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Preparation and Characterization of Artisanal Jackfruit Vinegars with Different Sugar Concentrations

Elaboração e Caracterização do Vinagre Artesanal de Jaca com Diferentes Concentrações de Açúcar

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Abstract

The growing interest in natural, functional products obtained through sustainable processes has driven the valorization of fermented foods, including vinegar. This study highlights jackfruit (*Artocarpus heterophyllus* Lam.), a fruit rich in sugars and bioactive compounds, as a promising raw material for vinegar production. The objective was to develop and characterize artisanal jackfruit vinegars by evaluating different sugar concentrations (0%, 5%, 10%, 15%, and 20%) regarding fermentation efficiency and final product quality. The process included alcoholic fermentation with *Saccharomyces cerevisiae* and acetic fermentation with *Acetobacter* sp., in addition to physicochemical analyses. Parameters such as pH, titratable acidity, soluble solids, and color were evaluated. Sugar concentration significantly affected all evaluated parameters ($p < 0.05$). The pH decreased from 2.62 (0% and 5%) to 2.19 at 15%, with a slight increase to 2.15 at 20%. Titratable acidity increased progressively, meeting Brazilian regulatory standards. Soluble solids ranged from 3.73 to 6.27 °Brix, while alcohol content varied between 9.10% and 14.67% during fermentation. The 15% sugar concentration provided a balance between acidity (4.74 $g \cdot 100\ mL^{-1}$), pH (2.19), and soluble solids (5.73 °Brix), indicating optimal fermentation performance. Higher sugar levels (20%) reduced fermentation efficiency due to high osmotic pressure. These results confirm the feasibility of producing artisanal jackfruit vinegar, promoting the valorization of underutilized fruits and the diversification of the fermented food industry. The optimal sugar concentration ensures a balance between process efficiency and product quality, contributing to sustainability and technological innovation in food production.

Keywords: *Artocarpus heterophyllus*. Biotechnology. Acetic Fermentation. Technological Innovation. Agricultural Sustainability.

Resumo

O crescente interesse por produtos naturais, funcionais e obtidos por processos sustentáveis tem impulsionado a valorização de alimentos fermentados, entre eles o vinagre. Este estudo traz destaque para a jaca (*Artocarpus heterophyllus Lam.*), fruta rica em açúcares e compostos bioativos, como matéria-prima promissora para produção de vinagre. O objetivo foi desenvolver e caracterizar vinagres artesanais de jaca, avaliando-se diferentes concentrações de açúcar (0%, 5%, 10%, 15% e 20%) sobre a eficiência fermentativa e a qualidade do produto final. O processo incluiu fermentação alcoólica com *Saccharomyces cerevisiae* e acética com *Acetobacter sp.*, além de análises físico-químicas. Parâmetros como pH, acidez titulável, sólidos solúveis e cor foram avaliados. A concentração de açúcar afetou significativamente todos os parâmetros avaliados ($p < 0,05$). O pH diminuiu de 2,62 (0% e 5%) para 2,19 em 15%, com um leve aumento para 2,15 em 20%. A acidez titulável aumentou progressivamente, atendendo aos padrões regulamentares brasileiros. Os sólidos solúveis variaram de 3,73 a 6,27 °Brix, enquanto o teor alcoólico variou entre 9,10% e 14,67% durante a fermentação. A concentração de açúcar de 15% proporcionou um equilíbrio entre acidez ($4,74\ g \cdot 100\ mL^{-1}$), pH (2,19) e sólidos solúveis (5,73 °Brix), indicando desempenho ótimo da fermentação. Níveis mais altos de açúcar (20%) reduziram a eficiência fermentativa devido à alta pressão osmótica. Esses resultados confirmam a viabilidade da produção de vinagre artesanal de jaca, promovendo a valorização de frutas subutilizadas e a diversificação da indústria de alimentos fermentados. A concentração ideal garante um equilíbrio entre eficiência do processo e qualidade do produto, contribuindo para a sustentabilidade e inovação tecnológica na produção de alimentos.

Palavras-chave: *Artocarpus heterophyllus*. Biotecnologia. Fermentação Acética. Inovação Tecnológica. Sustentabilidade Agrícola.

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1 Introduction

Vinegar is widely recognized as one of the oldest fermented products in human history, with evidence of its use dating back to ancient Egyptian and Babylonian civilizations (Muhialdin et al., 2022). Produced through the acetic fermentation of carbohydrate-rich raw materials, this product plays a central role in culinary practices and food preservation across diverse cultures (Mota; Vilela, 2024). In recent years, the production of artisanal vinegars has gained increasing attention, particularly due to the growing consumer demand for natural and differentiated products in the marketplace (Abid *et al.*, 2024).

Jackfruit (*Artocarpus heterophyllus* Lam.), a tropical fruit widely cultivated in countries such as Brazil and India, is a promising raw material for vinegar production due to its high content of carbohydrates, vitamins, and bioactive compounds, including phenolics and carotenoids (Mandhare *et* *al.*, 2020; Sarangi *et al.*, 2023). Studies indicate that, in addition to its nutritional properties, jackfruit possesses a unique flavor profile that can be enhanced in fermented products, offering an attractive alternative for diversifying the vinegar market (Hoang *et al.*, 2024; Sabidi *et al.*, 2020).

The production of artisanal vinegars from tropical fruits has been explored using other raw materials, such as pineapple, mango and banana. These studies have demonstrated that initial sugar concentration and the control of fermentation conditions directly influence the final composition of vinegar (Hu *et al.,* 2024; Luzón-Quintana *et al.*, 2021; Ouattara *et al.*, 2023). Moreover, factors such as the alcohol concentration generated during the initial fermentation and the acetic acid content in the final product significantly affect sensory characteristics and consumer acceptability.

In the case of jackfruit vinegar, the addition of different sugar concentrations during fermentation is a critical factor for the development of its physicochemical properties. Previous research suggests that increasing sugar concentrations may enhance initial ethanol production, thereby favoring its conversion into acetic acid and, consequently, increasing the acidity of the final product (De Vuyst *et al.,* 2020; Li *et al.*, 2023). In addition, parameters such as pH, soluble solids and color are essential for assessing vinegar quality and microbiological stability, ultimately influencing market acceptance (Boasiako *et al.*, 2024; Martínez-Sánchez *et al.*, 2024).

Luzón-Quintana *et al.* (2021) emphasized that, in fruit vinegar production, the different conditions and methods applied during alcoholic and acetic fermentations significantly influence the final characteristics of the vinegar. Roda *et al.* (2017) reported that the use of physical and enzymatic treatments combined with saccharified pineapple residues resulted in an alcohol yield of approximately 7%, which is considered satisfactory and desirable for vinegar production.

Based on these findings, the present study aimed to physicochemically characterize an artisanal jackfruit vinegar produced using different sugar concentrations during the fermentation process.

2 Material and Methods

The experiment was conducted in the industrial kitchen of the Regional Training Center of the National Rural Learning Service of Bahia. Jackfruit, demerara sugar, bentonite, and baker's yeast (*Saccharomyces cerevisiae*) were purchased from the local market in the municipality.

2.1 Artisanal jackfruit vinegar production with different sugar concentrations

Ripe jackfruit fruits were externally sanitized with running water followed by immersion in a 200 ppm sodium hypochlorite solution to remove dirt and microorganisms from the peel. After sanitation, the fruits were cut, and the seeds were manually removed. The pulp was separated from the bulbs and homogenized using a blender until a uniform consistency was obtained. The homogenized pulp was then weighed for use in must formulation.

In a clean pan, 500 g of the extracted pulp were mixed with 1 L of water. The mixture was slowly heated to approximately 65-70 °C and maintained at this temperature for 20 min, performing a slow pasteurization to reduce undesirable microbial load without compromising the must's properties. After pasteurization, the must was cooled to room temperature and transferred to a sterilized container. Prior to the onset of alcoholic fermentation, different sugar concentrations (0, 5, 10, 15, and 20%, based on pulp weight) were added to the must and thoroughly homogenized.

Following homogenization, 5 g of dry baker's yeast (*Saccharomyces cerevisiae*) were added as a yeast source for alcoholic fermentation. The mixture was covered with a clean cloth to allow gas exchange. During this stage, the must was stirred every 8 h using a sterilized spatula to ensure homogeneity and to accelerate the fermentation process.

The must was maintained in a dry, well-ventilated environment at room temperature to allow alcoholic fermentation to occur. After 10 days, signs of fermentation completion were observed, such as a reduction in bubble formation and the development of a characteristic wine aroma, indicating the conversion of sugars into ethanol by the yeast.

At the end of alcoholic fermentation, the must was filtered using a clean and sterilized strainer to remove solids and residues. The resulting liquid (jackfruit wine) was transferred back to the previously sanitized container. At this stage, 10 mL of a commercial acetic acid bacteria culture (*Acetobacter* sp.) were added to initiate acetic fermentation. The container was again covered with a clean cloth.

The wine was stored in a dry, well-ventilated environment at room temperature to allow the conversion of ethanol into acetic acid by acetic acid bacteria. During this stage, which lasted 15 days, the wine was not stirred. A progressive increase in the characteristic acidic aroma of vinegar was observed throughout the process.

After completion of acetic fermentation, hydrated bentonite was added (2 g per 10 L of water), and 10 mL of the hydrated suspension were added per liter of vinegar for clarification and stabilization purposes. Subsequently, the vinegar was filtered again using paper filters to ensure the purity of the final liquid.

The vinegar was then subjected to slow pasteurization by heating at 65–70 °C for 20 min to ensure the inactivation of remaining microorganisms and to extend shelf life. After pasteurization, the vinegar was packaged in 250 mL polyethylene terephthalate (PET) bottles, previously cleaned and sterilized (Figure 1).

Figure 1 – Homemade jackfruit vinegar packaged in PET (polyethylene terephthalate) bottles

Source: the authors.

The bottles were sealed and stored in a dry, well-ventilated environment for subsequent physicochemical and sensory analyses.

2.2 Physicochemical characterization of jackfruit pulp and artisanal jackfruit vinegar produced with different sugar concentrations

The following physicochemical parameters were evaluated in jackfruit pulp samples: pH, titratable acidity (TA), soluble solids (SS), and the SS/TA ratio. In vinegar samples, in addition to the parameters mentioned above, alcohol content was also determined. All analyses were performed in triplicate.

pH was determined using the potentiometric method with a digital benchtop pH meter, calibrated with standard buffer solutions at pH 4.0 and 7.0 at 20 °C, with a precision of 0.01. Soluble solids, expressed as °Brix, were determined by refractometry using a digital refractometer (Hanna Instruments, model HI96804). Titratable acidity was determined by acid–base volumetric titration using 0.1 mol L^{-1} NaOH as the alkaline solution and 1% alcoholic phenolphthalein as the indicator. For jackfruit pulp, titratable acidity was expressed as citric acid (g 100 g^{-1}), whereas for vinegar it was expressed as acetic acid (g 100 g^{-1}). The SS/TA ratio was calculated as the ratio between soluble solids and titratable acidity. All analytical procedures described above followed the methodologies established by the Instituto Adolfo Lutz (IAL, 2008).

Alcohol content was determined by refractometry using an analog refractometer suitable for alcohol measurement. The results were expressed as percentage of ethanol by volume (% v/v) based on readings obtained from filtered vinegar samples.

2.3 Color analysis

Color was measured using a portable digital colorimeter (Konica Minolta, model CR-400) operating in the CIELAB color space. The following parameters were obtained: L*, which represents lightness and ranges from 0 (black/dark) to 100 (white/light); a*, which indicates chromaticity on the green (−) to red (+) axis; and b*, which indicates chromaticity on the blue (−) to yellow (+) axis.

2.4 Statistical analysis

Statistical analysis was performed using Sisvar® *software*, version 5.6 (Ferreira, 2019). The experiment was conducted in a completely randomized design (CRD), consisting of five treatments corresponding to sugar concentrations (0%, 5%, 10%, 15%, and 20%), with three biological replicates per treatment.

The data were subjected to analysis of variance (ANOVA) using the F-test at a 5% significance level. Before performing the ANOVA, the assumptions of normality of residuals and homogeneity of variances were verified. When significant differences were detected, the means were compared using Tukey's test at a 5% probability level.

For variables showing significant effects, regression graphs were constructed based on the mean values of the treatments using Microsoft Excel software. Regression models were fitted according to the nature of the data, and the relationships between variables were quantitatively described, allowing the evaluation of response behavior as a function of sugar concentration. Model fitting was assessed using the coefficient of determination (R^2), and parameter significance was verified based on p-values.

3 Results and Discussion

3.1 Physicochemical and Color Evaluation of Jackfruit Pulp Used in the Production of Artisanal Vinegar

The pH value of the jackfruit pulp (4.12 ± 0.04) was characterized as slightly acidic, which is considered ideal for fermentation (Table 1). This pH range is favorable for the growth of acidophilic microorganisms, particularly acetic acid bacteria responsible for the conversion of ethanol into acetic acid during acetic fermentation (Gomes et al., 2018). Previous studies have reported that fermentations conducted at pH values between 3.5 and 5.0 exhibit higher acidification efficiency and a reduced risk of contamination by undesirable microorganisms (Lynch *et al.,* 2019; Trček *et al.*, 2015).

Table 1 – Physicochemical and color parameters of jackfruit pulp used in the production of artisanal vinegar

Parameter	Mean value ± Standard deviation
pH	4.12 ± 0.04
Soluble solids (°Brix)	25.9 ± 0.20
Titratable acidity (g citric acid·100 g^{-1})	0.33 ± 0.20
Ratio (SS/TA)	78.97 ± 5.24
L*	26.24 ± 0.03
a*	2.11 ± 0.10
b*	11.97 ± 0.07

Source: research data.

The soluble solids content of the jackfruit pulp (25.9 ± 0.20 °Brix) was remarkably high, indicating a substantial concentration of natural sugars (Table 1). These sugars are essential for the initial alcoholic fermentation, during which yeasts convert sugars into ethanol. Tropical fruits such as apple and grape, which are widely used in vinegar production, typically present soluble solids values ranging from 15 to 24 °Brix, highlighting the potential of jackfruit as a sugar-rich raw material for fermentation processes (Lynch *et al.*, 2019; Praveena *et al.*, 2021; Ousaaid *et al.*, 2021).

The titratable acidity of the pulp (0.33 ± 0.20 g citric acid·100 g^{-1}) was low, reflecting the characteristic sweetness of jackfruit (Table 1). This initial feature, commonly observed in tropical fruits, is compensated by the increase in acidity during the fermentation process, resulting in vinegars with balanced sensory characteristics and acetic acid levels that comply with standards required for consumption (Lynch *et al.,* 2019; Praveena *et al.*, 2021; Ousaaid *et al.*, 2021).

The SS/TA ratio (78.97 ± 5.24), which represents the proportion between soluble solids and titratable acidity, is indicative of the balance between sweetness and acidity of the raw material. A high ratio, such as that observed in this study, favors the production of products with a smoother palate, a characteristic highly valued in artisanal vinegars (Lynch et al., 2019; Praveena et al., 2021; Ousaaid et al., 2021).

Color parameters (Table 1) indicated that the pulp exhibited a light hue with a slight tendency toward yellow, which is typical of ripe jackfruit. The initial color of the raw material is relevant, as it directly influences the appearance of the final vinegar. The yellow intensity (b*) is desirable for attracting consumers and reinforces the perception of product naturalness, as highlighted by Zaini et al. (2024), who reported that color parameters significantly impact the acceptance of tropical vinegars.

3.2 Physicochemical and Color Evaluation of Artisanal Jackfruit Vinegar Produced with Different Sugar Concentrations

Table 2 shows the results of the 2 shows the results of the statistical analysis for pH, soluble solids (°Brix), acidity (g acetic acid·100 g^{-1}), ratio (SS/TA), and alcohol content as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%) in the jackfruit vinegar formulation.

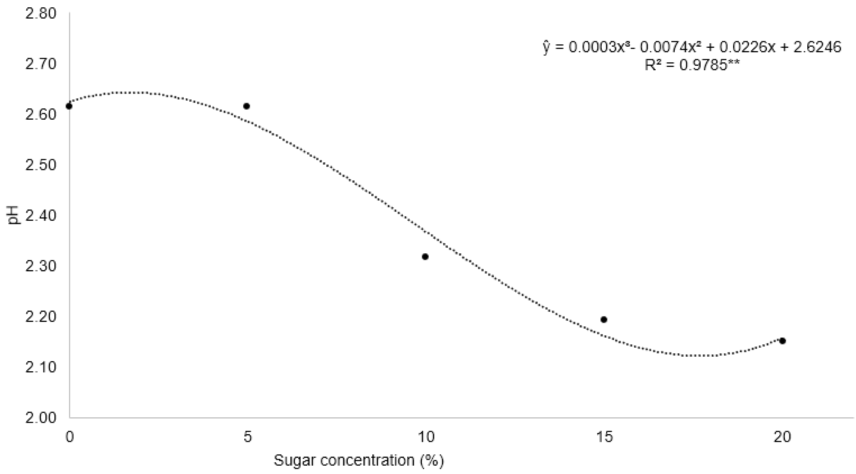
Table 2 – Analysis of variance for pH, soluble solids, acidity, ratio (SS/TA), and alcohol content as a function of different concentrations of sugar in the jackfruit vinegar

Treatment	pH	°Brix	Acidity	SS/AT	Alcohol content
Value F	1525.00*	385.10*	402.30*	42.33*	73.56*
LSD (5%)	0.02	0.23	0.28	0.18	1.07
0%	2.62 ± 0.01 a	3.73 ± 0.06 d	2.04 ± 0.12 d	1.83 ± 0.14 a	9.10 ± 0.36 c
5%	2.62 ± 0.01 a	5.07 ± 0.15 c	3.68 ± 0.07 c	1.38 ± 0.05 bc	12.00 ± 0.01 b
10%	2.32 ± 0.01 b	5.67 ± 0.06 b	3.82 ± 0.15 c	1.48 ± 0.05 b	12.00 ± 0.01 b
15%	2.19 ± 0.01 c	5.73 ± 0.06 b	4.74 ± 0.10 b	1.21 ± 0.02 cd	12.33 ± 0.58 b
20%	2.15 ± 0.01 d	6.27 ± 0.06 a	5.30 ± 0.07 a	1.18 ± 0.03 d	14.67 ± 0.58 a
CV (%)	0.42	1.62	2.74	4.94	3.32

Mean ± standard error, CV = coefficient of variation, LSD = least significant difference.
Source: resource data.

The relationship between jackfruit vinegar pH and sugar concentration showed an initial decreasing trend, followed by a slight recovery at higher concentrations (Figure 2). The pH progressively decreased up to 15% sugar concentration, likely due to the efficient conversion of ethanol into acetic acid by acetic acid bacteria. A similar pattern was reported by Chalchisa and Dereje (2024), who observed a decrease in pH during fermentations with increasing substrate availability.

Figure 2 – Variation in pH of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%)



Source: research data.

However, at higher sugar concentrations, such as 20%, the slight increase in pH may be explained by an inhibitory effect caused by excess sugar, which increases osmotic pressure and hinders the activity of acetic acid bacteria, as described by Hoppert, Kölling and Einfalt (2022).

This behavior suggests the existence of a threshold sugar concentration at which fermentative reactions occur optimally without compromising organic acid production.

The data demonstrated a high statistical fit of the cubic model ($R^2 = 0.9785$), indicating that pH variation was strongly influenced by sugar concentration (Figure 2). This result reinforces that controlling the initial substrate concentration is crucial for producing vinegars with suitable physicochemical characteristics.

The slight recovery in pH observed at 20% further suggests that high osmolarity conditions may partially inhibit bacterial metabolism, which is consistent with studies showing that elevated sugar concentrations can limit acetic acid production (Chalchisa; Dereje, 2024; Hoppert; Kölling; Einfalt, 2022).

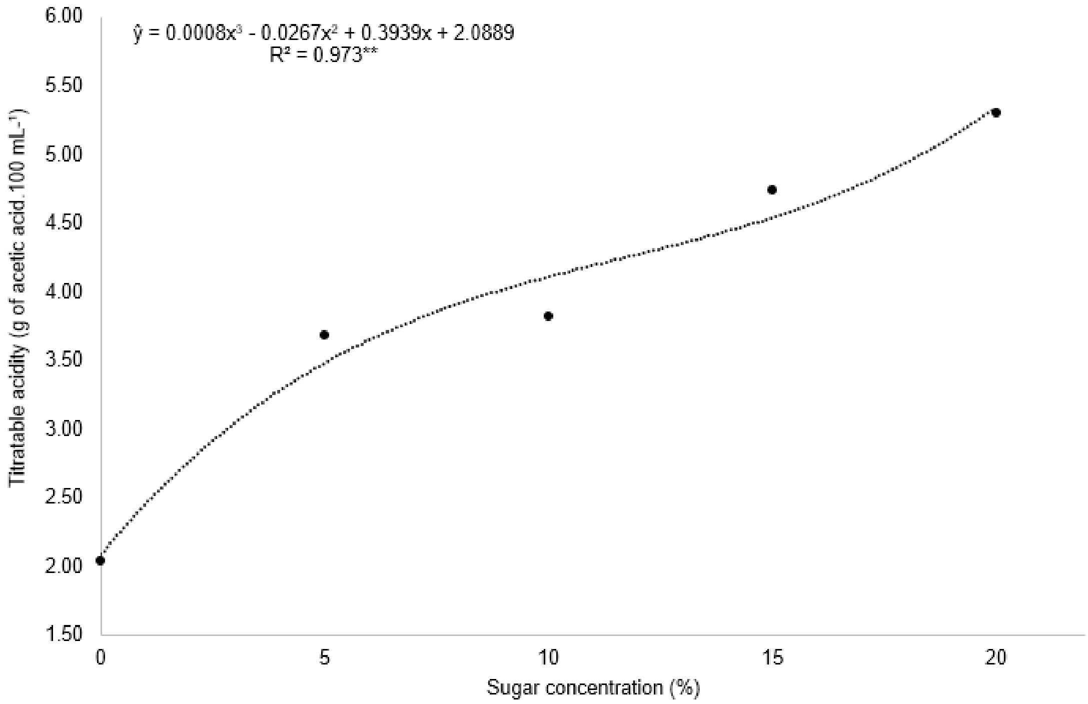
Comparatively, similar behaviors have been reported for artisanal vinegars produced from other fruits, in which excess substrate reduced fermentation efficiency, thereby compromising final acidity and the sensory quality of the product (Chalchisa; Dereje, 2024; Hoppert; Kölling; Einfalt, 2022).

Titratable acidity is an essential parameter in vinegar characterization, as it is directly related to both sensory quality and product safety. As shown in Figure 3, a progressive increase in titratable acidity of artisanal jackfruit vinegar was observed as the sugar concentration during fermentation increased.

This behavior can be attributed to the greater availability of substrate for fermentative microorganisms, such as bacteria of the genus *Acetobacter*, which convert ethanol produced during alcoholic fermentation into acetic acid during acetic fermentation (Vavřiník et al., 2022; Yassunaka *et al.*, 2023).

This gradual increase corroborates findings from studies on artisanal vinegars, in which higher carbohydrate levels favor increased production of organic acids (Vavřiník *et al.,* 2022; Yassunaka *et al.*, 2023).

Figure 3 –Variation in titratable acidity (g acetic acid·100 mL⁻¹) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%)



Source: research data.

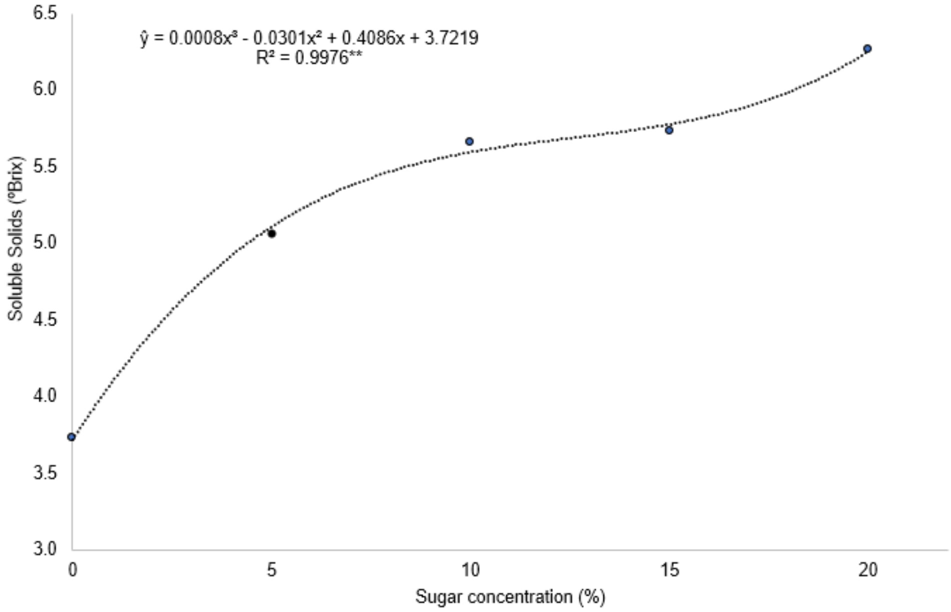
Brazilian legislation, according to Normative Instruction No. 6 of February 4, 2019, issued by the Ministry of Agriculture, Livestock, and Food Supply (MAPA), establishes that vinegars must contain a minimum of 4 g of acetic acid per 100 mL.

The data demonstrated that only samples produced with higher sugar concentrations (15% and 20%) reached or exceeded this threshold, indicating that formulation adjustments are necessary to ensure legal compliance in vinegars produced with lower sugar levels.

When compared with more conventional fruit vinegars, such as apple and grape vinegars, jackfruit vinegar shows competitive potential in terms of acidity, although variations in fermentation conditions may influence the final results (Yuan *et al.*, 2024).

The soluble solids content (°Brix) of jackfruit vinegar increased gradually with increasing sugar concentration, a behavior explained by the greater availability of initial substrate (Figure 4). Even after metabolism by yeasts and acetic acid bacteria, part of the residual sugar remained in the product, particularly at higher concentrations such as 15% and 20%.

Figure 4 – Variation in soluble solids (°Brix) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%)



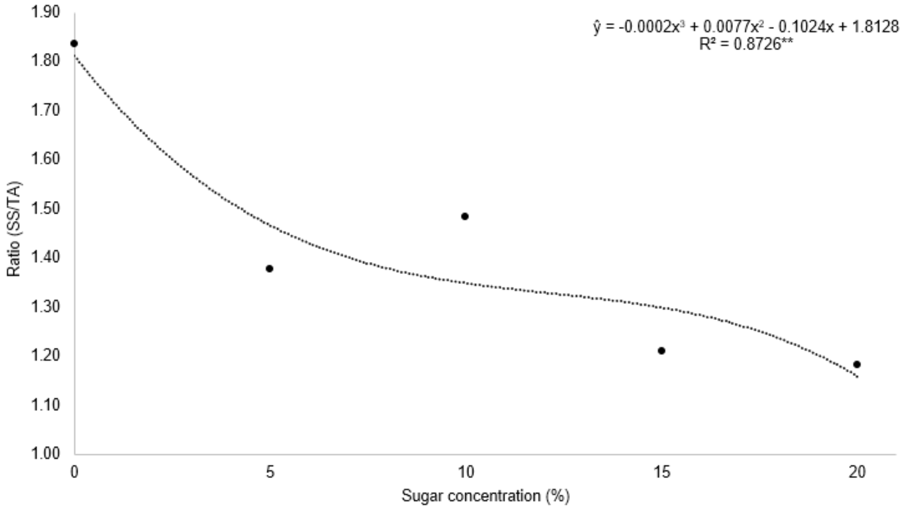
Source: the authors.

According to Hoppert, Kölling, and Einfalt (2022), in acetic fermentations, an increase in the initial substrate often results in higher final soluble solids values due to limitations in complete sugar conversion, a phenomenon influenced by factors such as high osmolarity. These residual values directly affect product density and flavor, in addition to contributing to specific sensory characteristics.

The statistical fit of the cubic model ($R^2 = 0.9976$) further supports the reliability of the relationship between the variables, indicating that the initial sugar concentration is a determining factor for the soluble solids content of the final vinegar (Figure 4). Comparatively, elevated sugar concentrations in fermentations increase soluble solids values both through direct addition and through the accumulation of intermediate or final fermentation compounds. These results highlight the importance of controlling the initial substrate concentration to ensure a balance between fermentation efficiency and product sensory quality.

Figure 5 shows a decrease in the ratio between total soluble solids and titratable acidity (ratio) as a function of increasing sugar concentration in artisanal jackfruit vinegar. This trend occurs due to the greater conversion of sugars into ethanol and subsequently into acetic acid during alcoholic and acetic fermentation processes. The production of acetic acid increases total acidity, while sugar consumption reduces total soluble solids, resulting in a decrease in the SS/TA ratio. Studies indicate that these effects are expected in artisanal vinegar fermentations, particularly when sugar-rich substrates are used (Chalchisa; Dereje, 2024; Hoppert; Kölling; Einfalt, 2022; Vavřiník *et al.,* 2022; Yassunaka *et al.*, 2023).

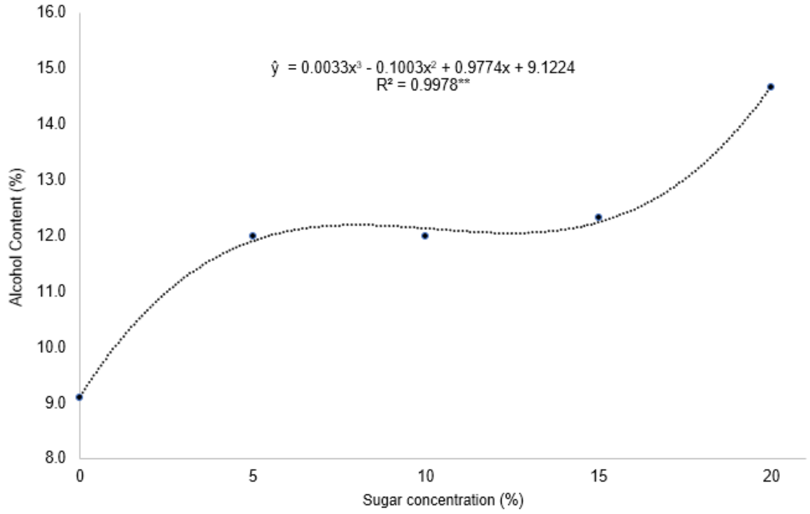
Figure 5 – Variation in the ratio (SS/TA) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%)



Source: the authors.

In the context of similar fermentations, such as those involved in fruit vinegars, the addition of sugars has been shown to significantly influence physicochemical characteristics, including pH reduction, an increase in total acidity, and the stabilization of total soluble solids at the end of the process. In addition, the coefficient of determination ($R^2 = 0.8726$) indicates a strong correlation between the variables presented in the graph, demonstrating that the fitted equation is reliable for predicting the observed behavior.The alcohol content of artisanal jackfruit vinegar increased with sugar concentration, reaching higher values at concentrations above 10% (Figure 6). This behavior is consistent with studies on alcoholic fermentation, which demonstrate that sugar addition provides substrate for yeasts to convert sugars into ethanol.

Figure 6 – Variation in alcohol content of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%).



Source: the authors.

At sugar concentrations between 5% and 10%, stabilization of the alcohol content was observed, likely due to the maximum efficiency of yeasts. At higher concentrations (15% to 20%), the increase in alcohol content may be associated with the selection of strains more tolerant to osmotic pressure, which are able to sustain fermentation even under extreme conditions, as described by Liszkowska and Berlowska (2021).

From a regulatory perspective, the Ministry of Agriculture, Livestock, and Food Supply (MAPA) establishes that, during the acetic fermentation stage, the initial alcohol content of the substrate must be sufficient to generate the acidity required for vinegar production, while the residual alcohol content in the final product must be lower than 1.0% (v/v). The range observed in Figure 6 (8%–15%) is consistent with values recommended for efficient fermentation (Saelee; Cheong; Chaijan, 2023).

From a regulatory perspective, Brazilian legislation establishes that vinegar must contain a maximum residual alcohol content of 1.0% (v/v). However, the alcohol levels observed at the end of the fermentation process (8%–14.67%) indicate that the conversion of ethanol into acetic acid was not complete under the evaluated conditions. These results suggest that adjustments in the acetic fermentation stage—such as extended fermentation time, improved aeration, or optimization of bacterial activity—are necessary to ensure full ethanol oxidation and compliance with regulatory standards. Despite this limitation, the ethanol concentrations obtained demonstrate adequate substrate availability for acetic acid production (Saelee; Cheong; Chaijan, 2023). This analysis suggests that although higher sugar concentrations promote increased alcohol content, strict control of this parameter is essential to ensure regulatory compliance as well as the sensory and chemical quality of the product. Table 3 shows the results of the statistical analysis for the parameters lightness (L*), greenness intensity (a*), yellow intensity (b*), yellowing index and browning index as a function of different sugar concentrations (0%, 5%, 10%, 15% and 20%) in the jackfruit vinegar formulation.

Table 3 - Analysis of variance for L*, a*, b*, yellowness index, and darkening index as a function of

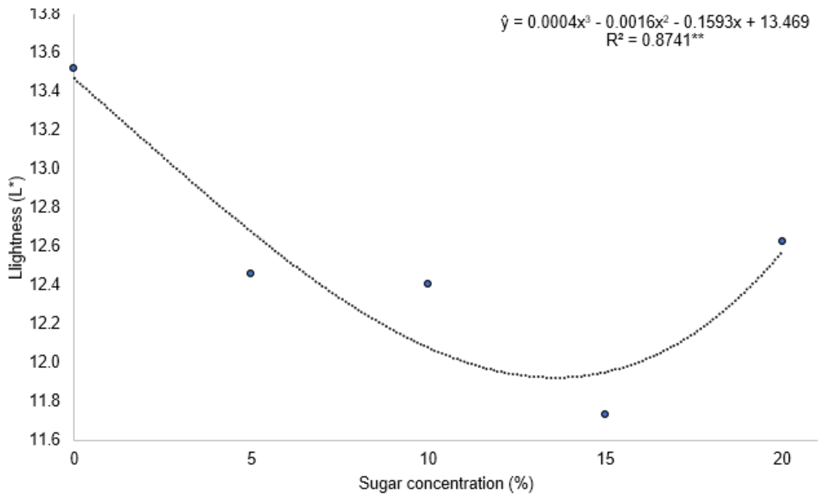
different concentrations of sugar in the jackfruit vinegar

Treatment	L*	a*	b*	Yellowing Index	Darkening Index
Value F	742.70*	ns	16.68*	58.25*	107.60*
LSD (5%)	0.11	0.27	0.28	3.27	2.26
0%	13.52 ± 0.02 a	-0.50 ± 0.12 a	4.49 ± 0.17 b	47.47 ± 1.76 d	-1,79 ± 0.85 d
5%	12.46 ± 0.06 c	-0.32 ± 0.14 a	4.95 ± 0.08 a	56.75 ± 0.86 b	7.16 ± 0.64 b
10%	12.41 ± 0.04 c	-0.24 ± 0.09 a	4.96 ± 0.05 a	57.11 ± 0.70 b	8.05 ± 0.68 b
15%	11.74 ± 0.05 d	-0.35 ± 0.08 a	5.07 ± 0.12 a	61.68 ± 1.69 a	11.31 ± 1.37 a
20%	12.63 ± 0.02 b	-0.35 ± 0.07 a	4.64 ± 0.04 b	52.48 ± 0.47 c	3.23 ± 0.27 c
CV (%)	0.32	28.99	2.14	2.21	15.03

ns = not significant (p>0.05), mean ± standard error, CV = coefficient of variation, LSD = least significant difference.
Source: Prepared by the authors (2024).

The initial reduction in lightness (L*) of artisanal jackfruit vinegar, followed by a slight increase at higher sugar concentrations, reflects changes in the formation of browning compounds during the fermentation process (Figure 7). This behavior is associated with the intensification of reactions such as the Maillard reaction and the formation of phenolic compounds at intermediate sugar concentrations, processes that directly affect product color (Zhang et al., 2024).

Figure 7 – Variation in lightness (L) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%).



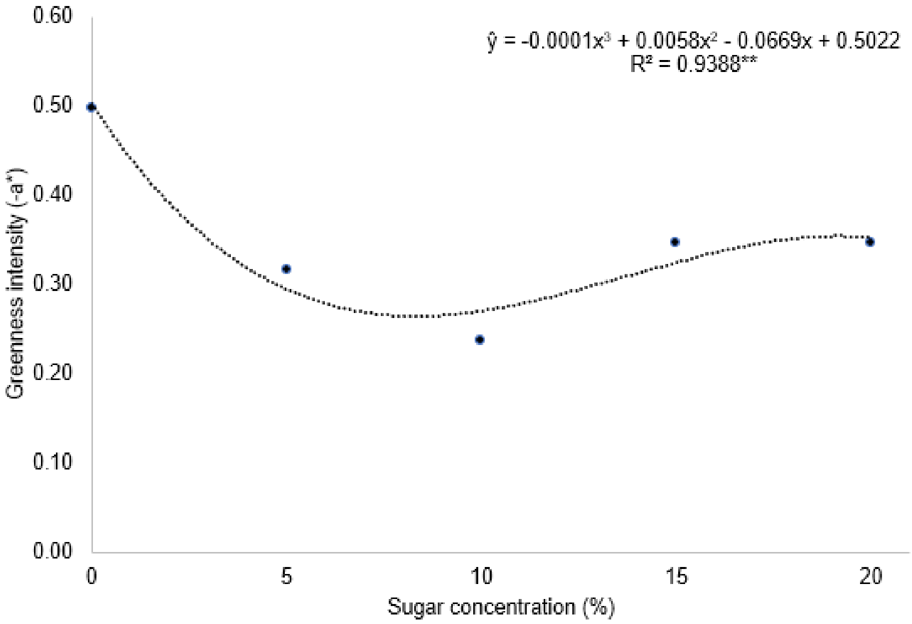
Source: the authors.

Comparatively, fruit vinegars such as apple and grape also exhibit similar browning patterns when fermented with high carbohydrate levels, due to the production of secondary metabolites that interact with natural pigments (Vilela, 2023). The slight increase in lightness observed at 20% sugar may be related to reduced conversion of sugars into browning compounds or to pigment dilution within the product.

From a commercial perspective, lightness is a crucial sensory attribute, especially for artisanal vinegars, which are distinguished by their visual appeal and perceived quality (Vilela, 2023). Vinegars with higher lightness values are generally more valued, whereas darker products may be associated with defects or a lack of standardization. Thus, the lightness behavior observed in jackfruit vinegar reinforces the need for precise formulation adjustments to meet consumer preferences and market requirements.

The intensity of greenness (−a*) in artisanal jackfruit vinegar exhibited a non-linear behavior as a function of sugar concentration, with an initial reduction up to 10% followed by a slight increase at higher concentrations (Figure 8). This variation may be explained by the influence of Maillard reactions and the degradation of natural pigments during the fermentation process.

Figure 8 – Variation in greenness intensity (−a) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%).



Source: Prepared by the authors (2024).

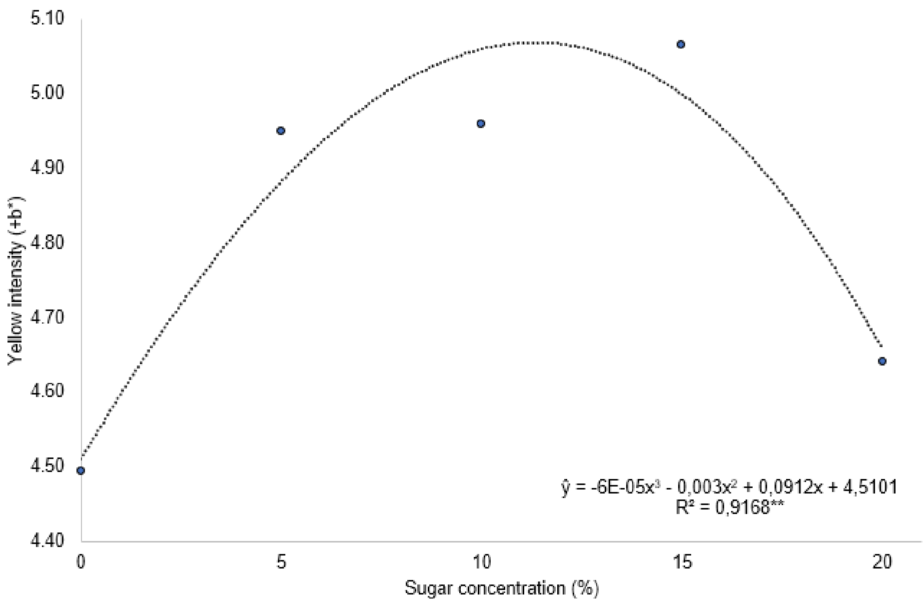
The reduction in greenness intensity at intermediate sugar concentrations may be attributed to the degradation of chlorophylls or related compounds, a phenomenon commonly observed in fruit fermentations, especially under conditions of high microbial activity and complex chemical reactions (Jung *et al.*, 2018). Comparatively, fruit vinegars such as pineapple and apple also exhibit similar changes in (−a*) values, suggesting that both the type of raw material and fermentation conditions have a direct impact on the final hue (Sousa et al., 2020).

The increase in greenness intensity at higher sugar concentrations, as observed from 15% onward, may be associated with the formation of specific phenolic compounds that interact with residual pigments, thereby intensifying the green hue. In addition, reduced oxidative degradation at these levels may contribute to the preservation of visual characteristics associated with green coloration (Dai *et al*., 2024; Vilela, 2023).

From a sensory and commercial standpoint, greenness intensity is a relevant attribute, particularly for consumers who associate more vivid tones with freshness and quality. Therefore, controlling sugar concentration during the fermentation process is essential to balance visual properties and meet market expectations. These results highlight the importance of further studies on the impact of fermentation on bioactive compounds and color parameters in artisanal vinegars.

The yellow intensity (+b*) of artisanal jackfruit vinegar exhibited a parabolic behavior as a function of sugar concentration, with an initial increase reaching a peak around 10%–15%, followed by a subsequent decrease (Figure 9).

Figure 9 – Variation in yellow intensity (+b) of artisanal jackfruit vinegar as a function of different sugar concentrations (0%, 5%, 10%, 15%, and 20%).



Source: the authors.

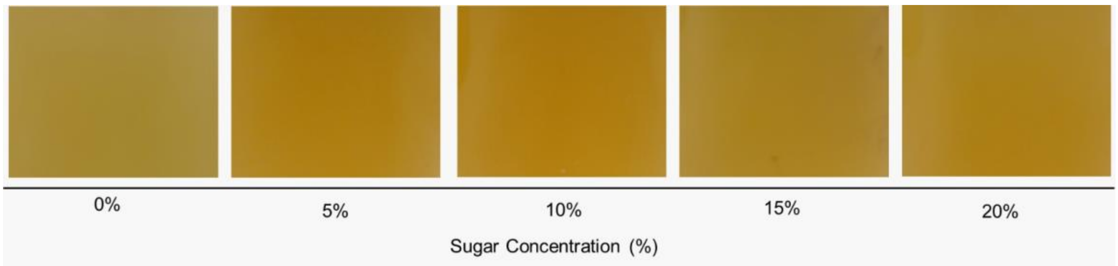
The initial increase may be attributed to chemical reactions such as the Maillard reaction and caramelization, which intensify yellow coloration as phenolic compounds interact with sugars. These reactions are favored at moderate sugar concentrations, particularly during fermentation, when the metabolic activity of yeasts and bacteria promotes the formation of chromophoric pigments. Leonard *et al.* (2021) highlighted that interactions between phenolic compounds and sugars are common in fermented foods, contributing to color development and visual stability. Thus, this intermediate sugar range optimizes microbial activity and the generation of compounds that positively influence coloration.

However, sugar concentrations above 15% appear to cause a reduction in yellow intensity. This effect may be explained by osmotic stress imposed on microorganisms, which reduces metabolic efficiency and, consequently, the formation of compounds of interest. In addition, high sugar concentrations may trigger more intense non-enzymatic browning reactions, masking yellow coloration (Silva *et al*., 2018). These findings indicate that sugar concentrations between 10% and 15% are the most suitable for producing jackfruit vinegar with superior visual quality, highlighting the importance of formulation adjustment to balance sensory attributes and fermentation efficiency.

The color of fermented products, such as vinegar, can be influenced by the concentration and color of the sugar used, by the natural pigments of the raw material (jackfruit pulp), and by compounds formed during fermentation, including melanoidins and other phenolic compounds.

Figure 10 indicates that the visual color of jackfruit vinegar was significantly influenced by the sugar concentration used during the fermentation process. Higher sugar concentrations (15% and 20%) were associated with more intense colors, which may be explained by the higher content of residual solids in the product. These solids may include unfermented sugars and compounds formed during chemical reactions such as caramelization and the Maillard reaction, which intensify color tone and provide greater color depth.

Figure 10 – Visual appearance of the color of artisanal jackfruit vinegar produced with different sugar concentrations (0%, 5%, 10%, 15%, and 20%).



Source: the authors.

Conversely, vinegar produced without sugar addition (0%) exhibited a less intense coloration, closer to the natural tone of the raw material. This behavior is attributed to the limited availability of substrate for chemical reactions, resulting in a product with lower chromatic complexity. Although this lighter color may be perceived as more natural, it can negatively affect consumer sensory perception, as more vibrant colors are often associated with higher quality and product freshness.

In addition, color is a crucial attribute in the commercial acceptance of vinegars, influencing visual attractiveness and market positioning. The ability to adjust color tone through the control of sugar concentration represents a strategic opportunity to enhance product competitiveness and appeal, balancing innovation potential with consumer sensory expectations. However, it is essential to ensure that intensified coloration is aligned with other sensory parameters, such as flavor and aroma, in order to provide a harmonious consumption experience.

4 Conclusion

This study demonstrated that the production of artisanal jackfruit vinegar is feasible, yielding products with attractive physicochemical organoleptic characteristics. Sugar concentration directly influenced the fermentation process and the final quality of the vinegar.

The produced vinegar exhibited suitable pH values and color attributes. In addition, jackfruit proved to be a promising raw material due to its high natural sugar content, enabling the development of an innovative product.

Vinegar produced with 15% sugar showed the best balance between acidity and fermentation efficiency, meeting regulatory standards and exhibiting desirable physicochemical attributes.

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