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Physicochemical Comparison of Banggai Yam Starch Hydrolysates Produced by Acid and Enzymatic Hydrolysis

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Abstract

Banggai yam (*Dioscorea alata* L.) is an underutilized indigenous tuber with potential as an alternative starch source for liquid-sugar production. This study compared the physicochemical characteristics of Banggai yam starch hydrolysates produced by enzymatic and acid hydrolysis under three processing conditions (P1–P3). Reducing sugar content, total soluble solids (TSS), moisture content, and final pH were evaluated. Acid hydrolysis produced higher average reducing sugar content (10.72%) and TSS (12.50 °Brix) than enzymatic hydrolysis (5.18% and 6.33 °Brix, respectively). Among all treatments, acid hydrolysis under P3 conditions yielded the highest reducing sugar content (12.39%) and TSS (14.50 °Brix), together with the lowest moisture content (80.14%) and a final pH of 4.60. These results demonstrate that acid hydrolysis achieved higher concentrations of reducing sugars and soluble solids than the tested enzymatic process. However, the high moisture content of all hydrolysates indicates that further concentration is necessary before they can meet the total-solids criterion for commercial starch hydrolysate. The findings highlight the potential of Banggai yam starch as a feedstock for liquid-sugar production while emphasizing the need for further process optimization.

Keywords

acid hydrolysis; Banggai yam; enzymatic hydrolysis; reducing sugars; starch hydrolysate

Introduction

Starch-derived starch hydrolysates are multifunctional carbohydrate ingredients used in food, fermentation, pharmaceutical, and other bioprocessing applications because their sweetness, viscosity, water-binding capacity, fermentability, and crystallization behavior can be adjusted through the extent of starch depolymerization (1,2). Commercial production has traditionally relied on a limited group of well-established starch crops, particularly maize (3,4), wheat, rice, cassava, and potato (5,6,7). This concentration of raw-material supply has stimulated interest in non-conventional starch sources that could broaden industrial feedstock options, create value from locally underutilized crops, and support more geographically diversified carbohydrate-processing chains (8). However, the suitability of an alternative starch cannot be inferred from starch content alone, because botanical origin, molecular organization, granule morphology, amylose-to-amylopectin ratio, gelatinization behavior, and process conditions collectively determine hydrolysis performance and final syrup quality.

Although acid and enzymatic hydrolysis of *Dioscorea alata* L starch have been investigated previously, available studies do not establish whether reported hydrolysis responses are directly transferable to Banggai yam, an indigenous *D. alata* resource from the Banggai Islands of Central Sulawesi, Indonesia. This distinction is relevant because starch origin and structural characteristics, including amylose content and gelatinization behavior, can influence enzyme accessibility and hydrolysis efficiency. Therefore, the present study does not aim to establish the acid-versus-enzymatic comparison as a new concept. Instead, it provides a comparative physicochemical assessment of Banggai yam starch hydrolysates produced under defined acid and enzymatic processing conditions, using reducing sugars, total soluble solids, moisture/dry solids, and final pH as complementary indicators of hydrolysis performance. The study further identifies the relative response of the tested enzymatic conditions and the treat-

ment condition producing the highest soluble-sugar response, thereby providing a basis for subsequent optimization of enzymatic conversion of Banggai yam starch.

The crop is particularly relevant for starch-based product development because isolated starch from three Banggai yam varieties contained approximately 88.00-88.89% starch. Notably, the reported amylose content was high (60.29-62.88%), while the pasting temperature ranged from 80.10 to 80.35 °C (9); the starch granules were predominantly ellipsoidal, polyhedral, and triangular (10). Earlier characterization of Indonesian D. alata cultivars likewise demonstrated substantial variation in granule size (11), and functional properties among cultivars (12,13). These characteristics indicate that Banggai yam starch is not merely an interchangeable substitute for conventional cereal or root starches (14,15,16). Its high amylose content and relatively high pasting temperature are expected to influence water penetration, gelatinization requirements, paste rheology, and accessibility of glycosidic linkages to chemical or enzymatic catalysts (17,18,19).

Conversion of starch into liquid-sugar hydrolysates requires cleavage of the alpha-1,4 and, depending on the desired product profile, alpha-1,6 glycosidic linkages that organize amylose and amylopectin (20). Two major technological routes are acid hydrolysis (21) and enzymatic hydrolysis (22,23). Acid hydrolysis promotes relatively non-selective depolymerization under acidic and thermal conditions and can provide rapid solubilization, but the reaction must be carefully controlled to limit excessive sugar degradation, color development, and the need for downstream neutralization (24,25). Enzymatic processing is generally conducted through liquefaction with alpha-amylase followed by saccharification with glucoamylase or related amylolytic enzymes, thereby allowing more selective control of molecular-size distribution under comparatively mild conditions (26,27,28). Nevertheless, enzyme performance is highly sensitive to gelatinization efficiency, pH, temperature, enzyme activity, enzyme-to-substrate ratio, reaction time, solids loading, and mass-transfer limitations (8,29). Comparative work on Dioscorea spp. has confirmed that both acid and enzymatic routes can release fermentable sugars, although their relative effectiveness varies with catalyst conditions and pretreatment strategy (30).

The intrinsic structure of yam starch makes this comparison particularly important. Enzymatic hydrolysis of D. alata starch has been demonstrated in studies using conventional and intensified processing schemes (29,31). Sugar syrups prepared from D. alata starch or flour with exogenous amylases exhibited measurable dextrose equivalent, moisture content, pH, viscosity, and individual sugar profiles, confirming that yam starch can serve as a substrate for syrup manufacture (32). More recently, consecutive enzymatic hydrolysis of starch recovered from purple-yam processing residues achieved high starch conversion when liquefaction and saccharification were performed under enzyme-specific conditions, while the authors also showed that substrate concentration strongly affected process economics (29). These findings demonstrate the technical feasibility of D. alata valorization, but they also emphasize that conversion data obtained for one cultivar, starch preparation method, or processing sequence cannot be transferred directly to Banggai yam without experimental verification (33,34).

Accordingly, this study compared enzymatic and acid hydrolysis for producing liquid-sugar hydrolysates from Banggai yam starch under three processing conditions for each route (P1-P3). The resulting hydrolysates were characterized in terms of reducing-sugar content, pH, total soluble solids, and moisture content. This study aims to analyze the reducing sugar content, total soluble solids , moisture content, and pH hydrolysate of Banggai yam and compare the effectiveness of enzymatic hydrolysis and acid hydrolysis in converting starch into simple sugar**.**

Materials and methods

The ingredients used in the manufacture of liquid glucose are Banggai yam Starch, Water, Enzymes α Amylase, and glucoamylase Enzymes. The materials used for the analysis of chemical parameters are distilled water, (NH4)2HPO4 10%, Pb-acetate 5%, concentrated H2SO4, HCl 0.1 N, NaOH 30%, Luff Schrool, KI 20%, Na2S2O3, and amylum. A comparative laboratory experiment was conducted to evaluate the physicochemical characteristics of liquid sugar produced from Banggai yam (*Dioscorea alata* L.) starch by enzymatic and acid hydrolysis. The experiment comprised two hydrolysis routes, each with three treatment conditions designated P1, P2, and P3. Three starch-loading conditions were evaluated in the enzymatic hydrolysis process. P1 consisted of 1000 g Banggai yam starch mixed with 1000 mL water, P2 consisted of 500 g starch mixed with 1,000 mL water, and P3 consisted of 300 g starch mixed with 1,000 mL water. Each treatment received 1 g α-amylase during the liquefaction stage and 1 g glucoamylase during the subsequent saccharification stage. The same hydrolysis sequence and enzyme treatment conditions were applied to P1, P2, and P3.

Making Banggai Yam Starch

Banggai yam starch is made using the method (15,35) with slight modifications. Banggai yam are peeled, washed, and sliced ±10 mm thick, then mashed using a blender. The Banggai yam porridge is soaked in water for 3 days with water replacement every 24 hours, followed by the precipitation and separation of the starch. The sediment is dried in the sun for 3 days, ground, then sifted

using an 80 mesh sieve until Banggai yam starch is obtained, Fig:1.



Figure 1: Banggai Yam Starch

Manufacture of Liquid Sugar by Enzymatic Hydrolysis

Enzymatic hydrolysis was conducted through gelatinization, liquefaction, and saccharification. For the enzymatic treatments, Banggai yam starch was mixed with water according to the experimental treatment. The starch suspension was first gelatinized by heating to facilitate starch granule disruption and increase the accessibility of starch polymers to the hydrolytic enzymes. After gelatinization, α-amylase was added to initiate the liquefaction step. In the experimental formulation, 1 g of α-amylase was used for each treatment.

Following liquefaction, glucoamylase was added to convert the partially hydrolyzed starch and dextrins into smaller sugars, particularly glucose, during the saccharification stage. Saccharification was conducted at 60 °C for 24 h. The enzymatic treatments consisted of different starch loadings with a constant water volume and enzyme quantities. After completion of saccharification, the hydrolysate was heated and filtered to separate residual insoluble material. The resulting liquid hydrolysate was subsequently reheated before physicochemical analysis. The reducing sugar content, total soluble solids (TSS), moisture content, and final pH were then determined according to the analytical procedures described below.

Manufacture of Liquid Sugar by Acid Hydrolysis

Acid hydrolysis was performed using hydrochloric acid (HCl) as the hydrolyzing agent. Briefly, Banggai yam starch (100 g for A-P1, 50 g for A-P2, and 30 g for A-P3) was suspended in 500 mL of distilled water and stirred until a homogeneous suspension was obtained. The suspension was heated with continuous stirring at approximately 70–80 °C until gelatinization occurred. After gelatinization, 0.05 N HCl was added according to the experimental treatment, and the mixture was maintained at 99 °C for 8 h with periodic stirring to promote hydrolytic cleavage of starch glycosidic linkages. The acidity of the hydrolysis medium was determined by the HCl concentration used (0.05 N); the pH of the reaction mixture immediately after HCl addition was not measured in the original experiment. Therefore, no initial reaction pH value was estimated or retrospectively assigned.

After hydrolysis, the mixture was cooled to room temperature and gradually neutralized with 0.1 N NaOH to a final pH of 4.5–5.5. The neutralized hydrolysate was filtered through Whatman No. 1 filter paper to remove residual insoluble material. The filtrate was subsequently concentrated in a water bath at approximately 70–80 °C to obtain the liquid-sugar hydrolysate, Fig:2. For physicochemical analysis, the final pH was measured at approximately 25 °C using a digital pH meter calibrated with standard buffer solutions at pH 4.00 and 7.00.



Figure 2: Banggai Yam Starch Liquid Sugar

Physicochemical Analysis

Reducing Sugar Levels Analysis

The reducing sugar content of the hydrolysates was determined using the **Luff–Schoorl method** according to SNI 3547.2-2008. The analysis was performed to determine the amount of reducing sugars formed during the hydrolysis of Banggai yam starch. The results were expressed as percentage (%) of reducing sugar (36).

pH Analysis

After completion of the acid hydrolysis treatment, the hydrolysate was allowed to cool and was gradually neutralized with 0.1 N NaOH until a final pH of 4.5–5.5 was obtained. The final pH was then measured at approximately 25 °C using a calibrated digital pH meter, with calibration performed using standard buffer solutions at pH 4 and 7. Thus, the pH values reported for the acid-hydrolyzed samples represent the final pH of the hydrolysate after neutralization, rather than the pH of the reaction medium during acid hydrolysis. The neutralized hydrolysate was subsequently filtered using Whatman No. 1 filter paper and concentrated at 70–80 °C before further analysis (37).

Total soluble solids Testing

The total measurement of dissolved solids is carried out using a hand refractometer. The appliance prism is first washed with aqueducts, then dried using a fine cloth to ensure that there are no residues that can affect the measurement results. The sample is dripped on a prism, then the total value of the dissolved solids is determined based on the °Brix scale reading. Total soluble solids (TSS) of the Banggai yam starch hydrolysates were measured using a hand refractometer. Before measurement, the refractometer prism was cleaned with distilled water and dried using a clean, soft cloth to remove residual materials that could interfere with the reading. A sufficient amount of hydrolysate sample was then placed on the prism, and the TSS value was read directly from the refractometer scale. The results were expressed as degrees Brix (°Brix) (38).

Moisture Content Analysis

The moisture content of liquid sugar was analyzed using the oven method based on AOAC. The porcelain cups are dried in the oven at 105 ± 2°C for 1 hour, then cooled in a desiccant and weighed until a constant weight is obtained. A total of 2–5 g of liquid sugar samples areweighed into a cup, then dried in the oven at 105 ± 2°C for 3–4 hours or until they reach a constant weight. After drying, the cups are cooled in a desiccant for ±30 minutes, then weighed again. The moisture content is calculated based on the difference in weight before and after drying and is expressed as a percent (%) (39). Based on the oven method described in the manuscript, the moisture content is calculated from the loss of mass of the sample after drying to a constant weight at 105 ± 2 °C.

The formula:

$$\text{Moisture Content } (\%) = \frac{W_i - W_d}{W_i} \times 100$$

With: Wi = sample weight **before drying (g);** Wd = the weight of the sample **after drying to a constant weight (g).**

Statistical Analysis

The data obtained from the analyses of reducing sugar content, pH, total soluble solids (°Brix), and moisture content were analyzed using one-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$) to determine the effect of treatment on the physicochemical characteristics of Banggai yam starch liquid-sugar hydrolysates. Before performing ANOVA, the data were evaluated for normality and homogeneity of variances to ensure that the assumptions of the statistical model were satisfied. When ANOVA indicated a significant treatment effect ($p < 0.05$), mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at the 5% significance level. Differences among treatment means were considered statistically significant at $p < 0.05$.

Results

General Description of Hydrolysate Composition

The six Banggai yam starch hydrolysate showed wide variation depending on the treatment in the reducing sugar content, total soluble solids, moisture content, and final pH (Table 1 and Table 2). In all three coded conditions, acid hydrolysis yielded a higher descriptive mean of reducing sugars (10.72%) and total soluble solids (12.50 °Brix) than enzymatic hydrolysis (5.18% and 6.33 °Brix, respectively). Thus, the acid series produces approximately 2.07 times more reducing sugars and 1.97 times more dissolved solids based on the reported wet product base. Acid-hydrolyzed samples were also less diluted, with an average moisture content of 82.82% compared to 89.11% for the enzymatic series.

Table 1. Physicochemical characteristics of Banggai yam starch hydrolysates produced by enzymatic hydrolysis.

Analysis	P1	P2	P3
Reducing sugar (%)	8.00 ± 0.18^{a}	2.55 ± 0.12^{c}	5.00 ± 0.15^{b}
pH	3.50 ± 0.05^{b}	3.80 ± 0.04^{a}	3.70 ± 0.03^{a}
TSS (°Brix)	9.00 ± 0.20^{a}	3.00 ± 0.10^{c}	7.00 ± 0.15^{b}
Moisture content (%)	84.66 ± 0.28^{c}	94.50 ± 0.22^{a}	88.17 ± 0.25^{b}

Table 2. Physicochemical characteristics of Banggai yam starch hydrolysates produced by acid hydrolysis.

Analysis	P1	P2	P3
Reducing sugar (%)	11.22 ± 0.17^{b}	8.56 ± 0.14^{c}	12.39 ± 0.19^{a}
pH	4.50 ± 0.03^{b}	4.60 ± 0.03^{a}	4.60 ± 0.02^{a}
TSS (°Brix)	13.00 ± 0.20^{b}	10.00 ± 0.20^{c}	14.50 ± 0.20^{a}
Moisture content (%)	83.52 ± 0.22^{b}	84.79 ± 0.24^{a}	80.14 ± 0.24^{c}

Reducing sugar formation and hydrolysis efficiency

Reducing sugars increased in the order of E-P2 (2.55%) < E-P3 (5.00%) < E-P1 (8.00%) < A-P2 (8.56%) < A-P1 (11.22%) < A-P3 (12.39%). The higher value of the wet-based reducing sugars of the acid series indicates a wider chain break under the tested conditions. Acid-catalyzed hydrolysis is non-selective and can break the α-(1→4) bonds in amylose as well as branch-related α-(1→6) bonds in amylopectin. In contrast, enzymatic conversion depends on the accessibility of gelatinized starches to endo-active α-amylase during dilution and to exo-active glucoamylase during saccharification. As a result, acid hydrolysis can outperform enzymatic processes that are not fully optimized even though well-designed industrial enzymatic processes are generally more selective.

Incorporation between the reducing sugar and the total soluble solids

The total soluble solids rating reflects the reducing sugar rating. E-P2 had the lowest values for both variables (3 °Brix and 2.55%), while A-P3 had the highest values (14.5 °Brix and 12.39%). In all six treatment-level observations, the exploratory linear association between °Brix and reducing sugars was very strong ($R^2 = 0.986$) Fig:3. This suitability makes chemical sense because the breakdown of insoluble or high-molecular weight starches results in smaller, water-soluble saccharides and dextrins that simultaneously contribute to reductive power and refractive index.

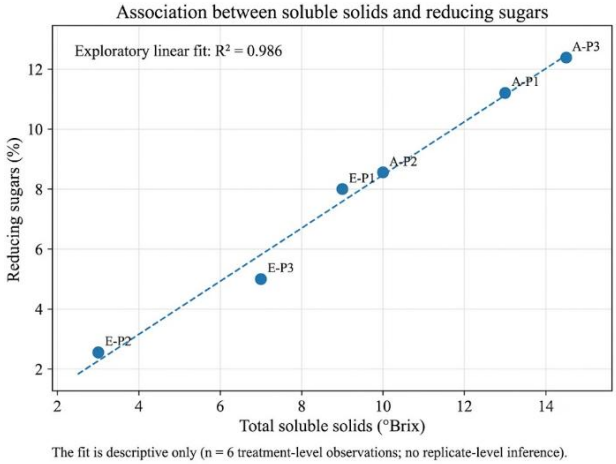


Figure 3: Total soluble solids from Banggai yam hydrolysate.

Moisture content

The moisture content ranges from 80.14% to 94.50%. The most diluted sample is E-P2 because it has the highest moisture content, while A-P3 is the most concentrated because it has the lowest moisture content. These values indicate that the product tested is a diluted starch hydrolysate and not a finished commercial starch hydrolysate. Codex Alimentarius CXS 212-1999 defines starch hydrolysate as a pure and concentrated solution of saccharide water obtained from starch or inulin, with a dextrose equivalent of at least 20% by dry weight and a total solids of at least 70% by mass. None of the samples came close to the total concentration of the required solid, despite the apparent reductive power.

pH interpretation

The final pH value is 3.5-3.8 for enzymatic starch hydrolysate and 4.5-4.6 for acid starch hydrolysate. The seemingly higher pH in products produced from acids is not evidence that acid hydrolysis occurs at milder acidity. This suggests that acid starch hydrolysate is neutralized or partially neutralized prior to laboratory analysis, whereas enzymatic starch hydrolysate may retain acidic conditions used for saccharification or enzyme inactivation. Therefore, the final pH cannot reconstruct the catalytic pH, mainly because the pH changes with temperature, buffer composition, neutralization, and cooling.

Discussion

The moisture content of the Banggai yam starch hydrolysates is closely associated with product dilution and the concentration of soluble solids. The acid hydrolysis treatment under P3 conditions exhibited the lowest moisture content (80.14%), corresponding to a dry matter content of 19.86%, and the highest reducing sugar content (12.39%) and total soluble solids (14.50 °Brix). In comparison, the enzymatic starch hydrolysates showed an average moisture content of 89.11%, indicating a greater proportion of water and a lower concentration of solids in the product. These findings suggest that the higher moisture content of the hydrolysates reflects greater product dilution, which can reduce the concentration of sugars and other solid constituents per unit mass of the liquid product. From a nutritional perspective, this distinction is important because a more dilute hydrolysate provides a lower concentration of carbohydrate solids per unit mass, whereas a more concentrated product may deliver more carbohydrate solids in the same serving mass. Nevertheless, reducing sugar content and total soluble solids alone do not provide a complete assessment of nutritive value, as the study did not determine the concentrations of other nutrients or the digestibility of the hydrolysates.

Banggai yam starch is reported to contain around 88.00-88.89% starch, a high amylose fraction of 60.29-62.88%, and a relatively high gelatinization temperature of 80.10-80.35 °C (10.40). High amylose content, strong molecular associations, and incomplete disruption of granule structure may limit enzyme adsorption and reduce the rate of glucose release (41). Granular starch hydrolysis studies

have also shown that the expansion of amorphous regions induced by the initial treatment increases enzyme adsorption and hydrolysis results (42). Therefore, low values on E-P2 and E-P3 may reflect inadequate gelatinization, insufficient dilution of α-amylase, suboptimal pH or temperature, short saccharification time, low enzyme activity, product inhibition, or simple dilution. These alternatives cannot be separated until a definite definition of P1-P3 and a process record are reported.

The comparison between P2 and P3 indicates that a lower moisture content does not necessarily correspond to a higher starch concentration. Although P3 exhibited a lower moisture content than P2, its starch concentration was also lower. This apparent discrepancy may be explained by the distinction between water content and the chemical composition of the dry matter. Moisture content reflects the proportion of water in the hydrolysate, whereas starch concentration represents the amount of starch remaining after hydrolysis. Under more extensive hydrolysis conditions, starch may be converted into smaller carbohydrates, including dextrins and reducing sugars. Consequently, the residual starch concentration may decrease even when the moisture content is lower. However, this explanation should be interpreted as a possible mechanism unless supported by direct measurements of residual starch and carbohydrate composition. Therefore, the results for P2 and P3 demonstrate that moisture content alone is insufficient to predict starch concentration or the extent of starch conversion.

In both hydrolysis pathways, P2 exhibited the lowest reducing sugar and TSS values among the three treatment conditions. In the enzymatic hydrolysis series, P2 produced 2.55% reducing sugars and 3.00 °Brix TSS, whereas P1 and P3 produced 8.00% and 5.00% reducing sugars and 9.00 and 7.00 °Brix TSS, respectively. A similar pattern was observed in the acid hydrolysis series, in which P2 produced 8.56% reducing sugars and 10.00 °Brix TSS, compared with 11.22% and 12.39% reducing sugars and 13.00 and 14.50 °Brix TSS for P1 and P3, respectively.

The P2 treatment also showed relatively high moisture contents in both hydrolysis routes, namely 94.50% for enzymatic hydrolysis and 84.79% for acid hydrolysis. However, these observations alone cannot establish that the lower reducing sugar and TSS values in P2 were caused by a higher water-to-starch ratio, lower starch concentration, shorter reaction time, or other specific processing factors. Such interpretations would require direct experimental evidence and independent evaluation of the corresponding process variables. Therefore, the P2 response is interpreted conservatively as a treatment-dependent variation in hydrolysate composition. The lower reducing sugar and TSS values indicate that less soluble reducing compounds were present in the final hydrolysate under the P2 conditions used in this study. The concurrent variation in moisture content further indicates that concentration effects may contribute to differences in the measured composition; however, the present experimental design does not permit the contribution of individual processing factors to be distinguished. Further experiments using a controlled factorial or response-surface design would be required to determine the effects and interactions of starch concentration, hydrolysis conditions, enzyme or acid concentration, temperature, and reaction time on starch conversion.

ISO 2173 defines refractometric solute solids as the approximate conventional value when a solute other than sucrose is present (43). In starch hydrolysate, the refractive index can indicate the presence of glucose, maltose, maltotrioso, dissolved dextrins, organic acids, minerals, and neutralizing salts (44). Therefore, the difference between the dry solids and °Brix in these samples likely represents insoluble components or weak refractometry, including residual starches, suspended particles, proteins, ashes, or non-sugar solutes.

The higher reducing-sugar content obtained by acid hydrolysis may be related to the cleavage of glycosidic linkages within the starch polymers. Starch consists primarily of amylose and amylopectin. Amylose is predominantly a linear polymer of glucose units linked by α-(1→4) glycosidic bonds, whereas amylopectin contains α-(1→4)-linked glucan chains with α-(1→6) glycosidic bonds at branch points. Under acidic conditions, hydrolysis can cleave glycosidic linkages in both starch components, producing shorter-chain dextrins and oligosaccharides and, with further hydrolysis, increasing the concentration of reducing sugars. In amylopectin, this process may involve cleavage of both α-(1→4) backbone linkages and α-(1→6) branch-point linkages. Therefore, the higher reducing-sugar values observed in the acid-hydrolyzed samples indicate greater conversion of starch polymers into soluble reducing carbohydrates under the conditions applied in this study. However, the present results do not allow the contribution of specific bond types or individual starch components to be quantified separately.

High moisture content also indicates high water activity unless there is a low molecular weight or sufficient preservatives in the presence of sugars. Therefore, the current hydrolysate should not be given a long shelf life based solely on its acidic pH. Microbiological stability requires water activity, total number of bacterial colonies, amount of yeast and fungus, packaging integrity, thermal processing conditions, and storage testing (45).

Studies of acid-catalyzed cassava starch have shown that the pH of the reaction and the refrigerated product can differ substantially, and that neutralization can result in salts that remain in the syrup (46,47). The acidity of the titration should be measured in conjunction with the pH because two products with the same pH can have very different acid loads and buffer capacities. Acid starch hy-

drolysate should also be analyzed for ash levels and relevant ions, such as chloride, sulfate, nitrates, sodium, or calcium, depending on the acid and neutralizing agent used (48).

Although acid hydrolysis produced higher reducing sugar content and total soluble solids than enzymatic hydrolysis under the conditions investigated, these physicochemical advantages alone do not establish its suitability for human consumption. Acid hydrolysis may be considered a potential approach for producing sugar-rich hydrolysates; however, its application in food products requires careful control of processing conditions and appropriate post-hydrolysis treatment. In particular, the acid must be adequately neutralized or removed, and the final product must be evaluated for residual acidity, relevant processing by-products, and compliance with applicable food-safety requirements. In the present study, the acid starch hydrolysates exhibited a final pH of 4.5–4.6, but this measurement alone does not demonstrate that the products are safe for consumption. Furthermore, the hydrolysates retained relatively high moisture contents, indicating that further processing would be necessary to obtain a more concentrated product.

In the present starch hydrolysates, the soluble fraction may also contain non-reducing and partially hydrolyzed carbohydrates, particularly oligosaccharides and soluble dextrins, as well as smaller amounts of organic acids, minerals, and salts originating from the hydrolysis and neutralization steps. The refractometric measurement therefore represents an overall estimate of soluble/refractometrically active material rather than a direct measurement of sugar concentration.

The strong linear relationship between total soluble solids (TSS, °Brix) and reducing sugars observed in the present study ($R^2 = 0.986$) can be explained primarily by the progressive depolymerization of starch during hydrolysis**.** As hydrolysis proceeds, the high-molecular-weight starch polymers are converted into lower-molecular-weight, water-soluble products, including reducing sugars and soluble oligosaccharides/dextrins. Therefore, treatments that promoted greater starch hydrolysis tended to simultaneously increase both the concentration of reducing sugars and the amount of refractometrically detectable soluble material.

Conclusions

Under the conditions investigated, acid hydrolysis produced higher reducing sugars and total soluble solids than enzymatic hydrolysis of Banggai yam starch. The A-P3 treatment gave the highest reducing sugar content (12.39%) and TSS (14.5 °Brix). However, all hydrolysates remained relatively dilute and were not comparable to finished commercial starch hydrolysate based on total-solids concentration. The lower response of enzymatic hydrolysis indicates that further optimization of starch accessibility, enzyme dosage, pH, temperature, and hydrolysis time is warranted.

List of abbreviations

- **AOAC**: Association of Official Analytical Collaboration (or Association of Official Analytical Chemists)
- **A-P1 / A-P2 / A-P3**: Acid Hydrolysis Treatment Conditions 1, 2, and 3
- **ANOVA**: Analysis of Variance
- **D. alata**: *Dioscorea alata*
- **E-P1 / E-P2 / E-P3**: Enzymatic Hydrolysis Treatment Conditions 1, 2, and 3
- **H_2SO_4**: Sulfuric Acid
- **HCl**: Hydrochloric Acid
- **HSD**: Honestly Significant Difference (Tukey's HSD test)
- **ISO**: International Organization for Standardization
- **KI**: Potassium Iodide
- **N**: Normality (unit of chemical concentration)
- **$Na_2S_2O_3$**: Sodium Thiosulfate
- **NaOH**: Sodium Hydroxide
- **$(NH_4)_2HPO_4$**: Diammonium Phosphate (Ammonium Phosphate Dibasic)
- **P1, P2, P3**: Processing / Treatment Conditions 1, 2, and 3
- **Pb-acetate**: Lead(II) Acetate
- **pH**: Potential of Hydrogen
- **R^2**: Coefficient of Determination
- **RS**: Reducing Sugars
- **SNI**: Standar Nasional Indonesia (Indonesian National Standard)
- **spp.**: Species (plural)
- **TSS**: Total Soluble Solids
- **Wd**: Sample Weight After Drying to Constant Weight
- **Wi**: Sample Weight Before Drying (Initial Weight)
- **°Brix**: Degrees Brix (unit of refractometric soluble solids)

Author Contributions

Ramadhani Chaniago: Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing, and Project Administration.

Sultan Nasyirah Bisinda: Investigation, Data Curation, Formal Analysis, Validation, Visualization, and Writing – Review & Editing.

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request. All laboratory data supporting the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this study.

AI Declaration

The authors used ChatGPT, developed by OpenAI, to assist with manuscript organization, language refinement, drafting, and the preparation of data visualizations. The generative AI tool was not used to generate or modify the laboratory data. All AI-assisted content was critically reviewed, verified, and revised by the authors, who take full responsibility for the accuracy, originality, interpretation, and integrity of the final manuscript.

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