Tucupi-added mayonnaise: Characterization, sensorial evaluation, and rheological behavior

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ABSTRACT

The aim of this work was to elaborate a tucupi-added mayonnaise and to assess the physicochemical characteristics, as well as the rheological behavior at temperatures from 20°C to 70°C of the product with greater sensorial acceptance. For this purpose, three mayonnaise formulations (10%, 12.5% and 15% of the concentrated tucupi) were developed and submitted to sensorial acceptance and purchase intention tests. Based on the results of acceptance test by Tukey’s test (p ≤ 0.05) and internal preference mapping by principal component analysis (PCA), the formulation with 10% of the tucupi was chosen. The purchase intention test showed that 95% of the judges would buy this product, which presented 41.52% moisture, 2.06% ashes, 43.95% lipids, 4.56% proteins, 3.12% total sugars, 1.51% starch, 1.29% chlorides, 9.40 µg/g β-carotene and energy value of 432 kcal/100 g. According to rheological analysis, the mayonnaise with 10% of the tucupi presented pseudoplastic fluid-like behavior and evidenced hysteresis (showing thixotropic characteristic) between the up-ramp and down-ramp flow curves from 60°C. The Herschel-Bulkley model was efficient in predicting product flow curve and an Arrhenius-like equation estimated activation energy value for the product (8.29 kJ/mol). Thus, the tucupi-added mayonnaise can be considered an excellent and promising alternative for the food industry.

Mayonesa adicionada con tucupí: caracterización, evaluación sensorial y comportamiento reológico

RESUMEN

El presente estudio se propuso elaborar una mayonesa adicionada con tucupí y evaluar las características fisicoquímicas y el comportamiento reológico a temperaturas de 20 a 70°C del producto que obtuviera mayor aceptación sensorial. Con este propósito se elaboraron tres formulaciones de mayonesa (conteniendo 10%, 12.5% y 15% de concentrado de tucupí) y se las sometió a pruebas de aceptación sensorial e intención de compra. A partir de los resultados de la prueba de aceptación, que se llevó a cabo mediante la prueba de Tukey (p ≤ 0.05) y el mapeo de preferencias interno efectuado por análisis de componentes principales (PCA), se eligió la formulación elaborada con 10% de tucupí. La prueba de intención de compra mostró que 95% de los jueces compraría este producto, en el que se identificaron las siguientes características: 41.52% de humedad, 2.06% de cenizas, 43.95% de lipidos, 4.56% de proteínas, 3.12% de azúcares totales, 1.51% de almidón, 1.29% de cloruros, 9.40 µg/G β-caroteno y un valor energético de 432 kcal/100 g. A través del análisis reológico se constató que la mayonesa que contenía 10% de tucupí presentó un comportamiento similar al de un líquido pseudoplástico, además de una histéresis evidente (que muestra la característica tixotrópica) entre las curvas de flujo de la rampa ascendente y la rampa descendente de 60°C. El modelo de Herschel-Bulkley resultó eficiente para predecir la curva de flujo del producto, estimándose el valor de la energía de activación para el producto (8.29 kJ/mol) mediante una ecuación similar a la de Arrhenius. Por lo tanto, la mayonesa adicionada con tucupí puede considerarse una excelente y prometedora alternativa para la industria alimentaria.

1. Introduction

Cassava (Manihot esculenta Crantz) is native to South America and distributed in Southern Amazon (Carvalho et al., 2011; Leotard et al., 2009). Roots are the most important parts of the plant because they are rich in starch, which is widely used in human and animal food and as a raw material in many industries (Demiate & Kotovich, 2011).

Roots are ground and pressed during the cassava flour manufacturing process in order to get its aqueous extract, which is a process byproduct. This extract is called “manipueira” and is used to produce tucupi, which is a product of great commercial importance in Northern Brazil (Carvalho et al., 2018; Chisté, Cohen, & Oliveira, 2007). Industrialized food consumption has been significantly increasing in Brazil since the 1970s. Mayonnaise is among these products and has been calling the attention of the food industry (Salgado, Carrer, & Danieli, 2006). It is a stable oil-in-water emulsion (O/W) prepared from vegetal oils, water, and eggs that must be acidified and can be added with other...
ingredients, which cannot deprive the final product (Ma & Boye, 2013). Studies report some issues related to mayonnaise physical properties and rheological behavior when this product is subjected to different temperature conditions (Håkansson, Chaudhry, & Innings, 2016; Maruyama, Sakashita, Hagura, & Suzuki, 2007).

Fluid food is subjected to several temperature changes throughout processing and storage, and it requires knowing the temperature effects on its rheological properties (Rao, 2014). When temperature increases, the spacing between suspended particles also enlarges due to greater mobility, which favors viscosity decrease. Studies about this effect are usually conducted through the activation energy determination; an Arrhenius-like equation is used in such calculation (Costa, Carmo, Braga, & Pena, 2017; Rao, 2014).

Food rheological behavior can be described by rheological models. Newton model is the simplest one among them, as well as the one used to describe the rheological behavior of Newtonian fluids. However, most fluid food presents non-Newtonian behavior, and this type of product demands more complex models to describe its rheological behavior, such as the Ostwald-de Waele, Bingham Plastic and Herschel-Bulkley models (Holdsworth, 2014; Minim, 2013).

The first study with tucupi just determined the physicochemical properties and the total and free cyanide contents of 10 samples of the product (Chisté et al., 2007). Despite the tucupi being largely consumed in Brazilian Northern Region, where it is used in typical meals, as tacacá, duck in tucupi sauce and Pará’s rice (Santos & Pascoal, 2013), new alternatives of consuming for the product were conducted for the first time by our research team. In these studies, a tucupi creamy paste (Costa et al., 2017), a tucupi powder (Pires & Pena, 2017), a powdered tucupi condiment (Costa, Carmo, & Pena, 2018a) and concentrated tucupi (Costa, Rodrigues, & Pena, 2018b) were developed. Thus, the aim of this study was to elaborate a new-based tucupi product, a tucupi-added mayonnaise, as well as to assess its physicochemical characteristics and the product rheological behavior at different temperatures.

2. Materials and methods

2.1 Raw materials

An unseasoned tucupi was used in the research, which matched the identity and quality standards set for the product (Agência de Defesa Agropecuária do Estado do Pará – ADEPARÁ, 2008). Tucupi sample was provided by a local producer in the municipality of Acrará (latitude 1°57’39’’ S and longitude 48°11’48’’ W) (Pará, Brazil). The following ingredients were used in mayonnaise formulations: corn oil (Bunge, São Paulo, Brazil), mineral water (Indaiá, Belém, Brazil), concentrated tucupi, pasteurized and dried egg powder (Salto’s, Saltos, Brazil), refined sugar (Camil, Sertâozeros, Brazil), refined salt (Unisal, Mossoró, Brazil), cassava starch (Docel, Belém, Brazil), dried garlic powder and dried onion powder (Mariza, Castanhal, Brazil).

2.2 Concentrated tucupi obtaining

Tucupi used in mayonnaise production was concentrated in rotary evaporator (Marconi, MA120/1/E, São Paulo, Brazil), at 70°C under absolute pressure 31.2 kPa (vacuum), until reaching 30% solids concentration (Costa et al., 2018b).

2.3 Mayonnaise development

Formulations used by Mun et al. (2009) and Su, Lien, Lee, and Ho (2010) were adopted to develop the tucupi-added mayonnaise formulation, with modifications. The cassava starch added with water was heated in a water bath for starch gelatinization (first mixture). The dried egg powder was reconstituted with water and homogenized in the mixer for 1 min with concentrated tucupi, salt, sugar, dried garlic powder and dried onion powder (second mixture). Corn oil was slowly added to the second mixture, which was kept under constant homogenization for 3 min in the mixer. The first mixture was also added, and the final mixture was homogenized for 1 min. Three mayonnaise formulations were elaborated, being that each formulation differed only on tucupi and water proportion (Table 1).

2.4 Microbiological evaluation

Coliforms and Salmonella sp. were assessed at 45°C, based on the methodologies described by Downes and Ito (2001). Results were performed according to the parameters set by the Brazilian laws for mayonnaises standards (Brasil, Ministério da Saúde, 2001) and expressed as the most probable number per gram of product (MPN/g).

2.5 Sensory evaluation

The sensorial analysis was approved by the Research Ethics Committee of Federal University of Pará CEP/ICS/UFPA (Protocol no. 1.123.945).

One hundred judges (non-trained volunteers), who affirmed to consume tucupi often, participated in the sensorial analysis. Tests were performed in the Sensorial Analysis Laboratory of UFPA, in individual booths under white light. Each judge received four samples (formulation 1, 2 and 3, and commercial product) in a 50 mL plastic cup with approximately 30 g of the product at room temperature (≈25°C). Brazilian-style French bread was the vehicle, and a disposable cup with water was provided for palate cleaning between tastings. All tests were conducted between 09:00 and 10:30 AM. The samples were randomly labeled with three digital codes and served in

| Ingredients | Formulation |
|-------------|-------------|
| Corn oil    | 40          |
| Mineral water | 36.9    |
| Concentrated tucupi | 10     |
| Dried egg powder | 7    |
| Refined sugar | 3     |
| Refined salt | 1.5  |
| Cassava starch | 1 |
| Dried garlic powder | 0.3 |
| Dried onion powder | 0.3 |

Table 1. Ingredients’ composition (%) used in the tucupi mayonnaise formulations.
a random and balanced way. The samples were offered to judges in a sequential monadic form, along with an evaluation form. Judges’ acceptance grades given to the attribute, samples preference order and product purchase intention were registered in the form. A commercial mayonnaise was used as a control sample to allow the comparison in the sensorial tests (Moraes, 1993).

Acceptance analysis was applied to the tucupi-added mayonnaise formulations and to the control sample. The mixed 9-point hedonic structured scale was used with its extremes fixed at disliked extremely (score 1) and liked extremely (score 9). Attributes such as color, aroma, flavor, texture and overall impression were evaluated at this very order. A ranking test was applied for attribute overall impression, which was statistically analyzed by the Friedman Test. The product purchase intention was evaluated based on the hedonic 5-point scale, which was moored on the extremes “would certainly not buy” (Score 1) and “would certainly buy” (Score 5). The acceptability index (AI) of the assessed attributes is calculated by Equation 1 (Minim, 2013).

\[
\text{AI} \% = \frac{A_m \cdot 100}{B}
\]

where \( A_m \) = mean score obtained for the product and \( B \) = maximum score that the product may be rated (note 9 from the hedonic scale).

Sensorial acceptance data were subjected to principal component analysis (PCA) in order to set the internal preference mapping, which shows graphically the correlation between judges’ acceptance data and the first two principal components and the acceptance dispersion for the formula- tion (Greenhoff & Macfie, 1994; Westad, Hersleth, & Lea, 2004). The internal preference mapping analysis applied to all the assessed attributes was performed with data collected during the acceptance test.

### 2.6 Product characterization

Only the mayonnaise formulation with the best sensorial acceptance was characterized at this stage. Moisture, ashes, lipids and crude protein (6.25 nitrogen-protein conversion factor) analyses were conducted, based on the Association of Official Analytical Chemists (2010). The methodologies recommended by Instituto Adolfo Lutz – IAL (2008) were used for the total sugars, starch, chlorides, and titratable total acidity analyses. Sample pH was measured in digital potentiometer (Hanna Instruments, HI9321, Woonsocket, EUA) and water activity (\( a_W \)) was set in digital thermohygrometer (Decagon, Aqualab Series 4TE, Pullman, EUA) at 25°C. The energy determination was determined according to recommendations by Brasil, Ministério da Saúde (2003).

Carotenoids were extracted with acetone and further extracted with petroleum ether partition, in order to set the total carotenoids. The extract was quantified in a spectrophotometer at 450 nm (\( A_{450} \) cm = 2592 for petroleum ether), based on Rodriguez-Amaya (2001), and the results were expressed in \( \mu g \) of \( \beta \)-carotene/g of product.

Color evaluation was performed by tristimulus colorimetry in digital colorimeter (Konica-Minolta, CR 400, Tokyo, Japan). Equipment operation conditions were: diffuse light/0° visualization angle (including the specular component) and D65 light source. Light parameters (\( L^* = 100 \) white) and chromaticity coordinates (-\( a^* \) = green and +\( a^* \) = red/-\( b^* \) = blue and +\( b^* \) = yellow) were used to set the chroma values (\( C^* \)), which indicates color saturation (0 = neutral color and 60 = intense color); and Hue angle (\( h^* \)), which indicates the basic unit of color (0° and 360° = red, 90° = yellow, 180° = green and 270° = blue) (Smith, 2014). All the analyses were performed in triplicate.

### 2.7 Product rheological analysis

The mayonnaise rheological evaluation recording the best sensorial acceptance was conducted based on Singla, Verma, Ghoshal, and Basu (2013). Measurements were taken in a rheometer (Brookfield, R/S PLUS-SST, Massachusetts, EUA) attached to a thermostatic bath (Lauda Ecoline, RE 200, New Jersey, EUA) and connected to a computer for data collection. The CR ramp method (Control Rate), at shear rate 0–300 s\(^{-1}\) for ascending curve (up ramp), and 300 to 0 s\(^{-1}\) for descending curve (down ramp) was applied. A plate/plate type configuration system was used with spindle A25, with a distance of 1 mm between the plates. The flow curves were obtained at temperature 20–70°C in order to simulate the storage, consumption and thermal treatment conditions for the product. Assays were performed in triplicate.

### 2.8 Rheology mathematical modeling

The fits of the Newton (Equation 2), Bingham (Equation 3), Ostwald-de-Waele (Equation 4) and Herschel-Bulkley (Equation 5) (Steffe, 1996) rheological models were applied to mayonnaise experimental rheological data. Coefficient of determination (\( R^2 \)), reduced chi-squared value (\( \chi^2 \)) and root mean square error (RMSE) were the statistical parameters used to assess the fit efficiency of the models.

\[
\tau = \eta \cdot \gamma
\]

(2)

\[
\tau = \tau_0 + \eta_{pl} \cdot \gamma
\]

(3)

\[
\tau = k \cdot \gamma^n
\]

(4)

\[
\tau = \tau_0 \cdot k \cdot \gamma^n
\]

(5)

where: \( \tau \) = shear stress (Pa), \( \tau_0 \) = yield stress (Pa), \( \gamma \) = shear rate (s\(^{-1}\)), \( \eta \) = viscosity (Pa.s), \( \eta_{pl} \) = plastic viscosity (Pa.s), \( k \) = consistency index (Pa.s\(^n\)) and \( n \) = behavior index.

Apparent viscosity values (\( \eta_a \)) are calculated by Equation 6, replacing the \( \tau \) value by the rheological model which presented the best fit to the experimental data. Temperature effect on \( \eta_a \) was evaluated through the activation energy value (\( E_a \)), which was calculated according to an Arrhenius-like equation (Equation 7) (Rao, 2014), from the slope of the straight line obtained through the linear regression of the ln \( \eta_a \) versus 1/T correlation. The \( \eta_a \) values set for shear rate 100 s\(^{-1}\), for each working temperature, were used in the linear regression.

\[
\eta_a = \frac{\tau}{\gamma}
\]

(6)

\[
\eta_a = A \cdot e^{\frac{E_a}{RT}}
\]

(7)

where: \( \eta \) = viscosity (Pa.s); \( A \) = Arrhenius’ constant (non-dimensional); \( e \) = Napier’s constant; \( E_a \) = activation energy.
(kJ/mol); \( R \) = universal gas constant (8.314 J/mol.K); \( T \) = absolute temperature (K).

### 2.9 Statistical analysis

Tucupi-added mayonnaise sensorial analysis results were subjected to analysis of variance (ANOVA) and to the mean comparison Tukey’s test at 5% significance level. The calculations were conducted in the Statistica for Windows 7.0 software. This software was also used to fit the rheological models to the experimental data by non-linear regression, using the Levenberg-Marquardt algorithm and a convergence criterion of \( 10^{-6} \).

Multivariate statistical analysis was used to apply the internal preference mapping technique based on PCA. It was done in order to find a graphic representation in a single multidimensional space, with differences between product formulation acceptances of each assessed attribute; it identified each individual and its preferences. Procedures in the SAS for Windows 9.0 environment were used in these calculations.

### 3 Results and discussion

#### 3.1 Microbiological analysis

The elaborated products met the microbiological standards set by the Brazilian legislation (Brasil, Ministério da Saúde, 2001) since they presented absence of *Salmonella* sp. and maximal coliform counting 7.4 MPN/g lower than the recommended amount (10 MPN/g).

### 3.2 Sensorial analysis

#### 3.2.1 Acceptance tests and purchase intention

35 men and 65 women, at the age group 17–35 years, participated of the tests. The means of the acceptance test for the assessed attributes, as well as sample acceptability index values (AI) are shown in Table 2. The statistical analysis evidenced that mayonnaise formulations presented significant differences to the commercial one for texture and overall impression attributes. On the other hand, the product with 10% tucupi was statistically similar to the commercial mayonnaise for color, aroma and flavor attributes. Fernandes and Mellado (2018) developed mayonnaises with the replacement of oil or egg yolk by freeze-dried chia mucilage and found means of the acceptance (6.88–8.02), which are in the same magnitude order of the tucupi-added mayonnaise (6.94–7.51).

The sensorial properties of a product are accepted when they reach AI \( \geq 70\% \) (Dutcosky, 2013; Monteiro, Coutinho, & Recine, 2005); thus, although the commercial mayonnaise recorded the highest AI values, all tucupi-added mayonnaise formulations were sensorially accepted. According to the results, the formulation with 15% tucupi was statistically different from the commercial mayonnaise for most of the attributes, which has been attributed to the pronounced acidity of this product, reported by the judges. Kishk and Elsheshetawy (2013) developed a garlic-added mayonnaise and found higher product sensory acceptance due to garlic-concentration increase in the formulation.

The purchase intention test showed that 32% of the judges would certainly buy a tucupi-added mayonnaise, 40% of them would possible buy it, 23% might -or not- buy it, and 5% would possibly not buy it. Thus, 95% of the judges would buying the product, and it evidenced a positive result in this study. Costa et al. (2017) and Costa et al. (2018a) observed very satisfactory results for purchase intention of tucupi creamy paste (99%) and of powdered tucupi condiment (94%).

#### 3.2.2 Internal preference mapping

The internal preference mapping results are shown in Figure 1. Judges’ correlation with at least one of the components (\( |r| \geq 0.50 \)) indicated acceptance differences between mayonnaise formulations. According to Minim (2013), the sum of the two components must reach at least 70% in order to explain the correlation between acceptance data of a certain product. The PCA was capable of explaining all the assessed attributes of the tucupi-added mayonnaise, since the two principal components explained 90.81% of product acceptance variances in attribute color, 88.81% in aroma, 84.14% in flavor, 91.24% in texture and 87.90% in overall impression.

The spatial distribution of attribute color showed that most judges had positive correlation with the first principal component, and it indicates their preference for the commercial mayonnaise and for the formulation with 10% tucupi. With respect to aroma, the mayonnaises added with 10% and 12.5% tucupi were considered similar by the judges. When it comes to flavor, most judges also had positive correlation with the first principal components and considered the flavor of formulations added with 12.5% and 15% tucupi similar.

Texture analysis showed that mayonnaise formulations with 10% and 12.5% tucupi were considered similar by the judges; they preferred the commercial mayonnaise. According to the value presented on the composition table, the commercial

### Table 2. Mean scores of the attributes and of the acceptability index for the formulations with tucupi and for commercial mayonnaise.

| Attributes       | Commerical | 1       | 2       | 3       |
|------------------|------------|---------|---------|---------|
| Color            | 7.51 ± 1.30* | 7.13 ± 1.31ab | 7.03 ± 1.37ab | 6.94 ± 1.70b |
| (83.44 ± 14.43)  | (79.22 ± 14.53) | (78.11 ± 15.27) | (77.11 ± 18.94) |
| Aroma            | 7.18 ± 1.30* | 6.65 ± 1.67a  | 6.59 ± 1.86a  | 6.57 ± 1.78a  |
| (79.78 ± 15.42)  | (73.89 ± 18.51) | (72.32 ± 20.66) | (73.00 ± 19.74) |
| Flavor           | 7.33 ± 1.56* | 6.68 ± 1.99a  | 6.57 ± 2.15a  | 6.47 ± 2.23b  |
| (81.44 ± 17.30)  | (74.22 ± 22.10) | (73.00 ± 23.86) | (71.89 ± 24.79) |
| Texture          | 8.03 ± 0.88b | 7.02 ± 1.68a  | 6.67 ± 1.58a  | 6.57 ± 1.85b  |
| (89.22 ± 9.79)   | (78.00 ± 18.68) | (74.11 ± 17.52) | (73.00 ± 20.61) |
| Overall impression| 7.57 ± 1.25a | 6.94 ± 1.56b  | 6.79 ± 1.64b  | 6.60 ± 1.98b  |
| (84.11 ± 13.88)  | (77.11 ± 17.29) | (75.44 ± 18.23) | (73.33 ± 22.00) |

*Values with the same letters on the line do not significantly differ from each other (\( p < 0.05 \)) in the Tukey’s test.

Los valores con las mismas letras en la fila no diferiran significativamente entre sí (\( p < 0.05 \)) según la prueba de Tukey.
product had approximately 21% lipids in its formulation, whereas the mayonnaise added with 10% tucupi had more than the double of lipids (Table 3). Thus, since it presented lower lipid content, the commercial mayonnaise was more consistent, and it was positively identified by the judges. With regard to overall impression, judges were dispersed in the four quadrants and it evidenced their acceptance to both the commercial and the three tucupi-added mayonnaise formulations.

Overall, the spatial separation in the samples highlights three groups encompassing the four analyzed products. Such behavior shows that tucupi in mayonnaise formulations changed the product sensorial characteristics. The best acceptances to attributes color and overall impression were recorded for the commercial mayonnaise and for the formulation with 10% tucupi, since most judges had positive correlation with the first principal component. Judges were mainly located in the first and fourth quadrants, where the two products are placed in (Figure 1). Based on such results and on the acceptance test, the mayonnaise formulation with 10% tucupi was the one closest to the commercial mayonnaise and it was the formulation selected for the subsequent research stages. Color, aroma and flavor similarity between this formulation and the commercial mayonnaise (Table 2) justified its preference by the judges. The characteristic tucupi flavor was identified in all formulations.

### Table 3. Composition, physicochemical properties and color parameters of mayonnaise with 10% concentrated tucupi.

| Parameters                  | Values       |
|-----------------------------|--------------|
| Moisture (%)                | 41.52 ± 0.76 |
| Ashes (%)                   | 2.06 ± 0.06  |
| Lipids (%)                  | 43.95 ± 1.82 |
| Proteins (%)                | 4.56 ± 0.09  |
| Total sugars (%)            | 3.12 ± 0.21  |
| Starch (%)                  | 1.51 ± 0.10  |
| Chlorides (%)               | 1.29 ± 0.12  |
| Total acidity (mEq NaOH/100 g) | 10.37 ± 0.15 |
| pH                          | 3.79 ± 0.02  |
| a_w                         | 0.98 ± 0.01  |
| Total carotenoids (µg/g)    | 9.40 ± 1.62  |
| Energy value (kcal/100 g)   | 432 ± 21.02  |
| Color                       |              |
| L*                          | 82.90 ± 0.06 |
| a*                          | −5.46 ± 0.14 |
| b*                          | 37.51 ± 1.09 |
| C*                          | 37.44 ± 1.79 |
| h°                          | 98.38 ± 0.09 |

### Figure 1

Figure 1. Judges and tucupi mayonnaise formulations graphic representation for the two principal components regarding color, aroma, flavor, texture and overall impression. Judges (●) and commercial mayonnaise formulation (C), and formulations with 10% (1), 12.5% (2) and 15% (3) concentrated tucupi.

Figura 1. Representación gráfica de las opiniones de los jueces sobre los dos componentes principales de la mayonesa con tucupí en cuanto a color, aroma, sabor, textura e impresión general. Jueces (●) y formulación de mayonesa comercial (C), y formulaciones con 10% (1), 12.5% (2) y 15% (3) de tucupí concentrado.

### 3.3 Mayonnaise characterization

The characterization data of the mayonnaise with 10% tucupi are presented in Table 3. Moisture and lipids content in the product were similar to values reported by Ghazaei, Mizani, Piravi-Vanak, and Alimi (2015), who observed from 41.44% to 45.94% moisture and from 40.32 to 41.45% lipids in the mayonnaise formulations in which egg yolk was partially replaced by modified potato starch. The tucupi-added mayonnaise presented higher protein content than the ones recorded in emulsion-type mayonnaise added with green banana (0.27–0.38%) (Izidoro, Scheer, Negre, Haminiuk, & Sierakowski, 2008) and ashes content similar to mayonnaises with the replacement of egg yolk by freeze-dried chia mucilage (2.01–2.36%) (Fernandes & Mellado, 2018). The energy value of mayonnaise with 10% tucupi was higher than that recorded on the composition table of the commercial mayonnaise (225 kcal/100 g); however, it was lower than results observed by Rahbari, Aalami, Kashaninejad, Maghsoudlou, and Aghdaei (2015) in mayonnaise formulations with low cholesterol content, which were prepared with wheat germ protein isolate (626.94–639.73 kcal/100 g).
The pH of mayonnaise with 10% tucupi complied with the values reported by Jay, Loessner, and Golden (2005) for mayonnaise formulated with vinegar and lemon juice (3.30–3.80). This pH level was assured only by the addition of tucupi, once in the mayonnaise was not added any acidifier. Although the product presented high $a_w$, its pH allows classifying it as high-acidity product ($\text{pH} < 4.0$) (Lehninger, Nelson, & Cox, 2017). Such condition is capable of controlling deterioration processes caused by bacteria. However, fungi can develop in the product even at this pH level, and such outcome suggests the need of adding preservatives to the formulation in order to eliminate the action of these microorganisms (Alzamora, 1994).

According to the color parameters, the mayonnaise with 10% tucupi presented high luminosity, which is typical of products such as mayonnaise, that often present light and whitish color (Karshenas, Goli, & Zamindar, 2018; Worrasinchai, Suphantharika, Pinjai, & Jamnong, 2006). The chromaticity coordinate $a^*$ recorded negative value and it indicated the slight trend to green, whereas the chromaticity coordinate value $b^*$ evidenced yellow, which was attributed to the product by the addition of tucupi, whose characteristic color is yellow. These values have the same magnitude of the ones recorded by Costa et al. (2017) for a tucupi creamy paste ($a^* = -6.58$ and $b^* = 42.33$). Based on the $C^*$ value, the product did not tend to neutral and saturated color, whereas the value for parameter $h^*$ close to $90^\circ$ confirm the prevalence of the yellow color in the product. Fauziah, Zaibunnisa, Osman, and Wan Aida (2016) observed $C^* = 39.42$ and $h^* = 92.03$ in mayonnaises samples produced with different levels of three fat replacers (xanthan, guar and pregelatinized corn starch and egg/soy milk mixture).

Besides the dependence of $\tau$ with $\dot{\gamma}$, fluids presenting pseudoplastic characteristics can be thixotropic when they are time-dependent. In this case, when $\gamma$ values are constant, viscosity decrease with time (Figoni & Shoemaker, 1983; Schramm, 2000). Up-ramp and down-ramp flow curves were not coincident when the fluids were thixotropic, and it triggered the formation of a hysteresis loop (Schramm, 2000). In addition, for thixotropic fluids the down-ramp curve is lower than the up-ramp curve (Van Wazer et al., 1963). Such behavior was observed in tucupi-added mayonnaise at 60°C and 70°C (Figure 3(a,b)).

Table 4 shows statistical parameter values and Newton, Bingham, Ostwald-de-Waele and Herschel-Bulkley model parameters fitted to mayonnaise flow experimental data.

### 3.4 Rheological analysis applied to mayonnaise

Figure 2(a) shows the flow curves of the formulation with 10% tucupi, at temperature range from 20°C to 50°C. Curve slope decreased under such conditions due to shear rate increase ($\dot{\gamma}$); this outcome classifies the product as a non-Newtonian fluid with pseudoplastic fluid characteristics (Van Wazer, Lyons, Kim, & Colwell, 1963). The $\dot{\gamma}$ decrease due to $\gamma$ increase (Figure 2(b)) confirmed the pseudoplastic behavior of the product. Similar behavior was reported by Chivero, Gohtani, Yoshii, and Nakamura (2016) for mayonnaise-like emulsions, developed with hydrocolloid emulsifiers (soy soluble polysaccharide, gum arabic and octenyl succinate starch), as well as by Rahmati, Tehranì, Daneshvar, and Koocheki (2015) for mayonnaises samples produced with different levels of three fat replacers (xanthan, guar and pregelatinized corn starch and egg/soy milk mixture).

![Figure 2](image2.png)

**Figure 2.** Temperature effect on the shear stress (a) and viscosity (b) of mayonnaise with 10% concentrated tucupi. (◊) 20°C, (□) 30°C, (Δ) 40°C and (○) 50°C.

![Figure 3](image3.png)

**Figure 3.** Temperature effect on the shear stress (a) and viscosity (b) of mayonnaise with 10% concentrated tucupi, highlighting the hysteresis. (◊) Up-ramp and (□) down-ramp at 60°C; (♦) up-ramp and (●) down-ramp at 70°C.
The means values of the flow curves (up-ramp and down-ramp) were presented up to 50°C, since hysteresis was not observed at these temperature levels. However, the up-ramp and down-ramp curve values were individually presented at 60°C and 70°C, once hysteresis was evident at these temperatures. Costa et al. (2017) did not observe the hysteresis effect between the up-ramp and down-ramp curves of a tucupi creamy paste at temperature range from 25°C to 60°C. The hysteresis phenomenon observed in mayonnaise was attributed to emulsion stability loss caused by changes in emulsifier solubility due to temperature increase (Guilmineau & Kulozik, 2007). This phenomenon was observed by Frange and Garcia (2009) in olive oil/water emulsification at 50°C.

Based on the parameters used to assess the quality of the fits, the Newton model was the only one not capable of predicting mayonnaise flow curves under most of the assessed conditions. This outcome was justified by the non-Newtonian behavior of the product (Steffe, 1996). The Bingham and Ostwald-de-Waele models presented good fits under most conditions, but the Herschel-Bulkley model was the only one capable of predicting product flow curves with extreme precision within the experimental domain (Su et al., 2010). This model was also the best to describe the flow curves of mayonnaises with and without eggs (Singla et al., 2013), as well as of a low-fat mayonnaise, due to the addition of modified wheat bran (Aslanzadeh, Mizani, Alimi, & Gerami, 2012), and of a mayonnaise with the replacement of egg yolk by sesame–peanut defatted meal milk (Karschens et al., 2018).

Based on parameters of the Herschel-Bulkley model (Table 4), the product needed initial stress (τ0) at 20–70°C to start flowing, which is evident in the flow curves shown in Figures 2(a) and 3(a). The τ0 value, which is known as the apparent elasticity limit, is an important parameter to compare the global characteristics of products manufactured in different production lines (Haminik, Sierakowski, Vidal, & Masson, 2006). Temperature raise led to τ0 value drop until 50°C. This decrease happened due to temperature increase, which made the product structure more susceptible to deformation (Haminiuk et al., 2006). However, the τ0 raise to the up-ramp to 60°C and 70°C suggested that temperature increase promoted considerable change in the initial structural organization of the product, which was reset at down-ramp, besides contributing to hysteresis loop non-closing (Figure 3(a)).

Behavior index values (n) of the Herschel-Bulkley model confirmed the pseudoplastic behavior of the product (n < 1), except at 70°C, and of the down-ramp curve at 60°C, which recorded n > 1. Although these values were characteristic of dilatant fluids, such behavior was not observed in viscosity curves (Figure 3(b)). According to Krokida, Maroulis, and Saravacos (2001), it is common to have n recording slight increase at high temperatures. The consistency index (k) decreased from 50°C and it evidenced a more significant product viscosity reduction from this temperature due to emulsion-stability loss (Costa et al., 2017; Guilmineau & Kulozik, 2007; Haminiuk et al., 2006).

There was good (R² > 0.97) fit between the calculated ηa by the Herschel-Bulkley model (for γ = 100 s⁻¹) and the inverse temperature described by Equation 7. Thus, the slope of the line was used to calculate the Ea value necessary for the flow of the 10% tucupi mayonnaise, which was of 8.29 kJ/mol. According to Krokida et al. (2001), non-Newtonian fluids, such as mayonnaise, present low Ea values, and this outcome indicates little dependence between temperature and viscosity. The Ea value set for the product was close to the values set by Juszczak,>Oczadłowski, and Galkowska (2013) for the six catchup samples developed with different modified starch types (4.2–9.0 kJ/mol). Seesung, Thongngam, and Klinkesorn (2016) observed Ea value higher to that recorded for cholesterol-free mayonnaise containing red palm olein (15.79 kJ/mol).

4 Conclusion

Mayonnaise formulations added with 10% to 15% concentrated tucupi (30% solids) presented satisfactory acceptability indexes (> 70%) and excellent purchase intention values,

| Table 4. Values of the modeling parameters to rheological data collected from mayonnaise with 10% concentrated tucupi. |

| Model          | Parameter | 20°C | 30°C | 40°C | 50°C | 60°C | 70°C |
|----------------|-----------|------|------|------|------|------|------|
| Newton         | η (Pa.s)  | 1.15 | 1.12 | 1.07 | 0.95 | 0.81 | 0.64 |
|                | η R²      | 0.756| 0.774| 0.759| 0.871| <0.100| 0.994|<0.100|<0.100|0.996|
|                | RMSE      | 1.143| 10.94| 10.66| 7.89 | 13.43| 1.66 |
| Bingham        | τ₀ (Pa)   | 86.24| 82.52| 80.01| 59.10| 101.97| 4.31 |
|                | η R²      | 0.74 | 0.72 | 0.68 | 0.67 | 0.31 | 0.62 |
|                | RMSE      | 1.15 | 0.992| 0.992| 0.987| 0.992| 0.981| 0.989|
| Ostwald-de-Waele| k (Pa s⁻¹) | 16.52| 15.32| 15.20| 9.20 | 41.37| 0.60 |
|                | n         | 0.53 | 0.51 | 0.51 | 0.58 | 0.26 | 1.01 |
|                | R²        | 0.995| 0.995| 0.997| 0.996| 0.954| 0.988|
|                | RMSE      | 1.26 | 1.26 | 0.94 | 1.02 | 1.70 | 1.73 |
| Herschel-Bulkley| τ₀ (Pa)   | 52.24| 48.15| 36.04| 30.42| 92.89| 24.35|
|                | k (Pa s⁻¹) | 4.09 | 4.18 | 5.97 | 3.39 | 1.04 | 0.06 |
|                | n         | 0.72 | 0.71 | 0.65 | 0.73 | 0.80 | 1.39 |
|                | R²        | 0.999| 0.999| 0.999| 0.999| 0.984| 0.999|
|                | RMSE      | 0.23 | 0.26 | 0.42 | 0.50 | 0.10 | 0.40 |

The results of the model parameters at 20°C, 30°C, 40°C, 50°C, 60°C, and 70°C are represented in Table 4. The parameters are presented for the up-ramp and down-ramp curves. The RMSE values are calculated for each temperature level. The results show that the Herschel-Bulkley model is the best model to describe the flow curves of mayonnaise with 10% tucupi.
but PCA and judges’ observations showed that the product with 10% tucupi was the formulation preferred. This product presented 41.52% moisture, 2.06% ashes, 43.95% lipids, 4.56% proteins, 4.63% carbohydrates, 9.40 µg/g ß-carotene and energy value of 432 kcal/100 g. The obtained mayonnaise presented a non-Newtonian fluid behavior, with pseudoplastic characteristics. The Herschel-Bulkley model was capable of predicting the product flow curve with extreme precision. The temperature effect on the product’s η vs was described by an Arrhenius-like equation, which showed E* of 8.29 kJ/mol for the product. Thus, the mayonnaise with 10% tucupi becomes another new alternative for the tucupi industrial use.

Disclosure statement
The authors have no conflict of interest.

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