Research Article

Phosphorylation of Banggai Yam (*Dioscorea alata* L.) Starch Using Sodium Trimetaphosphate: Effects on Chemical Composition, Functional Properties, and Bioactivity

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Abstract | This study investigated the phosphorylation of Banggai yam (*Dioscorea alata* L.) starch using sodium trimetaphosphate (STMP) to produce Banggai yam phosphate starch (BYPS) with improved chemical, functional, and bioactive properties. Proximate analysis showed that phosphorylation did not significantly affect protein content but led to a decrease in lipid and carbohydrate levels. At the same time, crude fiber increased, indicating the formation of resistant starch fractions. Functional evaluation revealed a progressive increase in water holding capacity (WHC) and oil holding capacity (OHC) with higher STMP concentrations, reflecting enhanced hydration and binding ability due to crosslinking within the starch matrix. Structural analysis demonstrated variations in amylose and amylopectin proportions, suggesting molecular restructuring under intensive phosphorylation. Bioactive analysis showed a reduction in anthocyanin content, yet β-carotene and antioxidant activity significantly increased, highlighting the protective effect of STMP against oxidative degradation of lipophilic compounds. Overall, the findings demonstrate that STMP phosphorylation successfully enhanced the nutritional and functional value of Banggai yam starch. BYPS thus holds substantial potential as a novel functional food ingredient with applications in analog rice, edible films, and other health-oriented products, supporting both food diversification and sustainable food security.

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Introduction

Starch is a natural biopolymer that plays a vital role in the food and non-food industries due to its abundant availability, relatively low price, and diverse functional properties (Ropikoh *et al*., 2024; Mbonambi *et al*., 2025). Globally, the demand for modified starch continues to increase along with the development trends of functional foods, environmentally friendly packaging, and sustainable biomaterial products (Punia Bangar *et al*., 2021; Yudhistira *et al*., 2024) . However, natural starch has several limitations, including low functional stability, sensitivity to heat and pH, and unfavourable retrogradation properties, so its application in industry is still limited (Marta, 2016; Gałkowska *et al*., 2023; Nadhira and Cahyana, 2023; Paternina-Contreras *et al*., 2025) . Therefore, an appropriate modification strategy is needed to improve the quality and expand the use of starch as an industrial raw material.

One widely used modification method is phosphorylation, which is the process of introducing phosphate groups into the structure of starch molecules. The addition of phosphate groups has been shown to increase hydration capacity, pasta stability, and resistance to extreme processing (Chen *et al*., 2019). Sodium trimetaphosphate (STMP) is an effective phosphorylation agent because it can produce crosslinks between starch chains, thereby strengthening granule stability and improving its functional properties. (Chaniago *et al*., 2025). Various studies on corn starch (Gui-Jie *et al*., 2006; Gao *et al*., 2014; Shah *et al*., 2016), cassava (Nabeshima and Grossmann, 2001; Sondari *et al*., 2021; Joseph *et al*., 2024; Ferreira Karow *et al*., 2025), and potato (Wang *et al*., 2012; Heo *et al*., 2017; Bodjrenou *et al*., 2023) show that phosphorylation with STMP can improve water binding capacity, oil binding capacity, and increase thermal stability and bioactive activity.

However, studies on phosphorylation in local starch sources, particularly Banggai yam (*Dioscorea alata* L.), are still minimal. Banggai yam has great potential because, in addition to containing starch with a distinctive amylose–amylopectin profile (Ulyarti *et al*., 2016; Jumari *et al*., 2019; Tortoe *et al*., 2019; Kusnandar *et al*., 2021). It is also rich in bioactive compounds such as anthocyanins and β-carotene (Jose and Muhammed, 2015; Nadia *et al*., 2015), which contribute to antioxidant activity (Zhang *et al*., 2022). However, to date, there has been no systematic report evaluating how variations in STMP concentration affect the proximate composition, starch structure, functional properties, and bioactive content of Banggai yam. This limited knowledge is an obstacle to the optimal use of Banggai yams as an innovative raw material in the food and non-food industries.

This study is novel because it utilizes a relatively unexplored local starch source, with a focus on integrating proximate composition analysis, functional properties, starch structure, as well as bioactive compounds and antioxidant activity. This study aimed to evaluate the effect of phosphorylation with STMP on proximate composition, Functional properties, Starch structure, Bioactive compounds, and antioxidant activity of BYPS.

The urgency of this research lies in its contribution to the development of functional foods based on local resources while simultaneously supporting food diversification and national food security. Furthermore, this research opens opportunities for the use of BYPS in innovative food products, such as analog rice and edible films, which are not only commercially valuable but also relevant to global issues regarding health, sustainability, and the use of local raw materials. Therefore, the results of this study are expected to provide a strong scientific basis to encourage the development of Banggai yam as a source of functional starch with broad application potential in the food and non-food industries.

Materials and Methods

The primary material used in this study was Banggai yam (*Dioscorea alata* L.) obtained from local farmers in Banggai Islands Regency, Central Sulawesi, Indonesia. Harvested tubers were selected based on physiological maturity criteria, free from physical damage or disease, then peeled, washed thoroughly, and processed into starch through a conventional extraction process. The phosphorylation agent used was food-grade sodium trimetaphosphate (STMP) obtained from Sigma-Aldrich (St. Louis, MO, USA). Other chemicals used in the analysis, such as sodium hydroxide (NaOH), hydrochloric acid (HCl), and ethanol (C_2H_5OH), were pro-analytical reagents (Merck, Darmstadt, Germany).

Instruments

The tools used included basic laboratory equipment such as a drying oven (Memmert, Germany), an analytical balance (Shimadzu, Japan), and a centrifuge (Eppendorf 5804R, Germany). Proximate analysis was performed using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan) to measure protein, anthocyanin, *β*-carotene, and antioxidant activity using the DPPH method. Amylose and amylopectin levels were analyzed using a colorimetric method based on iodine binding with spectrophotometry. Water holding capacity (WHC) and oil holding capacity (OHC) were measured using the gravimetric method after the centrifugation process.

Synthesis of Natural Banggai yam Starch was carried out according to the method (Chaniago *et al*., 2024) with slight adjustments, while Phosphorylation of Banggai yam starch was carried out according to the method developed by (Maulani and Hidayat, 2016) with slight modifications. The suspension consisting of Banggai yam starch and distilled water (225 mL) was stirred with a magnetic stirrer for one hour at room temperature. After that, the pH of the suspension was adjusted and maintained at pH 10.5 by adding 5% NaOH while continuing to stir, then adding STMP 2, 6, and 10%. The suspension was stirred for 45 minutes at 40 °C while maintaining pH 10.5. After phosphorylation was complete, the suspension was diluted with 0.5 N HCl to a pH of 4.5 to stop the reaction. The following process involves precipitation, followed by washing with distilled water three times and ethanol once. The sample is then dried with a cabinet dryer at 50°C for 12 hours, until the water content reaches 10-12%. After drying, the sample is ground and filtered with a 100 mesh sieve. The results of the phosphorylation of yam starch phosphate (BYPS) at various concentrations of STMP reagent were repeated 3 times in each treatment to become nine treatment units. Furthermore, the obtained BYPS was analyzed for Proximate composition (Protein, Lipid, Carbohydrates, Crude Fiber), Functional properties (WCH, OHC), Starch structure (Amylose, Amylopectin), and Bioactive compounds and antioxidant activity (Anthocyanin, β-carotene, IC_{50} DPPH).

Results and Discussion

Proximate composition

Proximate analysis is a fundamental approach in evaluating the nutritional quality and application potential of a food ingredient. Proximate parameters such as protein, lipid, carbohydrate, and crude fiber levels not only provide an overview of nutritional value but are also closely related to the functional properties of these ingredients in food product formulations. In this study, a proximate analysis was conducted on Banggai yam starch modified with sodium trimetaphosphate (STMP) at various concentrations (2%, 6%, and 10%). Variations in phosphate reagent concentration are expected to affect the chemical composition, both through the release and retention of non-starch components, as well as the formation of crosslinks that affect the stability and availability of nutrients. The results of the proximate analysis of BYPS phosphorylated with STMP are shown in Table 1.

Table 1: *Proximate content, functional properties, starch structure, bioactive compounds, and antioxidant activity of BYPS*

Content	Phosphate compounds		
	STMP 2%	STMP 6%	STMP 10%
Protein (%)	3,953	3,960	3,910
Lipids (%)	1,690	0.800	0.370
Carbohydrate (%)	76,830	80,557	74,627
Crude fiber (%)	0.773	0.860	0.810
WHC (%)	46,080	52,480	63,900
OHC (%)	54,620	61,120	75,760
Amylose (%)	56,537	58,123	54,090
Amylopectin (%)	43,463	41,877	45,910
Anthocyanin (mg/L)	0.433	0.450	0.190
β -Carotene (mg/100g)	0.0369	0.0375	0.0382
Antioxidants (ppm)	163,323	210,375	283,280

Protein

Proximate analysis of Banggai yam phosphate starch (BYPS) modified with sodium trimetaphosphate (STMP) showed variations in nutritional composition with increasing reagent concentration (Table 1). Protein content was relatively stable with values ranging from 3.910–3.960%, with 6% STMP producing the highest value (3.960%) (Figure 1). This variation indicates that the phosphorylation process does not significantly impact protein content, as protein is present in small amounts in starch and tends not to be directly involved in phosphate substitution reactions. This is consistent with previous findings on modified tuber starch, where protein content remained relatively unchanged after chemical processing.

The results of this study indicate that phosphorylation using sodium trimetaphosphate (STMP) did not significantly affect the protein content of Banggai yam starch phosphate (BYPS). This phenomenon can be explained by the fundamental nature of starch, which is naturally composed almost entirely of polysaccharides. At the same time, the protein content is only present in very low amounts and is mostly weakly bound to the granule surface. The phosphorylation process with STMP occurs specifically on the hydroxyl (-OH) groups in the glucose chain, forming phosphate crosslinks, without involving amino groups or peptide bonds that are part of the protein structure. Thus, this modification only affects the carbohydrate fraction without having a significant impact on the residual protein.

Furthermore, most of the protein was eliminated during the starch extraction stage, so the remaining amount was too small to show any significant changes. The phosphorylation reaction conditions used in this study, namely moderate alkaline pH and relatively low temperature, were also not extreme enough to denature or damage the protein. This finding is in line with previous reports on the modification of corn starch (Abdrabuo *et al*., 2020), potato starch (Zhang *et al*., 2025), and cassava starch (Noerwijati, 2015), where the protein content was relatively stable after phosphorylation because the phosphate agent was more reactive to polysaccharides than proteins.

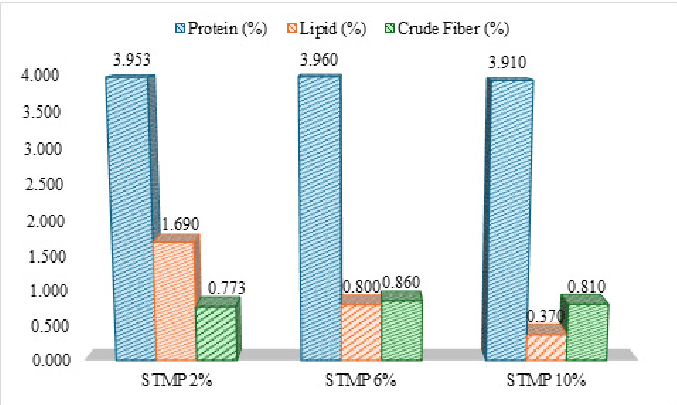

Figure 1: *Protein, Lipids, Crude fiber BYPS*

Lipids
The lipid content decreased quite sharply with increasing STMP concentration, from 1.690% (2% STMP) to 0.370% (10% STMP) as seen in Figure 1. This decrease is likely due to the phosphorylation process that can release bound lipids in starch granules, so that most of the lipids are lost during the washing stage. The loss of lipids is beneficial because lipids bound to starch are known to inhibit amylose availability, affect gelatinization properties, and reduce functionality. Thus, BYPS at high STMP concentrations has advantages in the functional aspects of food technology.

The results showed that the lipid content of Banggai yam phosphate starch (BYPS) decreased with increasing STMP concentration. This decrease can be explained by the presence of lipids in the starch, most of which are bound to amylose to form helical inclusion complexes, with a small portion located on the granule surface. The phosphorylation process with STMP introduces negatively charged phosphate groups into the starch chain, thereby destabilizing the amylose-lipid complex and triggering the release of lipids from the granule matrix. The released lipids are easily eliminated during the washing stage, resulting in lower lipid content in BYPS compared to the original starch. The reaction conditions used, namely a moderate alkaline pH, also accelerated the dissociation of the amylose-lipid complex, thereby increasing lipid loss. Nevertheless, this decrease in lipid content is positive, as the lipid fraction in starch granules is known to reduce the availability of free amylose and limit hydration capacity. With reduced lipids, the starch structure becomes more open, increasing water and oil absorption capacity, which is in line with the findings on the functional properties of BYPS in this study. These findings are consistent with previous studies on corn starch. (Yousif *et al*., 2012) Potato (Shujun *et al*., 2008) and modified arrowroot starch (Rohmayanti *et al*., 2025) also reported a decrease in lipid content due to the release of lipid–amylose complexes during the chemical modification process.

Crude fiber
The crude fiber content was relatively stable, ranging from 0.773 to 0.860%. The highest value was found in BYPS with 6% STMP (0.860%), while the lowest value was found in 2% STMP (0.773%), as seen in Figure 1. This increase in crude fiber may be due to the formation of crosslinks between phosphate groups and non-starch polysaccharide structures, resulting in a fraction that is more resistant to hydrolysis. This condition is relevant to BYPS's potential as a functional carbohydrate source, given that dietary fiber plays a role in slowing the glycemic response and supporting digestive health.

The increase in crude fiber content in Banggai yam phosphate starch (BYPS) after phosphorylation treatment with STMP can be attributed to structural changes that occur in starch granules during the modification process. Phosphorylation promotes the formation of crosslinks between phosphate groups and polysaccharide chains, resulting in a starch fraction that is resistant to enzymatic and chemical hydrolysis (Kustyawati, 2018). This fraction is detected as crude fiber in proximate analysis. Furthermore, the partial release of lipids and proteins during the post-phosphorylation washing process contributes to an increase in the relative proportion of oil fiber to total dry weight. This phenomenon is consistent with reports on other modified starches, where chemical treatment increases the undigested fraction, which behaves similarly to dietary fiber (Aristyarini *et al*., 2022). From a functional perspective, the increase in crude fiber content has positive implications, as the resistant starch fraction plays a vital role in lowering the glycemic index and supporting digestive health. Thus, the increase in crude fiber in BYPS not only indicates the presence of molecular restructuring due to phosphorylation but also strengthens the potential of BYPS as a functional food ingredient with added health value.

Overall, the proximate analysis results showed that phosphorylation with STMP at a medium concentration (6%) provided the best balance, with relatively high carbohydrate and protein content, low lipid content, and increased crude fiber. This profile supports BYPS's potential for application as a functional food ingredient, particularly in low-fat and low-fiber product formulations.

Carbohydrate

The carbohydrate content, which is the main component, showed significant fluctuations. The highest value was obtained at 6% STMP (80.557%), while the lowest value was at 10% STMP (74.627%), as seen in Figure 2.

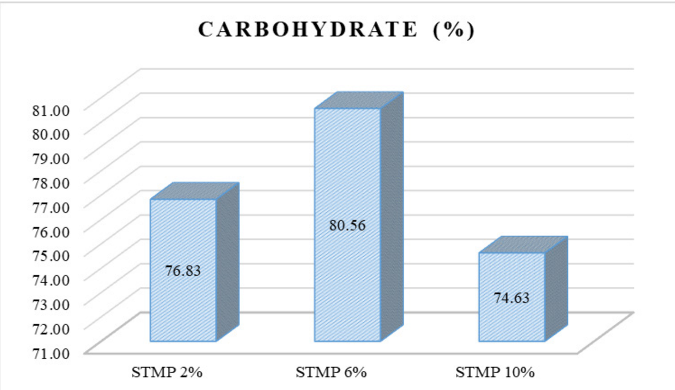

Figure 2: *BYPS carbohydrate*

The increase in STMP at 6% can be attributed to a decrease in lipid and protein content, increasing the relative proportion of carbohydrates. However, the sharp decline in STMP at 10% indicates the possibility of partial starch degradation due to more aggressive phosphorylation conditions. The decrease in carbohydrate content at high concentrations can also be caused by excessive crosslinking reactions, which result in some starch fractions not being optimally detected by proximate analysis methods.

The observed decrease in carbohydrate content in Banggai phosphate-treated sweet potato starch (BYPS), particularly at high STMP concentrations, can be explained by the nature of the phosphorylation reaction, which causes structural changes in starch granules. Phosphorylation with STMP triggers the formation of crosslinks between glucose chains through the substitution of phosphate groups at the hydroxyl position, so that some glucose units are no longer detected as free carbohydrates in proximate analysis. Furthermore, more intensive reaction conditions have the potential to cause partial degradation of starch molecules, especially in the linear amylose fraction, which is subsequently removed during the washing stage. This phenomenon has implications for the decrease in measured carbohydrate content, even though the total mass of starch granules is not significantly reduced. The decline in carbohydrate in modified starch was also reported in similar studies using yam flour (Sukma *et al*., 2019; Wahyuni *et al*., 2024) and corn starch (Utami and Sujaya, 2013), which showed that increasing phosphorylation intensity is often accompanied by a decrease in carbohydrate content due to the formation of non-carbohydrate fractions bound to phosphate groups. In a functional context, this decrease is not necessarily negative, as phosphate crosslinking strengthens the starch's stability against gelatinization and improves specific functional properties, such as water-holding capacity. Therefore, the measured changes in carbohydrate content in BYPS reflect chemical modifications and molecular restructuring rather than actual nutrient losses.

Functional properties

WHC and OHC

Functional properties are essential parameters that determine the potential application of modified starch in various food formulations. The two main properties examined in this study are water holding capacity (WHC) and oil holding capacity (OHC) (Table 1). These two parameters are strongly influenced by the molecular structure of starch, particularly the availability of hydrophilic and hydrophobic groups, as well as the porosity of the granules formed after the modification process.

The analysis results showed that BYPS phosphorylated with STMP experienced a gradual increase in both WHC and OHC as the reagent concentration increased. WHC increased from 46.080% at 2% STMP to 63.900% at 10% STMP. This increase indicates that phosphorylation can introduce negatively charged phosphate groups into the starch chain, thereby increasing the matrix's ability to interact with water molecules. The formed phosphate bonds can also widen the distance between polysaccharide chains, creating more space for water retention. This is in line with studies on other modified starches that report that the introduction of phosphate groups increases the affinity of starch for water and improves hydration properties.

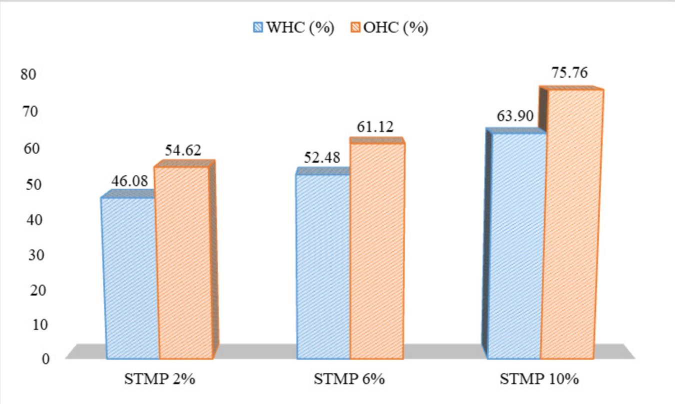

Figure 3: *WHC and OHC BYPS*

The same trend was also observed in OHC, where the oil-holding capacity increased significantly from 54.620% (2% STMP) to 75.760% (10% STMP). This increase in OHC can be explained by the formation of a more porous and heterogeneous starch structure due to excessive crosslinking at high STMP concentrations. This porosity allows oil molecules to be retained in the matrix. At the same time, the presence of hydrophilic and hydrophobic groups in the phosphate structure provides a balance of interactions that favors affinity for lipids.

The increase in *water holding capacity* (WHC) and *oil holding capacity* (OHC) in Banggai yam starch phosphate (BYPS) phosphorylated with STMP indicates that the modification process successfully improves the functional properties of starch through changes in molecular structure. Phosphorylation introduces negatively charged phosphate groups to the hydrophilic glucose chains, thereby increasing the starch's ability to bind water through electrostatic interactions and hydrogen bonds (Amin, 2015). In addition, the formation of crosslinks between polysaccharide chains produces a more porous matrix, allowing for greater water retention within the granule structure (Yulianto, 2023). This condition is reflected in the increase in WHC along with increasing STMP concentration. Meanwhile, the rise in OHC can be explained by granule restructuring that produces a larger and more heterogeneous surface area, thereby growing the affinity of oil molecules. The presence of phosphate groups also creates a balance of hydrophilic-hydrophobic interactions that support lipid binding ability. Similar phenomena have been reported in the modification of taro starch (Saudarah *et al*., 2023), palm starch (Rahim *et al*., 2018), and sago starch (Fitriani *et al*., 2023), where phosphorylation increases hydration and oil absorption capacity due to the formation of phosphate crosslinks. Thus, the increase in WHC and OHC in BYPS not only reflects compositional changes due to the release of lipids and proteins but also indicates a more functional restructuring of the starch molecule, which has broad implications for its application in food products with the need for water retention, emulsion stability, and better texture.

Overall, the increase in WHC and OHC values indicates that BYPS phosphorylated with STMP has higher functional advantages compared to native starch. The condition with a STMP concentration of 10% produced the highest value, indicating that intensive modification has a positive effect on water and oil absorption properties. These findings strengthen the potential of BYPS as a raw material in modern food formulations that require good texture, emulsion stability, and moisture retention.

Starch structure

Amylose and amylopectin

The composition of amylose and amylopectin is a fundamental parameter in determining the physicochemical and functional properties of modified starch. Phosphorylation with sodium trimetaphosphate (STMP) has the potential to alter the relative proportions of these two fractions through the interaction of phosphate groups with linear and branched glucose chains. The results of the compositional analysis showed variations in the proportions of amylose and amylopectin with increasing STMP concentration (Table 1).

The highest amylose content was obtained at 6%

STMP concentration (58.123%), while the lowest content was recorded at 10% STMP (54.090%). The increase in amylose content at the intermediate concentration (6%) can be interpreted because of the partial release of lipid-amylose bonds during the phosphorylation process, which makes the amylose fraction more detectable in the analysis. In addition, the phosphate group included in the linear polysaccharide chain has the potential to enhance amylose solubility and increase its relative proportion. However, at a higher STMP concentration (10%), the decrease in amylose content indicates the possible formation of excessive crosslinks that limit the solubility and detection of amylose, while increasing the relative amylopectin fraction.

In contrast, the proportion of amylopectin showed the opposite pattern. The lowest value was found at 6% STMP (41.877%) and increased again at 10% STMP (45.910%). The increase in amylopectin at high concentrations indicates that the phosphorylation process with greater intensity tends to maintain or even strengthen the branched fraction. This may occur because phosphate groups more easily bind to complex branched structures, resulting in more stable starch granules with a relatively higher amylopectin content.

The decrease in amylose and amylopectin levels in Banggai yam phosphate starch (BYPS) phosphorylated with STMP indicates significant structural changes due to the chemical modification process. Phosphorylation introduces phosphate groups into the glucose chain through a substitution reaction, so that some glucose units are no longer detected as pure carbohydrates in the analysis, but rather as starch-phosphate complexes. This condition can reduce the measured levels of amylose and amylopectin. Furthermore, at higher STMP concentrations, excessive crosslinking can cause partial degradation of both linear (amylose) and branched (amylopectin) fractions, thus reducing their content. This degradation is often accompanied by the release of short-chain fragments that are soluble and discarded during the washing process. A similar phenomenon has also been reported in some modified natural starches (Eryani and Nurwaini, 2022), where high chemical reaction intensity reduces amylose–amylopectin detection due to granule restructuring and the formation of a resistant starch fraction. Thus, the decrease in amylose and amylopectin in BYPS reflects more on the occurrence of molecular modifications and an increase in the undigested fraction rather than a real loss of nutrients, which ultimately has implications for improving the stability and increasing the functional properties of the modified starch.

Overall, these changes in the proportions of amylose and amylopectin have direct implications for the functional properties of BYPS. Higher amylose levels at 6% STMP concentration can contribute to increased viscosity, gel-forming ability, and functional properties such as water-holding capacity. Meanwhile, the dominance of amylopectin at 10% STMP is more associated with granular stability, resistance to retrogradation, and the potential for improved textural properties. Thus, varying the STMP concentration allows control of the molecular structure of starch to suit the needs of specific food applications.

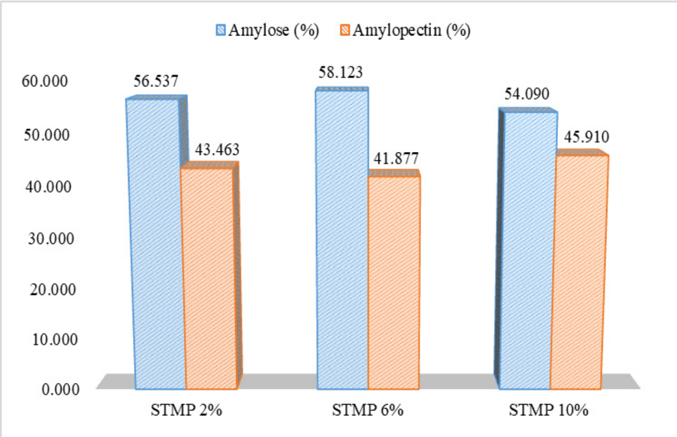

Figure 4: *Amylose and amylopectin BYPS*

Bioactive compounds and antioxidant activity
Anthocyanin, β-carotene, and antioxidant capacity
Bioactive analysis of Banggai yam starch phosphate (BYPS) shows that the phosphorylation process with STMP can modulate the content of functional compounds, especially anthocyanins, β-carotene, and antioxidant activity (Table 1). In general, these bioactive compounds play an essential role in determining the added functional value of food ingredients, both as natural colorants and as components with free radical scavenging capacity.

The anthocyanin content fluctuated with increasing STMP concentration. At 2% and 6% concentrations, the anthocyanin content remained relatively stable at 0.433 mg/L and 0.450 mg/L, respectively. However, at 10% concentration, a significant decrease occurred to 0.190 mg/L. The degradation of anthocyanin pigments can explain this decrease due to excessive crosslinking formed during the phosphorylation process. These crosslinks can inhibit the attachment of anthocyanins to the starch matrix, thereby reducing pigment stability. This phenomenon is consistent with previous reports that intensive chemical treatment can cause the degradation of phenolic pigments.

The decrease in anthocyanin levels in Banggai yam phosphate starch (BYPS) after phosphorylation treatment with STMP can be explained by the chemical nature of anthocyanins, which are highly labile to alkaline reaction conditions and intensive chemical treatments. Anthocyanins are phenolic pigments that are sensitive to changes in pH, temperature, and the presence of reactive ions. Therefore, under alkaline phosphorylation conditions, most of the pigments undergo degradation or transformation into colorless forms. At high STMP concentrations, excessive crosslinking occurs in the starch matrix, which can inhibit anthocyanin attachment and stabilization, thus reducing the amount of detectable pigment. In addition, during the post-phosphorylation washing stage, degraded or unstable anthocyanins are potentially eliminated from the system, thereby reducing the pigment content in BYPS. This phenomenon is in line with previous reports on modified purple sweet potato-based starch. (Husna *et al*., 2013; Eryani and Nurwaini, 2022) , which showed a significant decrease in anthocyanin content after chemical modification due to pigment instability under alkaline conditions. However, anthocyanin degradation does not completely reduce the functional potential of BYPS, because the restructuring of starch molecules and the retention of some other bioactive compounds, such as β-carotene, can still contribute to antioxidant activity.

β-carotene content showed a different trend. The β-carotene value tended to increase with increasing STMP concentration, from 0.0369 mg/100 g (2% STMP) to 0.0382 mg/100 g (10% STMP). This increase, although relatively small, was consistent and could be attributed to the increased stability of β-carotene due to the presence of phosphate crosslinks that protect the molecule from oxidative degradation, for example, in pinhão (Araucaria angustifolia) seed starch (Lestari, 2022). This suggests that phosphorylation has potential as a partial encapsulation technique that maintains the presence of lipophilic pigments such as carotenoids.

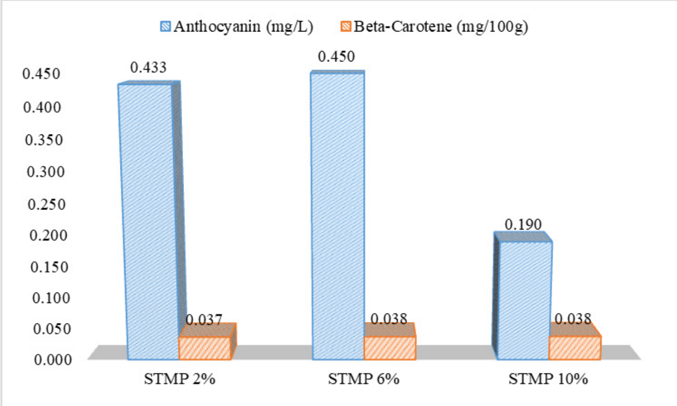

Figure 5: *Anthocyanin and β-carotene BYPS*

Interestingly, antioxidant activity showed the opposite pattern to anthocyanin content. Antioxidant activity increased sharply with increasing STMP concentration, from 163.323 ppm at 2% STMP to 283.280 ppm at 10% STMP. This confirms that although anthocyanins are reduced at high concentrations, the antioxidant mechanism is strengthened, likely due to the formation of phosphate crosslinks that increase the starch's ability to scavenge free radicals. Furthermore, the increased stability of β-carotene at high STMP also contributes to the total antioxidant capacity.

The increased antioxidant activity of Banggai yam phosphate starch (BYPS) after phosphorylation with STMP indicates that the chemical modification process can provide a protective effect against lipophilic bioactive compounds. Phosphorylation produces crosslinks in starch granules, creating a more compact structure that is relatively resistant to oxidative degradation. This condition has the potential to act as a kind of partial encapsulation system that protects β-carotene molecules from damage during the reaction process and storage, so that its concentration increases at higher STMP concentrations. Furthermore, the presence of negatively charged phosphate groups in the starch matrix can improve the ability of BYPS to interact with free radicals, thereby strengthening the antioxidant capacity even though the anthocyanin content decreases. This phenomenon is consistent with reports on modified tuber and cereal-based starches (Tarigan *et al*., 2015; Ratnaduhita *et al*., 2021), where the introduction of phosphate groups not only improves functional properties but also improves the stability of bioactive components. Thus, the increase in β-carotene and antioxidant activity in BYPS confirmed that STMP phosphorylation not only improves the technological properties of starch

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but also enriches its functional value as a candidate bioactive food ingredient with broad application potential in functional food formulations.

These findings confirm that starch modification with STMP not only affects the molecular structure (amylose–amylopectin) but also has implications for the retention and activity of bioactive compounds. Thus, BYPS phosphate has the potential to be developed as a functional food ingredient with high antioxidant capacity. However, the degradation of sensitive pigments such as anthocyanins at excessive phosphate concentrations needs to be considered.

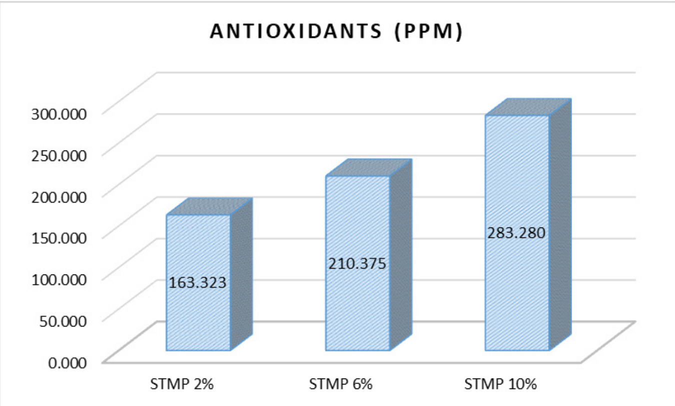

Figure 6: *BYPS antioxidant*

Conclusions and Recommendations

The results of this study indicate that phosphorylation of Banggai yam (*Dioscorea alata* L.) starch using sodium trimetaphosphate (STMP) significantly modifies the chemical, functional, and bioactive properties of the starch. Phosphorylation did not considerably affect protein content, but reduced lipid and carbohydrate levels due to the release of bound fractions and the formation of more stable crosslinks. Conversely, crude fiber content increased, indicating the formation of a resistant starch fraction with positive implications for digestive health. The functional properties of BYPS also significantly improved, indicated by an increase in *water holding capacity* (WHC) and oil holding capacity (OHC) with increasing STMP concentration, indicating a restructuring of starch granules toward a more porous and functional matrix. Changes in molecular structure were confirmed through a shift in the amylose–amylopectin proportion, where high STMP concentrations decreased the detected fraction due to the formation of starch-phosphate complexes. From the bioactive side, there was a decrease in anthocyanin levels, but this was offset by an increase in β-carotene and total antioxidant capacity, which confirms the role of phosphorylation in strengthening the stability of lipophilic compounds and increasing free radical scavenging activity.

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Novelty Statement

This study uniquely develops phosphorylated Banggai yam starch-based edible films, integrating STMP/STPP modification and glycerol variation to comprehensively optimize mechanical, functional, physical, and optical packaging properties.

Author's Contribution

Ramadhani Chaniago: Conceptualization, methodology, supervision, project administration, data curation, formal analysis, writing – original draft, writing – review & editing.
Samsu Adi Rahman: Methodology refinement, validation; formal analysis, resources, writing – review & editing; critical revision of the manuscript for important intellectual content.
Nur Alim Bahmid: Investigation, data collection, laboratory analysis of mechanical, functional, physical, and optical properties, assistance in data interpretation.
Darni Lamusu: Preparation and characterization of native Banggai yam starch and technical assistance.

Generative AI or AI assisted technology statement
AI-based tools were used solely to assist with language polishing and improve the clarity of English writing, and data interpretation, and conclusions were fully developed, verified, and approved by the authors.

Conflict of interest
The authors have no conflict of interest.

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