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Modified rejection banana starch: characterization and potential food application

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ABSTRACT: Postharvest losses of green bananas represent an underexploited source of starch with functional potential. The objective of this research was to extract starch from rejected green bananas, modify it using heat-moisture treatment HMT, annealing ANN, and pregelatinization PGS, characterize the resulting physicochemical and functional properties, and evaluate its performance as a fat substitute in a low-fat Frankfurter-type sausage. Pregelatinized starch showed the highest water absorption capacity (2.84 g/g) and a high amylose content (28.8%), while annealed starch exhibited the lowest water solubility (8.08%). Incorporation of pregelatinized banana starch into the sausage formulation showed favorable technological performance. Correlation analysis between instrumental texture measurements and sensory evaluation identified the 40% fat-replacement formulation as the most balanced in terms of sensory acceptance and textural properties. These findings confirm the potential of rejected bananas as a source of high-value functional ingredients, contributing to agroindustrial sustainability and offering viable technological alternatives for the development of reformulated, healthier meat products.
Keywords: rejected banana starch; physical starch modification; functional properties; fat replacement; meat products.

Amido de banana de rejeito modificado: caracterização e potencial aplicação em alimentos

RESUMO: As perdas pós-colheita de bananas verdes constituem uma fonte de amido subutilizada, com potencial funcional. O objetivo desta pesquisa foi extrair amido de bananas verdes descartadas, modificá-lo por meio de tratamento térmico com umidade controlada (HMT), recozimento (ANN) e pré-gelatinização (PGS), caracterizar as propriedades físico-químicas e funcionais resultantes e avaliar seu desempenho como substituto de gordura em salsichas tipo Frankfurt com baixo teor de gordura. O amido pré-gelatinizado apresentou a maior capacidade de absorção de água (2,84 g/g) e alto teor de amilose (28,8%), enquanto o amido submetido ao recozimento apresentou a menor solubilidade em água (8,08%). A incorporação de amido de banana pré-gelatinizado na formulação da salsicha apresentou desempenho tecnológico favorável. A análise de correlação entre as medidas instrumentais de textura e a avaliação sensorial identificou a formulação com substituição de 40% da gordura como a mais equilibrada em termos de aceitação sensorial e propriedades de textura. Esses resultados confirmam o potencial das bananas descartadas como fonte de ingredientes funcionais de alto valor, contribuindo para a sustentabilidade agroindustrial e oferecendo alternativas tecnológicas viáveis para o desenvolvimento de produtos cárneos reformulados e mais saudáveis.
Palavras-chave: amido de banana descartada; modificação física de amido; propriedades funcionais; substituição de gordura; produtos cárneos.

1. INTRODUCTION

Banana is one of the world's most important tropical crops. However, a considerable proportion of its production is discarded because it fails to meet the size, maturity, or appearance standards required by export markets. These rejected fruits, characterized by their high starch and dietary fiber contents, are frequently treated as waste despite representing a valuable raw material for the production of value-added ingredients (MARTA et al., 2022).

This issue has become increasingly significant considering that, in 2022, approximately 19% of the food produced worldwide, equivalent to 1.05 billion tonnes, was wasted at the household, food service, and retail levels (UNITED NATIONS ENVIRONMENT PROGRAMME, 2024). In addition, approximately 13% of global food production is lost throughout the supply chain, from post-harvest handling to retail distribution (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2022). Consequently, the valorization of rejected bananas represents a promising strategy for converting an underutilized agricultural by-product into a valuable source of raw materials for the development of innovative food ingredients.

Among the various components obtained from rejected bananas, green banana starch has attracted considerable attention because of its remarkable functional and technological properties. Experimental studies have demonstrated that green banana starch exhibits high water and oil absorption capacities together with favorable gelatinization characteristics (FONSECA et al., 2021; FONTES et al., 2017). In addition, its highly resistant starch content makes it a promising ingredient for the development of functional foods with potential health benefits (MUNIR et al., 2024). Owing to these technological and nutritional attributes, green banana starch has been increasingly explored as an ingredient for the formulation of functional, value-added, and reduced-fat food products (GRASSO et al., 2024)

Banana starch can be modified through physical, chemical, or enzymatic treatments to enhance its thermal stability, reduce retrogradation, and improve its rheological performance in complex food systems, including meat products (ADIYANTI; SUBROTO, 2020). Among the available physical modification techniques, heat-moisture treatment HMT, pregelatinization PGS, and annealing ANN have received particular attention because they improve starch functionality through different mechanisms. Heat-moisture treatment promotes molecular rearrangement within starch granules, thereby increasing structural stability and modifying physicochemical properties (ADEBOWALE et al., 2005). Pregelatinization produces starch that is readily soluble in cold water, facilitating its incorporation into instant food formulations, whereas annealing induces molecular reorganization without the use of chemical reagents while preserving starch granular integrity (VAN NGO; LUANGSAKUL, 2025).

Several studies have also demonstrated that banana biomass and flour improve water-holding capacity, increase dietary fiber content, and enhance the technological performance of different food systems (STRAGLIOTTO ET AL., 2022). Furthermore, the incorporation of plant-derived by-products into food formulations contributes to the development of more sustainable foods that meet current consumer demand for healthier products without compromising sensory quality. In this context, Marta et al. (2022) proposed the modification of native starch extracted from rejected bananas using HMT as an effective strategy for producing functional food ingredients, emphasizing that comprehensive physicochemical and functional characterization is essential for evaluating starch purity, stability, and rheological behavior.

However, despite the growing interest in physically modified banana starch, comparative information regarding the effects of heat-moisture treatment, pregelatinization, and annealing on the proximate composition, amylose content, and functional properties of starch extracted from rejected bananas remains scarce. Most previous studies have focused on individual modification methods or on starches obtained from other botanical sources, limiting direct comparisons among physical treatments and restricting the identification of the most suitable modification technique for agro-food applications.

Therefore, the aim of this study was to compare the effects of three physical modification methods heat-moisture treatment HMT, annealing ANN, and pregelatinization PGS on the proximate composition moisture, fat, fiber, ash, and protein, amylose content, and functional properties, including the water absorption index, water solubility index, and swelling power, of starch extracted from rejected bananas. The findings provide comparative scientific evidence for selecting the most suitable physical modification technique to improve the functional performance of banana starch and support its application as a value-added functional ingredient in the agro-food industry.

2. MATERIAL AND METHODS

2.1. Quality assessment of commercial pine wood shavings

2.1. Materials

Rejected green bananas (*Musa* spp.) unsuitable for export due to failure to meet commercial standards for size and appearance were obtained from banana packing facilities in Manabí Province, Ecuador. The fruits were visually inspected to ensure their sanitary condition, washed with running water to remove surface impurities, and manually peeled prior to starch extraction.

Distilled water was used throughout the experimental procedures for starch extraction and moisture adjustment during the physical modification treatments. All reagents employed in the physicochemical analyses were of analytical grade. The main equipment included an industrial blender, stainless-steel sieves (100–120 mesh), a temperature-controlled drying oven, a muffle furnace, a UV–Visible spectrophotometer, a digital pH meter, a heating magnetic stirrer, a TX-700 texture analyzer, and an analytical balance.

2.2. Experimental Design

The study was conducted using a quantitative experimental approach and comprised two independent experimental stages. In the first stage, the effects of three physical modification methods applied to rejected green banana starch were evaluated: heat-moisture treatment HMT, annealing ANN, and pregelatinization PGS. Native starch was included as the reference treatment. Physicochemical and functional characterization was carried out using a Completely Randomized Design CRD, considering the type of starch treatment native, HMT, ANN, and PGS as the single experimental factor. All determinations were performed in triplicate.

In the second stage, Frankfurt-type sausages were prepared using only pregelatinized starch PGS, selected based on the results obtained during the physicochemical and functional characterization. A Completely Randomized Design was used, considering the level of partial fat replacement with pregelatinized starch as the experimental factor, with four treatment levels: 0% control treatment, 20%, 40%, and 60%. Each treatment was prepared in four independent replicates.

2.3. Native Starch Extraction

Native starch was extracted from rejected green banana pulp. The pulp was homogenized with distilled water at a 1:3 (w/v) ratio using an industrial blender for 5 min to facilitate the release of starch granules. The resulting slurry was filtered through 100–120 mesh stainless-steel sieves to remove fibrous material. Subsequently, the starch was recovered by sedimentation followed by successive washing steps until a sediment-free of visible impurities was obtained. Finally, the starch was dried and stored for subsequent physical modification.

2.4. Physical Modification of Starch

The extracted native starch was subjected to three physical modification methods: heat-moisture treatment

HMT, annealing ANN, and pregelatinization PGS. Distilled water was used in all treatments to adjust the moisture content.

2.4.1. Heat-Moisture Treatment HMT

The moisture content of the native starch was adjusted to 25% by adding 142.25 mL of distilled water to 795 g of starch. The sample was then manually homogenized and stored in airtight containers at 4 °C for 24 h to ensure uniform moisture distribution. After the equilibration period, the starch was heated in a drying oven at 120 °C for 16 h. Subsequently, it was cooled to room temperature and dried at 50 °C until reaching a moisture content between 10% and 12%, after which it was ground and stored for further analyses.

2.4.2. Annealing ANN

The moisture content of the native starch was adjusted to 40% by adding 386.83 mL of distilled water to 790 g of starch. After homogenization, the sample was stored in airtight containers at 4 °C for 24 h to promote uniform moisture distribution. The starch was then incubated in a drying oven at 55 °C for 48 h. After treatment, the material was dried at 50 °C until reaching a moisture content between 10% and 12%, then ground and stored for subsequent analyses.

2.4.3. Pregelatinization PGS

Native starch was mixed with distilled water to obtain a suspension containing 423 g of starch and 657.22 mL of water. The suspension was heated in a water bath at 75 °C for 15 min under continuous stirring to promote partial starch gelatinization. The resulting material was subsequently dried in a forced-air oven at 50 °C until reaching a moisture content between 10% and 12%, then ground and stored for subsequent characterization.

The experimental conditions applied during each physical modification treatment, together with the initial and final moisture contents, are presented in Table 1.

Table 1. Experimental conditions applied during the physical modification of rejected green banana starch by heat-moisture treatment (HMT), annealing (ANN), and pregelatinization (PGS), including the initial, adjusted, and final moisture contents.
Tabela 1. Condições experimentais aplicadas durante a modificação física do amido de banana verde, por meio de tratamento térmico-úmido (HMT), *annealing* (ANN) e pré-gelatinização (PGS), incluindo os teores de umidade inicial, ajustado e final.

Parameter	HMT	ANN	PGS
Initial moisture (%)	10.62	10.62	10.62
Adjusted moisture (%)	25.00	40.00	65.00
Water added (mL)	142.25	386.83	657.22
Processing conditions	120 °C for 16 h (oven)	55 °C for 48 h (oven)	75 °C for 15 min (water bath)
Final moisture (%)	9.62	11.57	9.13

HMT: Heat-moisture treatment; ANN: Annealing; PGS: Pregelatinization.
HMT: Tratamento térmico-úmido; ANN: Recozimento; PGS: Pré-gelatinização.

2.5. Physicochemical and Functional Characterization

The modified starches were characterized through physicochemical and functional analyses to evaluate the effects of the physical modification treatments on their technological properties.

Proximate composition included the determination of moisture, ash, protein, fat, and crude fiber contents following the procedures described in the Manual de Técnicas de Análisis de los Alimentos (AVILÉS, 2002 *apud* NORIEGA et al., 2019). Moisture content was determined by the gravimetric oven-drying method until constant weight; ash content by incineration in a muffle furnace at 600 °C for 2 h; protein content using the Kjeldahl method; fat content by Soxhlet extraction; and crude fiber according to the procedure described by AVILÉS-VÉLEZ (2002). All determinations were performed in triplicate, and the results were expressed as percentages.

Amylose content was determined using the iodine colorimetric method described by Juliano (1971). Starch samples were dissolved in 1 N sodium hydroxide (NaOH), neutralized with 1 N acetic acid, and subsequently reacted with an iodine–potassium iodide solution. The absorbance of the amylose–iodine complex was measured at 620 nm using a UV–Visible spectrophotometer. Amylose content was quantified using a calibration curve prepared with standard amylose.

The functional properties of the starches were determined according to the methodology proposed by Anderson et al. (1969). The water absorption index WAI, water solubility index WSI, and swelling power SP were calculated using the equations proposed by Anderson et al. (1969). All determinations were performed in triplicate for each treatment.

2.6. Frankfurt Sausage Formulation and Evaluation

Based on the superior water absorption capacity and water solubility index observed during the physicochemical and functional characterization, pregelatinized starch PGS was selected as a fat replacer for the production of Frankfurt type sausages.

Four formulations were prepared with different levels of partial fat replacement: 0% control, 20%, 40%, and 60%, using pregelatinized starch PGS. In all formulations, the total moisture content of the meat emulsion was kept constant by adjusting the amount of added water according to the percentage of fat replaced, ensuring that the differences among treatments were exclusively attributable to the replacement level.

The meat emulsions were prepared according to the formulation presented in Table X, stuffed into artificial casings, and cooked by scalding until reaching an internal temperature of 72 °C.

Texture profile analysis (TPA) was performed using a TX-700 texture analyzer equipped with a TX-CY10H40SS cylindrical probe. The evaluated textural parameters included hardness, cohesiveness, springiness, gumminess, chewiness, and resilience, which are widely used to characterize the mechanical and structural properties of emulsified meat products. Data acquisition and processing were carried out using Setup Rheotex V2.55 W10–EN software. All samples were analyzed under identical instrumental conditions. Each treatment was prepared and analyzed in four independent batches, which were considered the experimental replicates.

In addition, cooking yield was determined based on weight loss during thermal processing. Sausages were weighed after the scalding process and again after an additional heat treatment in an air fryer at 180 °C for 8 min, until reaching an internal temperature of approximately 95 °C. Cooking yield was expressed as the percentage of the final weight relative to the initial weight after scalding.

2.7. Statistical Analysis

The physicochemical and functional properties of the starch samples were analyzed using one-way analysis of variance one-way ANOVA, considering the type of starch treatment native, HMT, ANN, and PGS as the experimental factor. When significant differences were detected ($p < 0.05$), treatment means were compared using Tukey's multiple comparison test. Before the analysis, the assumption of normality was verified using the Shapiro–Wilk test.

Similarly, the data obtained from the Frankfurt sausages were analyzed using one-way ANOVA, considering the level of partial fat replacement with pregelatinized starch 0%, 20%, 40%, and 60% as the experimental factor. When significant differences were observed ($p < 0.05$), treatment means were compared using Tukey's multiple comparison test.

All statistical analyses were performed using IBM SPSS Statistics version 25 IBM Corp., Armonk, NY, USA, with a significance level of $\alpha = 0.05$.

3. RESULTS

A native starch with white sediment, fine texture, and free of visible impurities was obtained. From 7 kg of green banana pulp, ~1 kg of starch was recovered. After sedimentation and draining, the starch had a moisture content of 47%, which was reduced to a final value of 10.62% after 48 hours of drying in an oven at 50 °C. The different modification methods produced observable changes in the behavior of the starch.

In HMT, the native starch, with a sample weight of 795 g, had an initial moisture content of 10.62%, which was adjusted to 25% by adding a calculated 142.25 ml of water. After applying heat and humidity treatment at 120 °C for 16 hours and cooling the material, the starch was pulverized again and subjected to moisture analysis. The final moisture content obtained was 9.626%, lower than the initial value, which shows a reduction in free water and greater starch stability after heat treatment.

In the ANN treatment annealed at 55 °C for 48 hours with ~40% humidity, the starch retained a moisture level similar to or slightly higher than the initial ~11.58% final level. This suggests that the slow redistribution of water during annealing stabilizes the structure without removing too much water, favoring an internal reorganization of the starch chains with lower solubility. These results are consistent with those described for annealed starches, where prolonged exposure to intermediate temperatures under high humidity conditions favors a more orderly internal reorganization of the starch chains, reducing the release of soluble components during heating(YE; BAIK, 2023).

Meanwhile, the PGS starch had an initial moisture content of 10.62%, which was adjusted to 65% by adding 657.22 mL of water. The sample was cooked in a water bath at 75°C for 15 minutes with constant stirring, promoting starch gelatinization. The material was then dried in an oven at 50 °C until it reached a final moisture content of 9.13%. According to the study by (Suri; Singh, 2023), pregelatinized starch can be incorporated directly into ready-to-eat foods without requiring additional cooking, as well as contributing to reduced preparation time in formulations that do require heat treatment. This property is attributed to the prior breakdown of the granular structure, which facilitates rapid hydration and viscosity formation in cold water.

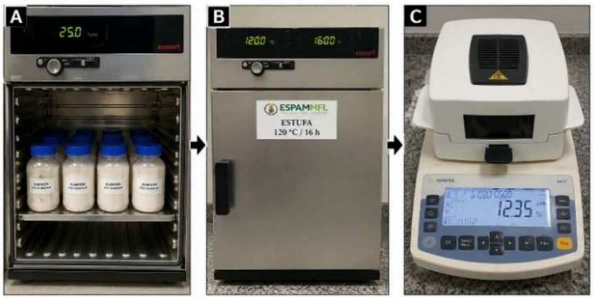

Figure 1. Heat-moisture treatment (HMT) process: (A) hermetic sealing of starch adjusted to 25% moisture content; (B) heat treatment in a drying oven at 120 °C for 16 h; and (C) determination of the final moisture content using a moisture analyzer.
Figura 1. Processo de tratamento térmico com umidade controlada (HMT): (A) selagem hermética do amido ajustado para um teor de umidade de 25%; (B) tratamento térmico em estufa a 120 °C por 16 h; e (C) determinação do teor de umidade final com um analisador de umidade.

Figure 2. Annealing (ANN) process: (A) hermetic sealing of starch adjusted to 40% moisture content; (B) heat treatment in a drying oven at 55 °C for 48 h; and (C) determination of the final moisture content using a moisture analyzer.
Figura 2. Processo de recozimento (ANN): (A) selagem hermética do amido ajustado para um teor de umidade de 40%; (B) tratamento térmico em estufa a 55 °C por 48 h; e (C) determinação do teor de umidade final por meio de um analisador de umidade.

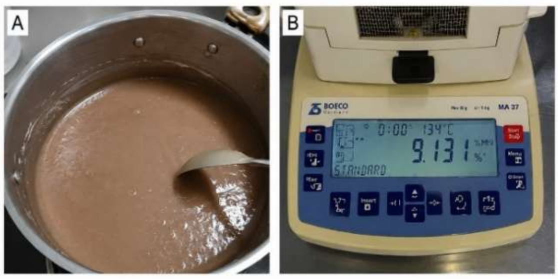

Figure 3. Pregelatinization (PGS) process: (A) starch suspension adjusted to 65% moisture content during partial gelatinization in a water bath at 75 °C for 15 min under continuous stirring; and (B) determination of the final moisture content using a moisture analyzer.
Figura 3. Processo de pré-gelatinização (PGS): (A) suspensão de amido com teor de umidade ajustado a 65% durante a gelatinização parcial em banho-maria a 75 °C por 15 min, sob agitação contínua; e (B) determinação do teor de umidade final utilizando um analisador de umidade.

Table 1 summarizes the conditions of each method and the moisture content of the starch before and after treatment. It should be noted that HMT and PGS involved final drying steps that reduced moisture content to below 10%, while ANN maintained moisture content at around 11–12%.

At the microscopic and functional levels, significant changes in absorption and solubility properties were observed. Table 2 summarizes the proximal, chemical, and functional composition of the starches modified by the HMT, ANN, and PGS treatments.

The proximal composition showed that fiber, ash, and protein remained at low levels in all treatments <0.22%, with no significant differences ($p > 0.05$), confirming the high purity of the extracted starch (Table 3). The fat content was equally low <0.4%, although PGS had a slightly higher value 0.31% than ANN 0.22% ($p < 0.01$). Moisture content showed highly significant differences ($p < 0.0001$), being highest in HMT at 10.40%, followed by PGS at 8.26% and lowest in ANN at 6.74%, suggesting structural variations associated with water reabsorption capacity after drying.

The amylose content showed marked differences ($p < 0.0001$), with higher values in HMT 30.64%, intermediate values in PGS 28.8%, and lower values in ANN 25.4%, reflecting the differential effect of each treatment on the molecular organization of the starch. In terms of functional properties, the IAA was significantly higher in PGS 2.85 g/g ($p < 0.001$), while ANN had the lowest solubility 8.08% ($p < 0.05$). No significant differences were observed in swelling power ($p = 0.147$).

Table 2. Physicochemical and functional properties of green banana starch modified by annealing (ANN), heat-moisture treatment (HMT), and pregelatinization (PGS).
Tabela 2. Propriedades físico-químicas e funcionais do amido de banana verde modificado por *annealing* (ANN), tratamento térmico-úmido (HMT) e pré-gelatinização (PGS).

Treatment	Replicate	Moisture (%)	Fat (%)	Fiber (%)	Ash (%)	Amylose (%)	Protein (%)	Water absorption index (WAI)	Water solubility index (WSI)	Swelling power (SP)
ANN	R1	6.79	0.21	0.16	0.22	25.40	1.69	2.170	8.878	2.172
	R2	6.74	0.24	0.19	0.17	25.43	1.72	1.994	7.290	1.998
	R3	6.68	0.22	0.13	0.26	25.34	1.63	2.082	8.084	2.085
HMT	R1	10.26	0.29	0.14	0.10	30.55	1.72	2.180	9.476	2.185
	R2	10.38	0.24	0.17	0.16	30.58	1.76	2.166	10.187	2.181
	R3	10.45	0.30	0.15	0.21	30.80	1.81	2.173	9.831	2.183
PGS	R1	8.22	0.32	0.18	0.15	28.77	1.76	2.929	9.223	2.108
	R2	8.26	0.31	0.17	0.19	28.72	1.71	2.777	9.795	2.797
	R3	8.29	0.30	0.18	0.20	28.80	1.74	2.853	9.509	2.473

ANN, Annealing; HMT, Heat-moisture treatment; PGS, Pregelatinization; WAI, Water absorption index; WSI, Water solubility index; SP, Swelling power. M1, M2 and M3 correspond to the three experimental replicates of each treatment.
ANN, Recozimento; HMT, Tratamento térmico-úmido; PGS, Pré-gelatinização; WAI, Índice de absorção de água; WSI, Índice de solubilidade em água; SP, Poder de inchamento. M1, M2 e M3 correspondem às três repetições experimentais de cada tratamento.

Table 3. Analysis of variance (ANOVA) and Shapiro–Wilk normality test for the physicochemical and functional properties of modified green banana starch.
Tabela 3. Análise de variância (ANOVA) e teste de normalidade de Shapiro–Wilk para as propriedades físico-químicas e funcionais do amido de banana verde modificado.

Variable	F-	ANOVA (p-	Shapiro–Wilk (p-
Moisture	2211.0	2.49×10^{-9}	0.964
Fat	12.59	0.0071	0.683
Fiber	1.11	0.388	0.924
Ash	1.43	0.311	0.652
Amylose	2851.0	1.16×10^{-9}	0.396
Water absorption index	117.70	1.53×10^{-5}	0.214
Water solubility index	9.28	0.0146	0.933
Swelling power (SP)	2.68	0.147	0.088

F-value corresponds to the ANOVA test statistic. ANOVA (p-value) indicates the probability associated with the treatment effect. Shapiro–Wilk (p-value) corresponds to the normality test of the residuals. Statistical significance was established at $p < 0.05$.
O valor F corresponde à estatística de teste da ANOVA. O valor p da ANOVA indica a probabilidade de se observar o efeito do tratamento observado, assumindo que o tratamento não tem efeito. O valor p do teste de Shapiro-Wilk corresponde ao teste de normalidade dos resíduos. A significância estatística foi estabelecida em p < 0,05.

Overall, HMT favored a higher amylose content, ANN generated a more stable and less soluble structure, and PGS showed the highest water absorption capacity, a key property for its application as a fat substitute in the formulation of reduced-fat sausages.

Figure 4. Samples of sausages with partial PGS starch substitution of pork fat.
Figura 4. Amostras de embutidos com substituição parcial da gordura suína por amido de PGS.

After cooking, differences in weight loss due to exudate were noted: sausages with starch showed less shrinkage than the control. The control treatment without starch, with full fat, lost around 15.6% of its weight during final cooking, while formulations with 20–60% fat replacement had weight losses between ~11% and 12%. In other words, sausages with rejected banana starch retained more juices during cooking, improving the final yield of the product. Higher fat replacement 60% tended to increase the loss slightly, 11.9%

vs. ~11.1% at 40%, possibly because at very high replacement levels the emulsion becomes more fragile due to a lack of sufficient fat phase, but even so, the yield was higher than the control.

TPA texture profile analysis is one of the most widely used methodologies for evaluating the textural properties of starch gels and food products based on this biopolymer. During the test, the sample is subjected to a double cyclic compression test that simulates the chewing process. Five fundamental parameters are determined from the force-time curve obtained: hardness, cohesiveness, elasticity, gumminess, and chewiness, which allow the mechanical and structural behavior of the food system to be characterized (HEENA et al., 2024). Table 5 shows the results obtained from the four tests performed using TPA texture analysis with the texturometer.

Table 4. Mean values and standard deviations of the physicochemical and functional properties of green banana starch modified by heat-moisture treatment (HMT), pregelatinization (PGS), and annealing (ANN).
Tabela 4. Valores médios e desvios-padrão das propriedades físico-químicas e funcionais do amido de banana verde modificado por tratamento térmico-úmido (HMT), pré-gelatinização (PGS) e recozimento (ANN).

Variable	HMT	PGS	ANN
Moisture (%)	10.40 ± 0.10	8.26 ± 0.04	6.74 ± 0.06
Fat (%)	0.277 ± 0.032	0.310 ± 0.010	0.223 ± 0.02
Crude fiber (%)	0.15 ± 0.02	0.176 ± 0.005	0.16 ± 0.03
Ash (%)	0.16 ± 0.06	0.18 ± 0.03	0.216 ± 0.05
Amylose (%)	30.64 ± 0.14	28.8 ± 0.04	25.4 ± 0.05
Protein (%)	1.76 ± 0.05	1.74 ± 0.03	1.68 ± 0.05
Water absorption index (WAI) (g/g)	2.17 ± 0.01	2.85 ± 0.08	2.08 ± 0.09
Water solubility index (WSI) (%)	9.83 ± 0.36	9.51 ± 0.29	8.08 ± 0.79
Swelling power (SP)	2.18 ± 0.002	2.46 ± 0.35	2.08 ± 0.09

Values are expressed as mean ± standard deviation (n = 3). Means within the same row followed by different lowercase letters indicate significant differences according to Tukey's multiple comparison test ($p < 0.05$). HMT: Heat-moisture treatment; PGS: Pregelatinization; ANN: Annealing; WAI: Water absorption index; WSI: Water solubility index; SP: Swelling power.
Os valores são expressos como média ± desvio-padrão (n = 3). Médias na mesma linha seguidas por letras minúsculas diferentes indicam diferenças significativas de acordo com o teste de comparações múltiplas de Tukey ($p < 0{,}05$). HMT: Tratamento térmico-úmido; PGS: Pré-gelatinização; ANN: Recozimento (*annealing*); WAI: Índice de absorção de água; WSI: Índice de solubilidade em água; SP: Poder de inchamento.

Table 5. Tabla 5. Parámetros del análisis del perfil de textura (TPA) de salchichas tipo Frankfurt elaboradas con diferentes niveles de sustitución de grasa mediante almidón de banano verde pregelatinizado (PGS).
Tabla 5. Table 5. Texture profile analysis (TPA) parameters of Frankfurt sausages formulated with different levels of fat substitution using pregelatinized green banana starch (PGS).

	Resultado (Media ± DE)					
Parameter	Replicate 1 0%	Replicate 2 20%	Replicate 3 40%	Replicate 4 60%	Range.	Reference range
Hardness	26.27 ± 13.17	19.95 ± 0.35	26.19 ± 1.83	31.36 ± 4.17	10 – 30	(Granados et al., 2013)
Cohesiveness	0.184 ± 0.047	0.418 ± 0.048	0.458 ± 0.058	0.372 ± 0.104	0.25 – 0.77	(Pietrasik, 1999)
Springiness	0.594 ± 0.246	0.959 ± 0.041	0.964 ± 0.038	0.932 ± 0.066	0.75 – 0.98	(Lyons et al., 1999)
Gumminess	4.48 ± 1.44	8.34 ± 0.92	12.01 ± 1.84	11.86 ± 4.64	10 – 27	(Pietrasik & Duda, 2000)
Chewiness	2.45 ± 0.67	8.00 ± 0.82	11.60 ± 1.91	11.13 ± 4.70	10 – 22	
Resilience	0.023 ± 0.012	0.029 ± 0.002	0.024 ± 0.001	0.024 ± 0.003	0.03 – 0.10	

Values are expressed as mean ± standard deviation (n = 4). Treatments correspond to fat substitution levels using pregelatinized green banana starch (PGS). Reference ranges were obtained from published studies on Frankfurt sausages and related meat emulsions.
Os valores são expressos como média ± desvio-padrão (n = 4). Os tratamentos correspondem a diferentes níveis de substituição de gordura, utilizando amido de banana verde pré-gelatinizado (PGS). As faixas de referência foram obtidas a partir de estudos publicados sobre salsichas do tipo Frankfurt e emulsões cárneas correlatas.

In regard to hardness, the treatment with 60% substitution presented the highest value of 31.36 ± 4.17, exceeding the range reported in the literature of 10–30, indicating a firmer structure and potentially less favorable from a sensory point of view. In contrast, the 20% treatment recorded the lowest value, 19.95 ± 0.35, falling within the range considered optimal.

Cohesiveness showed a progressive increase up to 40%, evidencing greater structural integration; however, the 0% treatment fell below the reference range of 0.25–0.77, suggesting lower matrix stability. In terms of elasticity, the 20% and 40% treatments remained within the optimal range of 0.75–0.98, while the 0% treatment had a lower value of 0.594 ± 0.246, reflecting limited recovery after deformation.

Guminess and chewiness increased up to 40%, remaining within the values reported in the literature, while the 0% treatment showed a less consistent texture. Finally, resilience remained below the reference range in all treatments, indicating a reduced capacity for immediate recovery after compression.

A sensory acceptance test was conducted using a panel of 100 participants with previous training in food sensory evaluation, comprising senior undergraduate students and three faculty members from the Agroindustry Program at the Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López (ESPAM MFL). Participation was voluntary, and participants were between 22 and 45 years of age.

Overall acceptability was evaluated using a five-point Likert hedonic scale, where 1 = unsatisfactory and 5 = satisfactory.

Samples corresponding to the control treatment (0%) and the 20%, 40%, and 60% levels of partial fat replacement using pregelatinized green banana starch PGS were coded and presented in a randomized order to minimize presentation-order bias. Drinking water was provided between samples to cleanse the palate and minimize the influence of residual flavors.

The sensory evaluation was conducted at the facilities of ESPAM MFL with senior undergraduate students from the Agroindustry Program. The mean and standard deviation were calculated for each treatment based on the sensory scores obtained. Subsequently, the mean sensory scores were used to evaluate the correlation between sensory acceptance and the instrumental parameters obtained from TPA.

The treatment with 40% substitution presented the highest mean score, 4.35 ± 0.87, indicating greater overall acceptance. The 20% treatment obtained an intermediate score of 3.72 ± 1.22, while the 0% treatment showed moderate acceptance of 3.23 ± 0.83. In contrast, the 60% substitution treatment recorded the lowest score, 2.50 ± 0.70, indicating lower preference by the sensory panel.

Table 6. Sensory evaluation scores of Frankfurt sausages formulated with different levels of fat substitution using pregelatinized green banana starch (PGS).
Tabela 6. Notas da avaliação sensorial de salsichas do tipo Frankfurt formuladas com diferentes níveis de substituição de gordura, utilizando amido de banana verde pré-gelatinizado (PGS).

Replacement	Result (Mean ± SD)
0%	3.23±0.83
20%	3.72±1.22
40%	4.35 ± 0.87
60%	2.50 ± 0.70

Values are expressed as mean ± standard deviation (n = 3), where n corresponds to three independent sensory evaluations.
Os valores são expressos como média ± desvio-padrão (n = 3), em que n representa três avaliações sensoriais independentes.

Table 7 presents a Pearson correlation analysis between the parameters obtained from the Texture Profile Analysis and the mean scores of the sensory evaluation, with the aim of determining the existence of linear associations between instrumental properties and consumer perception.

Table 7. Pearson correlation coefficients between texture profile analysis (TPA) parameters and sensory evaluation of Frankfurt sausages.
Tabela 7. Coeficientes de correlação de Pearson entre os parâmetros da análise do perfil de textura (TPA) e a avaliação sensorial de salsichas do tipo Frankfurt.

Parameter	Pearson's r	p-value	Interpretation
Hardness	-0.60	0.396	Moderate negative correlation
Cohesiveness	0.46	0.539	Moderate positive correlation
Springiness	0.26	0.737	Weak positive correlation
Gumminess	0.09	0.903	Very weak correlation
Chewiness	0.15	0.849	Very weak correlation
Resilience	0.25	0.753	Weak correlation

Pearson's r corresponds to the Pearson correlation coefficient. The p-value represents the statistical significance of the association. Statistical significance was established at $p < 0.05$.
O r de Pearson corresponde ao coeficiente de correlação de Pearson. O valor-p representa a significância estatística da associação. A significância estatística foi estabelecida em $p < 0,05$.

Hardness showed a moderate negative correlation ($r = -0.60$; $p = 0.396$), suggesting that increases in firmness tend to reduce sensory acceptance. Although this association was not statistically significant ($p > 0.05$), it shows a trend consistent with the sensory results obtained.

Cohesiveness showed a moderate positive correlation ($r = 0.46$; $p = 0.539$), indicating that more integrated structures may contribute to a better perception by consumers.

The parameters springiness, gumminess, chewiness, and resilience showed weak correlations ($r < 0.30$), suggesting that, under the experimental conditions evaluated, these attributes do not individually explain the variability in consumer acceptance.

The results indicate that the level of substitution significantly influences the internal structure of the product. While intermediate levels of 20% and 40% favor the formation of a more cohesive and elastic structural network, higher levels of 60% induce an increase in firmness accompanied by greater variability, which may compromise structural uniformity.

The combined behavior of gumminess and chewiness confirms that the formulation with 40% substitution provides the best balance between firmness and elasticity, avoiding both excessive rigidity and structural weakness.

Finally, a thermal cooking test was performed. This process was carried out in an air fryer for 8 minutes at 180 °C, with the sausage reaching an internal temperature of 95 °C. This procedure was applied to all treatments. The initial weight was recorded after the scalding process.

Table 8. Initial and final weights of Frankfurt sausages formulated with different levels of fat substitution using pregelatinized green banana starch (PGS).
Tabela 8. Pesos iniciais e finais de salsichas do tipo Frankfurt formuladas com diferentes níveis de substituição de gordura, utilizando amido de banana verde pré-gelatinizado (PGS).

Treatment	Initial weight (g)	Final weight (g)
Control	59.6	50.3
PGS 20%	96.2	85.5
PGS 40%	74.4	66.1
PGS 60%	59	52

Values correspond to the initial and final weights recorded for each treatment.
Os valores correspondem aos pesos inicial e final registrados para cada tratamento.

4. DISCUSSION

The article "Effect of modification of banana kepok starch substitution on ash, water, and protein content in cookie products" reports proximate parameters (protein, ash, and moisture) in cookies prepared with different proportions of modified banana starch and wheat flour. The substitution of 25–75% of wheat flour with kepok banana starch reduced the protein content from 6.26 ± 0.22% to 5.77 ± 0.20% and the ash content from 2.59 ± 0.05% to 2.13 ± 0.14% ($p < 0.05$). Cookie moisture ranged between 6.28 ± 0.43% and 8.83 ± 0.73% and did not show significant differences ($p = 0.125$). The authors attribute this behavior to the high amylose content of kepok banana starch, which limits its water retention capacity and favors cookies with lower moisture and a crisp texture.

In contrast, the present research provides a comprehensive compositional profile and techno-functional properties through physical modification. The initial moisture of native starch decreased after the treatments: the sample treated by annealing showed the lowest moisture (6.74 ± 0.06%), followed by the pregelatinization treatment 8.26 ± 0.04% and the heat–moisture treatment 10.40 ± 0.10%. Fat content was very low in all samples 0.223 ± 0.015% in ANN, 0.310 ± 0.010% in PGS, and 0.277 ± 0.032% in HMT. In this study, the treatments slightly modified the amylose content: HMT reached 30.6 ± 0.14% and PGS 28.8 ± 0.04%, while ANN reduced amylose to 25.4 ± 0.05%. These modifications were reflected in the functional properties: the water absorption index ranged from 2.08 ± 0.09 g in ANN to 2.85 ± 0.08 g in PGS. In contrast, the solubility index ranged between 8.08 ± 0.79% in ANN and 9.83 ± 0.36% in HMT (ADIYANTI; SUBROTO, 2020).

The study by Auriema et al. (2022) aligns with the present work by evaluating green banana derivatives as fat substitutes in emulsified meat products. In that research, the incorporation of green banana biomass in meat formulations demonstrated improvements in emulsion stability, water retention capacity, and nutritional profile, as well as its sensory impact. Similarly, the present study explores the potential of rejected banana starch; however, it further investigates the physical modification of starch HMT, ANN, and pregelatinization and its physicochemical and functional characterization as a strategy to optimize its technological performance in reduced-fat Frankfurt-type sausages. Together, both studies provide evidence of the viability of banana as a functional ingredient for the reformulation of healthier and more sustainable meat products.

The annealing treatment was carried out at temperatures close to gelatinization under high but controlled moisture conditions. In this study, this treatment did not significantly alter moisture or fat content but produced the lowest amylose concentration, 25.4%. At the functional level, the ANN generated the lowest water absorption index, 2.08 g and the lowest solubility, 8.08%, with no statistical differences in swelling power compared to HMT 2.18 g. This behavior is consistent with the literature, where annealing is described as a process that promotes the reorganization and improvement of the crystalline structure of starch. The increase in structural order reduces swelling power and solubility due to the more efficient packing of starch chains (JACOBS; DELCOUR, 1998; ADIYANTI; SUBROTO, 2020). Similarly, studies on red sorghum starch have shown that annealing and HMT reduce swelling power and solubility while increasing water absorption capacity (TÔ et al., 2020).

The study “Review of uses and benefits of plantain flour in foods as a basis for strengthening the productive chain of Putumayo” provides a comprehensive analysis of the nutritional, technological, and socioeconomic potential of plantain flour as an alternative ingredient in different food systems. The review highlights its dietary fiber content, resistant starch, and bioactive compounds, as well as its applications in bakery products, extruded foods, and traditional formulations, emphasizing its strategic role in strengthening regional production chains and agro-industrial diversification.

In contrast, the present study goes beyond a descriptive and productive approach by focusing on the physical modification of rejected banana starch through treatments such as HMT, ANN, and pregelatinization, with the aim of optimizing its structural and functional properties for specific applications in reduced-fat meat matrices. Thus, while the Putumayo review consolidates the conceptual foundation and added value of plantain flour as an agro-industrial input, our research advances ingredient engineering, providing experimental evidence of its technological performance and expanding its application potential in functional and sustainable foods (SILVA-JIMÉNEZ; ROJAS-NAVARRO, 2024).

The study “Nutritional Index Evaluation of Plant-Based Burger Patties Developed from Banana By-Products: Future Meat Analogues for Consumers” and the present research share a common conceptual axis focused on the valorization of underutilized raw materials for technological and nutritional purposes. While the former evaluates the compositional and functional impact of banana by-products in the development of plant-based meat analogues, the latter focuses on the physical modification of rejected banana starch to optimize its structural properties and performance in reduced-fat meat matrices.

Together, both studies fall within the framework of circular economy and agro-industrial innovation, integrating sustainability, rigorous physicochemical characterization, and technological performance evaluation as fundamental pillars for the development of healthier, functional, and environmentally responsible foods (ASHA et al., 2025)

Finally, the present study demonstrated that PGS starch exhibited the highest water absorption capacity, whereas HMT and ANN treatments showed lower but similar values. This trend is consistent with studies reporting that pregelatinization produces partially collapsed granules and a highly porous structure capable of retaining large amounts of water (FANG et al., 2022). In contrast, ANN and HMT promote microstructural ordering and increase chain interactions, reducing water absorption capacity. A study on rice modified by ANN and HMT showed that pregelatinized starch presented a higher water absorption index and greater cold-water retention than samples treated with ANN or HMT (VAN NGO; LUANGSAKUL, 2025).

Likewise, the literature indicates that starches subjected to ANN may slightly increase their water absorption capacity due to limited expansion of amorphous regions; however, this effect is considerably lower than that observed in pregelatinized starch (ADEBOWALE et al., 2005).

5. CONCLUSIONS

Rejected bananas were confirmed as a viable source of high-purity starch, whose functional properties can be tailored through simple physical modification methods. The heat–moisture treatment HMT, annealing ANN, and pregelatinization PGS generated starches with differentiated behaviors: HMT increased thermal stability and amylose content, ANN produced a more ordered and less soluble structure, while PGS stood out for its high-water absorption capacity and rapid cold gel formation, allowing the proposal of specific applications for each type of starch in the food industry.

Pregelatinized green banana starch showed high potential as a functional ingredient in reduced-fat emulsified meat products. Replacing 20–40% of fat in Frankfurt-type sausages improved cooking yield while maintaining textural properties within acceptable ranges.

Overall, the results demonstrate that properly modified rejected banana starch can be used as a functional and sustainable hydrocolloid, contributing to the valorization of agricultural residues and aligning with the principles of the circular economy and clean-label ingredient development.

Nevertheless, since this study was conducted at the laboratory scale and its application was evaluated only in Frankfurt-type sausages, future research should validate these findings at the pilot and industrial scales. In addition, further studies should investigate the storage stability, shelf life, and microbiological behavior of the modified starch, as well as provide a more comprehensive structural and functional characterization using advanced analytical techniques. Expanding its application to other food matrices would also contribute to confirming its technological potential and facilitating its transfer to the food industry.

6. REFERENCES

ADEBOWALE, K. O.; OLU-OWOLABI, B. I.; OLAYINKA, O. O.; LAWAL, O. S. Effect of heat, moisture treatment and annealing on physicochemical properties of red sorghum starch. In **International Journal of Microbiology Research and Reviews**, v. 9, n. 5, p. 928-933, 2005.

ADIYANTI, T.; SUBROTO, E. Modifications of banana starch and its characteristics: a review. **International Journal of Scientific & Technology Research**, v. 9, n. 3, p. 3524-2527, 2020.

ANDERSON, R. A.; CONWAY, H. F.; PEPLINSKI, A. J. Gelatinisation of corn grits by roll cooking, extrusion cooking and steaming. **Starch**, v. 22, n. 4, p. 130-135, 1969. https://doi.org/10.1002/star.19700220408

ASHA, S.; ZAHID, M. A.; PARVIN, R. Nutritional index evaluation of plant-based burger patties developed from banana by-products: Future meat analogues for consumers. **Applied Food Research**, v. 5, n. 1, e100930, 2025. https://doi.org/10.1016/J.AFRES.2025.100930

AURIEMA, B. E.; CORREA, F. J.; SILVA, R.; SOARES, P. T. S.; LIMA, A. L.; VIDAL, V. A. S.; RAICES, R. S. L.; POLLONIO, M. A. R.; LUCHESE, R. H.; ESMERINO, E. A.; MATHIAS, S. P. Fat replacement by green banana biomass: Impact on the technological, nutritional and dynamic sensory profiling of chicken mortadella. **Food Research International**, v. 152, e110890, 2022. https://doi.org/10.1016/J.FOODRES.2021.110890

FANG, G.; LIU, K.; GAO, Q. Effects of heat-moisture treatment on the digestibility and physicochemical properties of waxy and normal potato starches. **Foods**, v. 12, n. 1, e68, 2022. https://doi.org/10.3390/foods12010068

FONSECA, L. M.; HALAL, S. L. M. el; DIAS, A. R. G.; ZAVAREZE, E. da R. Physical modification of starch by heat-moisture treatment and annealing and their applications: A review. **Carbohydrate Polymers**, v. 274, n. 11, e118665, 2021. https://doi.org/10.1016/j.carbpol.2021.118665

FONTES, S. DE M.; CAVALCANTI, M. T.; CANDEIA, R. A.; ALMEIDA, E. L. Characterization and study of functional properties of banana starch green variety of Mysore (*Musa* AAB - Mysore). **Food Science and Technology**, v. 37, n. 2, p. 224-231, 2017. https://doi.org/10.1590/1678-457X.18916

FAO_Food and Agriculture Organization of the United Nations. (2022). Tracking progress on food and agriculture-related SDG indicators 2022. **Tracking Progress on Food and Agriculture-Related SDG Indicators**. Roma: FAO, 2022. 179p. Available online: https://doi.org/10.4060/CC1403EN

GRANADOS, C.; GUZMÁN, L. E.; ACEVEDO, D. (2013). Analysis proximal, sensory and texture of elaborated sausages by-products from the tuna processing industry (*Scombridae thunnus*). **Información Tecnológica**, v. 24, n. 6, p. 29-34, 2013. https://doi.org/10.4067/S0718-07642013000600005

GRASSO, S.; ESTÉVEZ, M.; LORENZO, J. M.; PATEIRO, M.; PONNAMPALAM, E. N. The utilisation of agricultural by-products in processed meat products: Effects on physicochemical, nutritional and sensory quality – Invited Review. **Meat Science**, v. 211, e109451, 2024. https://doi.org/10.1016/J.MEATSCI.2024.109451

JACOBS, H.; DELCOUR, J. A. Hydrothermal modifications of granular starch, with retention of the granular structure: a review. **Journal of Agricultural and Food Chemistry**, v. 46, n. 8, p. 2895-2905, 1998. https://doi.org/10.1021/jf980169k

JULIANO, B. O. A simplified assay for milled-rice amylose. **Cereal Science Today**, v. 16, p. 334-338, 1971.

LYONS, P. H.; KERRY, J. F.; MORRISSEY, P. A.; BUCKLEY, D. J. The influence of added whey protein/carrageenan gels and tapioca starch on the textural properties of low fat pork sausages. **Meat Science**, v. 51, n. 1, p. 43-52, 1999. https://doi.org/10.1016/S0309-1740(98)00095-3

MARTA, H.; CAHYANA, Y.; DJALI, M.; PRAMAFISI, G. The properties, modification, and application of banana starch. **Polymers**, v. 14, n. 15, e3092, 2022. https://doi.org/10.3390/POLYM14153092

MUNIR, H.; ALAM, H.; NADEEM, M. T.; ALMALKI, R. S.; ARSHAD, M. S.; SULERIA, H. A. R. Green banana resistant starch: A promising potential as functional ingredient against certain maladies. **Food Science & Nutrition**, v. 12, n. 6, e3787, 2024. https://doi.org/10.1002/FSN3.4063

NORIEGA, D.; VILLAVICENCIO, C.; DOMÍNGUEZ, L.; AVILÉS, R.; ECHAVARRÍA, A. P. Determinación del valor nutricional y la inocuidad de un puré infantil usando aditivos naturales. **Ingeniería Industrial. Actualidad y Nuevas Tendencias**, v. 6, n. 23, p. 57-74, 2019.

ONU_United Nations Environment Programme. **Think Eat Save: Tracking Progress to Halve Global Food Waste**. In: United Nations Environment Programme. 2024. 203p. Available online: https://wedocs.unep.org/handle/20.500.11822/45230

PIETRASIK, Z. Effect of content of protein, fat and modified starch on binding textural characteristics, and colour of comminuted scalded sausages. **Meat Science**, v. 51, n. 1, p. 17-25, 1999. https://doi.org/10.1016/S0309-1740(98)00068-0

PIETRASIK, Z.; DUDA, Z. Effect of fat content and soy protein/carrageenan mix on the quality characteristics of comminuted, scalded sausages. **Meat Science**, v. 56, n.

2, p. 181-188, 2020. https://doi.org/10.1016/S0309-1740(00)00038-3

SILVA-JIMÉNEZ, D.; ROJAS-NAVARRO, J. F. Revisión de usos y beneficios de la harina de plátano en alimentos, base para el fortalecimiento de la cadena productiva del Putumayo. **Revista ION**, v. 37, n. 1, p. 35-48, 2024. https://doi.org/10.18273/revion.v37n1-2024003

STRAGLIOTTO, L. K.; FERRARI, G. T.; CAMPAGNOL, P. C. B.; STRASBURG, V. J.; ZANDONADI, R. P.; OLIVEIRA, V. R. de. Green banana by-products on the chemical, technological and sensory quality of meat products. **International Journal of Gastronomy and Food Science**, v. 30, e100614, 2022. https://doi.org/10.1016/J.IJGFS.2022.100614

SURI, S.; SINGH, A. Modification of starch by novel and traditional ways: influence on the structure and functional properties. **Sustainable Food Technology**, v. 1, n. 3, p. 348-362, 2023. https://doi.org/10.1039/d2fb00043a

TÔ, H. T.; KARRILA, S. J.; NGA, L. H.; KARRILA, T. T. Effect of blending and pregelatinizing order on properties of pregelatinized starch from rice and cassava. **Food Research**, v. 4, n. 1, p. 102-112, 2020. https://doi.org/10.26656/fr.2017.4(1).245

VAN NGO, T.; LUANGSAKUL, N. Green modification techniques for modulating the properties and starch digestibility of rich-polyphenol low-amylose Riceberry rice (*Oryza sativa* L.) flour. **Food Chemistry: X**, v. 25, e102208, 2025. https://doi.org/10.1016/j.fochx.2025.102208

YE, S. J.; BAIK, M. Y. Characteristics of physically modified starches. **Food Science and Biotechnology**, v. 32, n. 7, e875, 2023. https://doi.org/10.1007/s10068-023-01284-3

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