerkinElmer LAMBDA 35 UV-Vis spectrophotometer. Phosphorus content (%) was calculated from a calibration curve prepared with $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$.

The degree of substitution (DS) was calculated according to Sitehy et al. (2000).

$$\text{DS} = (162 \times P) / (3100 - 102 \times P) \quad (4)$$

where,

P is the percentage of phosphorus content in the starch samples.

The estimated glycaemic index (eGI) was assessed following simulated gastrointestinal digestion. Samples were subjected to pepsin digestion (pH 1.5, 40°C, 1 h), followed by α -amylase hydrolysis (pH 6.9, 37°C). Aliquots (0-180 min) were treated with amyloglucosidase, and glucose was determined by GOPOD at 510 nm. The hydrolysis index (HI) was calculated from the area under the curve, and eGI was estimated as:

$$\text{eGI} = 39.71 + 0.549 \times \text{HI} \quad (5)$$

Swelling power (SP) and water solubility index (WSI) were determined by dispersing 1 g of starch in 10 mL distilled water, followed by incubation at 50, 60, 70, and 80°C for 30 min in a thermostatic water bath. The suspensions were cooled to room temperature and centrifuged (1600 rpm, 15 min). The supernatant was dried at 110°C for 24 h to determine WSI, while the sediment was weighed to evaluate SP. WSI was expressed as the percentage of dissolved solids in the supernatant, and SP was calculated as the ratio of sediment weight to the initial dry sample weight.

$$\text{SP (g/g)} = (m_2 - m_0) / m_0 \quad (6)$$

$$\text{WSI (\%)} = (m_1 / m_0) \times 100 \quad (7)$$

where,

m_1 is the mass of dissolved portion of the sample, g,

m_2 is the mass of the sediment paste, g, and

m_0 is the mass of the initial dry sample, g.

Water absorption capacity (WAC) and oil absorption capacity (OAC) were determined by dispersing 1 g of starch in 25 mL of distilled water or vegetable oil, respectively. The mixtures were thoroughly stirred and allowed to stand at ambient temperature for 1 h, followed by centrifugation (1500 rpm, 10 min). The supernatant was decanted, and the residue was weighed. WAC and OAC were expressed as grams of water or oil retained per gram of dry sample.

$$\text{WAC (g/g)} = (m_1 - m_0) / m_0 \quad (8)$$

$$\text{OAC (g/g)} = (m_2 - m_0) / m_0 \quad (9)$$

where,

m_1 is the mass of the starch after absorbing water following centrifugation, g,

m_2 is the mass of the starch after absorbing oil following centrifugation, g, and

m_0 is the mass of the original dry sample, g.

Freeze-thaw stability was evaluated using starch suspensions (6%, w/v) that were heated for 30 min to ensure complete gelatinisation and then cooled to ambient temperature. Aliquots (10 mL) were frozen at -20°C for 24 h and thawed at room temperature for 2 h. The samples were centrifuged (3000 rpm, 15 min), the supernatant was decanted, and the residue was weighed to assess stability.

$$\text{Syneresis (\%)} = (m_1 / m_0) \times 100 \quad (10)$$

where,

m_1 is the mass of water released after each freeze-thaw cycle, g and

m_0 is the mass of the gelatinised starch sample, g.

Analysis of noodles. Optimal cooking time (OCT) was determined by boiling 25 g of noodle sticks in 500 mL distilled water until the opaque core disappeared, confirmed by pressing between glass slides. Cooking properties were evaluated following [Xie et al. \(2023\)](#). Briefly, 25 g of noodles were cooked in 400 mL boiling water for the optimal time, rinsed (100 mL, 30 s), drained (5 min), and weighed. Cooking and rinsing water were dried at 105°C to constant weight. Dry matter water absorption (DMWA) and dry matter loss (DML) were calculated as:

$$\text{DMWA (\% wt.)} = [(m_1 - m_0) / m_0] \times 100 \quad (11)$$

$$\text{DML (\% wt.)} = (m_2 / m_0) \times 100 \quad (12)$$

where,

m_0 is the initial weight of the noodles, g,

m_1 is the weight of the noodles after cooking, g

and

m_2 is the dried weight of cooking/rinsing water, g,

Cooking breakage rate (BR) was determined by counting broken noodles:

$$\text{BR (\%)} = (N_2 / N_1) \times 100 \quad (13)$$

where,

N_2 is the number of broken noodles after cooking and

N_1 is the number of initially dry noodles.

Statistical analysis was carried out using one-way analysis of variance (ANOVA) followed by Bonferroni test ($p < 0.05$). Results were expressed as mean $\pm$ standard deviation (SD), and different superscript letters indicate significant differences among means.

Results and Discussion

Phosphorylation of jackfruit seed starch. Jackfruit seed starch (JFSS) was chemically

modified by phosphorylation using 6, 8, 10 and 12% (w/w) sodium trimetaphosphate/sodium tripolyphosphate (STMP/STPP) in a 99:1 (w/w) ratio. The resulting phosphorylated starch was designated as JFSS-6P, JFSS-8P, JFSS-10P, and JFSS-12P, respectively.

Table 1. Degree of substitution and starch digestibility (RDS, SDS, RS) of phosphorylated jackfruit seed starch at different STMP/STPP levels (6 - 12%, w/w)

Samples	DS ($\times 10^{-3}$), %	P content, %	RS, %	RDS, %	SDS, %
Control	—	—	22.57 ^e $\pm$ 0.86	25.67 ^c $\pm$ 1.03	51.76 ^a $\pm$ 2.15
JFSS-6P	7.88 ^d $\pm$ 0.24	0.15 ^d $\pm$ 0.005	26.38 ^d $\pm$ 1.37	21.45 ^a $\pm$ 1.64	52.17 ^c $\pm$ 1.97
JFSS-8P	12.11 ^b $\pm$ 0.41	0.23 ^b $\pm$ 0.006	31.05 ^{bc} $\pm$ 1.76	16.36 ^b $\pm$ 1.17	52.59 ^e $\pm$ 1.62
JFSS-10P	19.04 ^c $\pm$ 0.38	0.36 ^c $\pm$ 0.005	38.52 ^b $\pm$ 2.21	8.53 ^d $\pm$ 0.69	52.95 ^d $\pm$ 1.85
JFSS-12P	22.26 ^{ab} $\pm$ 0.45	0.42 ^a $\pm$ 0.007	40.22 ^a $\pm$ 2.54	6.55 ^{de} $\pm$ 0.35	53.23 ^b $\pm$ 2.13

*Data are presented as mean values (n=3). Different characters in the same column indicate statistically significant differences ($p < 0.05$) between mean values

Degree of substitution and digestive ability. The degree of substitution (DS) and digestibility fractions (RDS, SDS, and RS) of jackfruit seed starch (JFSS) phosphorylated with STMP/STPP at 6, 8, 10 and 12% (w/w) are presented in Table 1.

Phosphorylation of jackfruit seed starch (JFSS) using sodium trimetaphosphate/sodium tripolyphosphate (STMP/STPP) exhibited a clear concentration-dependent enhancement in both phosphorus content (P%) and degree of substitution (DS), reflecting improved chemical modification efficiency with increasing reagent levels. As the STMP/STPP concentration increased, P% rose from 0.15% in JFSS-6P to 0.42% in JFSS-12P, accompanied by a corresponding increase in DS from 7.88×10^{-3} to 22.26×10^{-3} . This trend indicates that higher cross-linker concentrations increase the availability of reactive phosphate species, thereby facilitating more effective phosphate incorporation and the formation of covalent cross-links within the starch matrix (Shi et al. 2013).

The increase in DS was closely associated with pronounced alterations in starch digestibility profiles (Shi et al. 2013; Vu et al. 2024). Phosphorylation replaces hydroxyl groups on

amylose chains with phosphate moieties, promoting the formation of inter- and intramolecular cross-links. These covalent linkages increase steric hindrance, reduce chain mobility, and restrict enzyme diffusion within the granule, ultimately lowering enzymatic hydrolysis efficiency (Bangar et al. 2024; Vu et al. 2024; Waliszewski et al. 2003). As a result, resistant starch (RS) content increased substantially from 22.57% to 40.22%, while slowly digestible starch (SDS) showed only a marginal increase from 51.76% to 53.23%. In contrast, rapidly digestible starch (RDS) decreased sharply from 25.67% to 6.55%, highlighting the strong inhibitory effect of cross-link density on rapid enzymatic degradation.

Among the modified samples, JFSS-10P prepared with 10% STMP/STPP achieved a phosphorus content of 0.36%, which remains within the FDA regulatory limit ($<0.4\%$) for food-grade phosphorylated starch (Falsafi et al. 2019). This processing condition therefore represents an optimal balance between achieving sufficient cross-link density for functional modification and maintaining regulatory compliance, in agreement with previous findings reported for phosphorylated banana starch (Vu et al. 2024).

Overall, the strong correlation among degree of substitution, phosphorus content, and resistant starch formation confirms that polyphosphate cross-linking helps reinforce starch granule integrity and creates sterically hindered domains that limit enzymatic accessibility. This structure-driven restriction of digestion is a defining characteristic of resistant starch type IV and underscores the importance of controlled cross-link density as a key parameter in starch digestibility.

Functional properties. The properties of jackfruit seed starch (JFSS) and phosphorylated jackfruit seed starch (JFSS-6P, JFSS-8P, JFSS-10P, and JFSS-12P) were evaluated in terms of swelling power, water solubility index, freeze-thaw cycle, and water/oil absorption capacity (Fig. 1).

Swelling power (SP) and water solubility index (WSI) were key indicators for assessing the extent of molecular interactions occurring in both amorphous and crystalline domains of starch granules (Li et al. 2015).

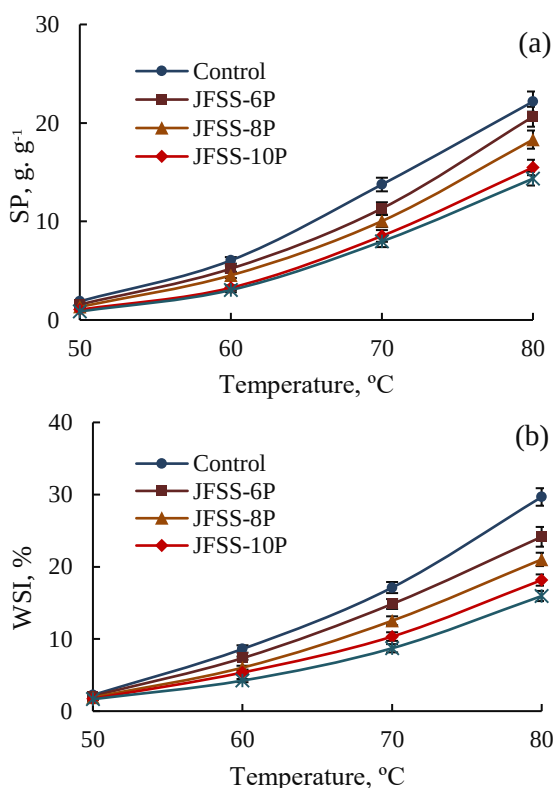


Figure 1. Swelling power (SP), water solubility index (WSI) of phosphorylated jackfruit seed starch. SP and WSI were measured in the current study over a temperature range of 60 to 90°C. Both parameters

rose with increasing temperature but declined with higher STMP/STPP concentrations. At 80°C, an increase in STMP/STPP content from 0% to 12% led to a reduction of SP from 22.17 g/g to 14.35 g/g and a decrease in WSI from 29.67% to 15.95%.

The swelling power (SP) reflects the potential of starch granules to retain water and swell when heated (Ma et al. 2025; Agvaandorj et al. 2025). Native starches generally exhibited higher swelling capacity as a result of their well-preserved and flexible granule architecture. The significant reduction in the SP of JFSS-PP was likely due to stronger interactions between amylose and amylopectin chains, resulting from covalent cross-links formed through phosphorylation. These phosphate cross-links enhanced intra- and intermolecular associations, which restricted the mobility and expansion of the starch granules (Agvaandorj et al. 2025).

Similarly, the higher WSI observed in native starch was associated with the greater amylose leaching, accompanied by partial structural disruption of starch granules at elevated temperatures. Additionally, the decreased solubility of phosphorylated jackfruit seed starch was likely due to the incorporation of phosphate groups, which enabled further covalent bonding between starch molecules (Bangar et al. 2024; Agvaandorj et al. 2025).

The water absorption capacity (WAC) of phosphorylated jackfruit seed starch (1.52 - 1.91 g·g⁻¹) was higher than that of the unmodified starch (1.33 g·g⁻¹). This improvement was attributed to the incorporation of hydrophilic phosphate groups during the phosphorylation process. These groups facilitated electrostatic repulsion between starch chains, which reduced intermolecular bonding forces and allowed for greater water absorption (Bangar et al. 2024; Agvaandorj et al. 2025). Furthermore, WAC rose proportionally with STMP/STPP concentration, indicating that a higher degree of phosphate substitution enhanced the effectiveness of the phosphorylation process (Vu et al. 2024).

Comparing STMP/STPP cross-linked starches to native starches, previous research similarly showed that incorporating negatively charged phosphate groups enhanced water binding and retention (Vu et al. 2024; Zhao et al. 2024; Agvaandorj et al. 2025).

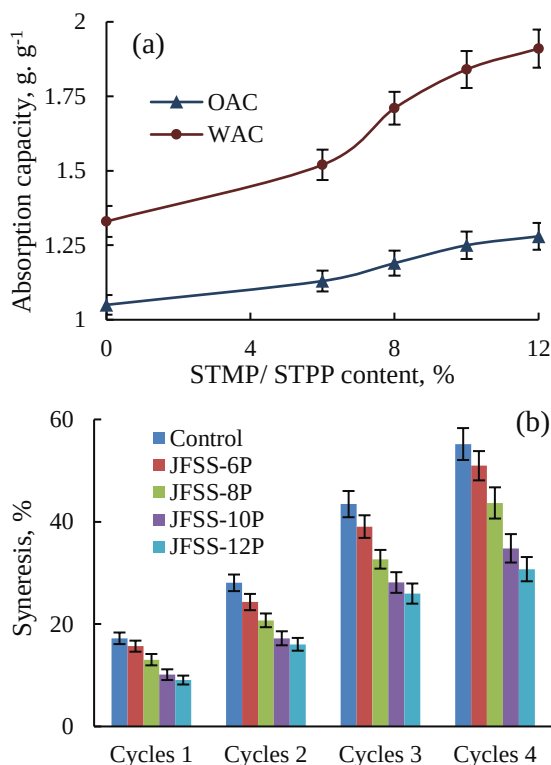


Figure 2. Water/oil absorption capacity (WAC/OAC), and rate of water loss during freeze–thaw cycle of phosphorylated jackfruit seed starch

Furthermore, OAC rose with increasing STMP/STPP concentrations, indicating that a greater degree of phosphorylation induced more pronounced structural rearrangements.

In terms of oil absorption capacity (OAC), phosphorylated jackfruit seed starch (1.13 - 1.28 g·g⁻¹) showed higher values compared to native JFSS (1.05 g·g⁻¹). The improved OAC of phosphorylated jackfruit seed starch suggested that phosphorylation altered the surface characteristics of starch granules, potentially exposing more hydrophobic regions that enhanced their affinity for oil binding (Vu et al. 2024).

Freeze-thaw stability, determined by the rate of water loss as a result of syneresis, was assessed over four consecutive freeze–thaw cycles. During freezing, ice crystals were formed in the starch gel, leading to higher starch concentration and facilitating molecular recrystallisation (Srichuwong et al. 2012). Upon thawing, the melting of these crystals disrupted the gel network, leading to syneresis – an undesirable process that

compromises product stability and shortens shelf life (Gu et al. 2024). Consequently, the gel's resistance to syneresis was a key metric for its freeze–thaw stability (Agvaandorj et al. 2025; Park et al. 2024).

As depicted in Fig. 2b, all samples exhibited a progressive increase in syneresis with repeated freeze–thaw cycles, a definite indication of water expulsion from the starch gel matrix and gradual structural degradation (Agvaandorj et al. 2025). Native jackfruit seed starch (JFSS) showed the highest degree of water release, with syneresis values rising from 17.23% in Cycle 1 to 55.19% by Cycle 4.

In contrast, the phosphorylated jackfruit seed starch samples displayed significantly lower syneresis values, ranging from 9.07 - 15.69% in Cycle 1 to 25.97 - 39.06% in Cycle 4. This indicated superior freeze-thaw stability, which was likely attributable to the phosphate cross-links introduced during phosphorylation. These cross-links reinforced the structure of the starch gel, reduced retrogradation, and restricted water migration. The phosphate groups also promoted the formation of a more stable and cohesive gel by strengthening hydrogen bonds and limiting the mobility of amylose chains (Huang et al. 2024). Furthermore, syneresis declined steadily as the STMP/STPP concentration rose, confirming that a higher degree of cross-linking provided a more stable gel network (Vu et al. 2024).

Properties of noodles containing jackfruit seed starch and phosphorylated jackfruit seed starch

Digestive ability of noodles. To increase the resistant starch (RS) content, phosphorylated jackfruit seed starch (JFSS) was incorporated into egg noodles at substitutions levels of 10, 20, 30 and 40% (w/w) as a partial replacement for wheat flour. Table 2 shows the contents of RDS, SDS, and RS in egg noodles containing phosphorylated jackfruit seed starch. As shown in Table 2, increasing the substitution level of polyphosphate-modified jackfruit seed starch (JFSS-PP) from 0 to 40% induced a pronounced shift in the starch digestibility profile of the noodles.

The rapidly digestible starch (RDS) fraction decreased substantially from 45.22 to 20.89%, while the proportion of slowly digestible starch (SDS) increased from 35.01% to 41.34%.

Concurrently, resistant starch (RS) content almost doubled, rising from 19.77% to 38.77%. These changes are due to the phosphorylated starch, which has a high RS content and cross-linked structure, thus limiting the enzymatic hydrolysis of starch (Vu et al. 2024; Zhao et al. 2025).

From a nutritional perspective, the reduction in RDS together with the enrichment of SDS and RS is highly desirable, as it promotes a slower and more sustained glucose release.

Consequently, the incorporation of JFSS-PP

significantly improves the nutritional quality of egg noodles by lowering their potential glycaemic impact and increasing the proportion of slowly available carbohydrates, thereby supporting improved metabolic health.

Estimated glycaemic index (GI) of noodles. Table 3 presented the changes in the hydrolysis index (HI) and expected glycaemic index (eGI) of egg noodles containing varying amounts of phosphorylated jackfruit seed starch.

Table 2. Contents of RDS, SDS, and RS in egg noodles containing phosphorylated jackfruit seed starch

Samples	RS, %	RDS, %	SDS, %
Noodles with 100% wheat flour	19.77 ^e ± 0.86	45.22 ^{cd} ± 1.43	35.01 ^c ± 1.24
Noodles with 10% JFSS-10P	22.45 ^d ± 0.93	40.14 ^c ± 1.47	37.41 ^b ± 1.25
Noodles with 20% JFSS-10P	27.62 ^a ± 1.35	34.09 ^a ± 1.64	38.29 ^e ± 1.17
Noodles with 30% JFSS-10P	33.86 ^c ± 1.16	25.25 ^e ± 1.38	40.89 ^a ± 1.32
Noodles with 40% JFSS-10P	38.77 ^{ab} ± 1.32	20.89 ^b ± 1.48	41.34 ^d ± 1.19

*Data are presented as mean values (n=3). Different characters in the same column indicate statistically significant differences ($P < 0.05$) between mean values.

The hydrolysis index (HI) and estimated glycaemic index (eGI) of egg noodles formulated with wheat flour partially substituted by phosphorylated jackfruit seed starch (JFSS-10P) were evaluated based on glucose release kinetics using a glucose standard calibration ($y = 0.5581x + 0.0234$). This calibration enabled accurate conversion of hydrolysis data into eGI values, ensuring reliable in vitro assessment of glycaemic response.

Egg noodles prepared from 100% wheat flour exhibited a relatively high HI (0.678) and eGI (76.94), classifying them as a high-glycaemic index (high-GI) food (Goñi et al. 1997). Progressive substitution of wheat flour with JFSS-10P resulted in a consistent decrease in both HI and eGI, indicating a clear formulation-dependent modulation of starch digestibility. Notably, eGI values declined from 70.10 at 10% substitution to 54.37 at 40% substitution, effectively shifting the product classification from medium- to low-GI.

The observed reduction in glycaemic response can be attributed to the structural characteristics of

phosphorylated starch. Polyphosphate-induced cross-linking introduces rigid and sterically hindered domains within the starch matrix, which restrict granule swelling and limit enzymatic accessibility during digestion. These structure-induced constraints slow the rate of enzymatic hydrolysis, resulting in a more gradual glucose release profile and a reduced glycaemic response (Li et al. 2022). Therefore, controlled substitution at JFSS-10P levels is a viable formulation strategy to improve postprandial glycemic control. From a nutritional perspective, this alteration in digestibility significantly enhances the nutritional quality of grain-based foods, highlighting phosphorylated jackfruit starch as a promising value-added functional component for the development of healthier staple products.

Evaluation of properties of cooked noodles. To assess the functional applicability of the modified starch under practical processing conditions, a wheat-based egg noodle was selected as a representative food matrix.

Table 3. The hydrolysis index (HI) and estimated glycaemic index (eGI) of egg noodles containing phosphorylated jackfruit seed starch as determined *in vitro*

Samples	HI	eGI
Noodles with 100% wheat flour	0.68 ^a ± 0.032	76.94 ^{cd} ± 2.21
Noodles with 10% JFSS-10P	0.55 ^b ± 0.029	70.12 ^a ± 2.32
Noodles with 20% JFSS-10P	0.44 ^c ± 0.023	64.07 ^e ± 2.06
Noodles with 30% JFSS-10P	0.35 ^{cd} ± 0.018	59.18 ^b ± 2.24
Noodles with 40% JFSS-10P	0.27 ^d ± 0.012	54.37 ^d ± 2.13

*Data are presented as mean values (n=3). Different characters in the same column indicate statistically significant differences ($P < 0.05$) between mean values.

Evaluation of properties of cooked noodles. To assess the functional applicability of the modified starch under practical processing conditions, a wheat-based egg noodle was selected as a representative food matrix. The cooking quality parameters of the prepared noodles, including optimal cooking time (OCT), dry matter water absorption (DMWA), dry matter loss (DML), and cooking breakage rate (CBR), are summarized in Table 4.

The incorporation of phosphorylated jackfruit seed starch (JFSS-10P) at substitution levels ranging from 0 to 40% markedly influenced the cooking performance and structural integrity of egg noodles. Compared with the control sample prepared solely from wheat flour, noodles containing JFSS-10P exhibited a progressive increase in optimal cooking time (OCT), from 480 to 595 s, along with a substantial rise in dry matter water absorption (DMWA), from 114.12% to 155.84%. These changes can be attributed to the introduction of hydrophilic phosphorylation, which enhance water-

binding capacity and delay starch gelatinization during cooking (Hoover et al. 1986; Ashogbon et al. 2013). The concentration-dependent increases in OCT and DMWA indicate that the water uptake behavior of the noodle matrix is strongly governed by the level of phosphorylated starch incorporation.

Conversely, higher levels of JFSS-10P resulted in increased dry matter loss (DML, 1.24–2.11%) and cooked breaking rate (CBR, 0.28–4.44%), reflecting a gradual deterioration in cooking stability and mechanical integrity. This effect is primarily associated with the partial replacement of wheat flour by non-gluten JFSS-10P, which diluted and weakened the gluten network responsible for maintaining noodle cohesiveness during thermal processing (Hoover et al. 1986). In addition, the highly substituted and sterically bulky phosphorylated starch molecules may disrupt starch–gluten interactions, limiting effective protein–starch binding and further compromising the structural continuity of the noodle matrix during cooking (Vu et al. 2024).

Table 4. Characteristics of egg noodles made from wheat flour–phosphorylated jackfruit seed starch blends

Samples	OCT, s	DMWA, %	DML, %	CBR, %
Noodles with 100% wheat flour	480 ^b ± 12	114.12 ^e ± 2.25	1.24 ^e ± 0.052	0.28 ^{ae} ± 0.011
Noodles with 10% JFSS-10P	501 ^e ± 8	125.06 ^{ac} ± 2.64	1.32 ^a ± 0.069	0.96 ^d ± 0.046
Noodles with 20% JFSS-10P	530 ^c ± 10	135.27 ^d ± 2.38	1.47 ^{bd} ± 0.058	1.45 ^{bc} ± 0.184
Noodles with 30% JFSS-10P	567 ^d ± 9	148.31 ^a ± 3.05	1.54 ^c ± 0.062	1.91 ^b ± 0.323
Noodles with 40% JFSS-10P	595 ^a ± 13	155.84 ^b ± 2.87	2.11 ^b ± 0.064	4.44 ^a ± 0.428

Data are presented as mean values (n=3). Different characters in the same column indicate statistically significant differences ($P < 0.05$) between mean values.

Overall, these results demonstrate a clear formulation–structure–function relationship in noodles enriched with phosphorylated starch. While JFSS-10P incorporation enhances water absorption and prolongs cooking time, excessive substitution adversely affects structural stability. Based on the combined evaluation of cooking quality parameters, a substitution range of 10 - 30% JFSS-10P is recommended to achieve an optimal balance between functional enhancement and acceptable cooking performance.

Colour of noodles. Table 5 summarizes the colour values (L^* , a^* , b^*) of egg noodles containing different substitution levels of phosphorylated jackfruit seed starch, emphasising its effect on the colour characteristics of the noodles. Visual inspection revealed significant changes in noodle appearance and texture, which corresponded to the type and amount of starch incorporated (Fig. 3). Egg noodles containing phosphorylated jackfruit seed starch (JFSS-10P) appeared noticeably darker than the 100% wheat flour control, with colour intensity increasing as the substitution level rose (Vu et al. 2024).

Consistent with visual observations, colorimetric analysis (Table 5) indicated a progressive decrease in L^* values (lightness) from 63.24 in the control to 46.51 at 40% substitution. Similarly, b^* values (yellowness) declined steadily from 17.71 to 11.14, while a^* values (redness) decreased slightly from 5.45 to 4.92. These findings confirmed that JFSS-10P incorporation reduced noodle brightness and yellowness, resulting in a darker and less vibrant product. This darkening is likely a result of the inherent colour of the phosphorylated starch, and

potential Maillard reactions or other browning processes that occur during manufacturing.

Mechanically, higher levels of JFSS-10P substitution resulted in increased brittleness and breakage. These textural deficiencies were attributed to a weakened structural network, as the partial replacement of wheat gluten with phosphorylated starch disrupted the vital starch–gluten interactions. This disruption reduced the continuity of the protein matrix responsible for dough elasticity. As the proportion of JFSS-10P increased, this effect becomes more pronounced, resulting in lower dough elasticity, reduced tensile strength, and a more brittle final product. Therefore, while JFSS-10P enhanced certain functional properties, excessive substitution adversely affected both colour and texture, indicating that an optimal incorporation level was within the range of 10 - 30%.



Figure 3. Images of egg noodles, wheat flour mixed with phosphate jackfruit seed starch at 0, 10, 20, 30 and 40 % wt.

Table 5. Colour of noodles containing phosphorylation jackfruit seed starch

Sample	L^*	a^*	b^*
Noodles with 100% wheat flour	63.24 ^a ± 1.89	5.45 ^a ± 0.19	17.71 ^c ± 0.35
Noodles with 10% JFSS-10P	58.45 ^c ± 1.52	5.29 ^c ± 0.17	15.23 ^a ± 0.43
Noodles with 20% JFSS-10P	54.62 ^b ± 1.67	5.17 ^e ± 0.14	14.02 ^d ± 0.32
Noodles with 30% JFSS-10P	50.76 ^{cd} ± 1.45	5.05 ^d ± 0.15	12.89 ^{ab} ± 0.41
Noodles with 40% JFSS-10P	46.51 ^e ± 1.38	4.92 ^b ± 0.18	11.14 ^e ± 0.27

Data are presented as mean values (n=3). Different characters in the same column indicate statistically significant differences ($P < 0.05$) between mean values

Conclusions

Polyphosphate-modified jackfruit seed starch demonstrated strong potential as a functional food ingredient for improving the nutritional quality of egg noodles. Phosphorylation effectively increased resistant starch content, reduced starch digestibility, and lowered the estimated glycemic index of noodle products. At substitution levels of 10 - 30%, the modified starch provided a favorable balance between enhanced nutritional functionality and acceptable cooking and structural properties. These findings highlight the feasibility of utilizing jackfruit seed starch as a value-added ingredient for the development of low-glycemic cereal-based foods.

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Author Contributions

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Data supporting the findings of this study are available from the authors upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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