Annals of Clinical and Medical
Case Reports

Research Article ISSN 2639-8109 |Volume 14

Rheological Characterization of Prickly Pear Juice (Opuntia Ficus Indica)

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Received: 03 Oct 2024
Accepted: 03 Nov 2024
Published: 07 Nov 2024
J Short Name: ACMCR

Citation:

Mori H, Rheological Characterization of Prickly Pear Juice (Opuntia Ficus Indica). Ann Clin Med Case Rep. 2024; V14(9): 1-8

Keywords:

Tuna juice; Consistency and flow indices; Rheological models; Yield point

1. Summary

The quality factors of tuna juice (Opuntia ficus indica) flow index, consistency index and creep index, were important in the rheological characterization and acceptance of this food; reducing the difficulties for technologies of this product. The objectives were to rheologically characterize the tuna juice, determine the flow index, creep threshold, consistency index (K)and Pearson's regression coefficients (r) and determination (r^2×100) for a temperature of 20 °C and concentrations of 5, 15, 25 and 40 °Brix. The methodology was based on the rheology of tuna juice in its natural state, red-violet variety, mixed with 25% cold boiled water (w/w), with a pH of 3.64 and acidity of 0.85%. Measurements were performed in a concentric cylinder viscometer, using a thermostatic bath for temperature control with a range of 0.5 °C, from 15 °C to 70 °C, obtaining the shear stress (τ) corresponding to the deformation gradients (γ). To determine the yield threshold (τ_0) d, the Herschel Buckley $\tau=K(\gamma)^{n}+$τ_0rheological model ( ) The procedure was carried out according to the theory of Bronshtein & Semendiaev (2018). The flow rate (n) and the yield point (τ_0) for tuna juice, for concentrations of 5, 15, 25 and 40° Brix were 0.5826; 0.7302; 0.7901 and 0.8611; and 58.0935; 65.2047; 73.3424 and 94.2155; respectively, being progressive and directly proportional to the concentrations; concluding that the consistency index decreases and grows in the range of working concentrations, the yield threshold and flow index are increasing and the regression coefficients (r) and determination (r^2×100) show a perfect correlation between the shear stress (τ) and the deformation gradient (γ).

2. Abstract

The quality factors of prickly pear juice (Opuntia ficus indica), flow index, consistency index and creep index, were important in the rheological characterization and acceptance of said food, reducing the difficulties for technologies of this product. The objectives were to rheologically characterize the prickly pear juice, determine the flow rate, the creep threshold, the consistency index (K) and the Pearson regression coefficients (r) and determination (r^2×100) for temperature of 20 °C and concentrations of 5, 15, 25 and 40 °Brix. The methodology was based on the rheology of prickly pear juice in its natural state, red-violet variety, mixed with 25% cold boiled water (w/w), with a pH of 3.64 and acidity of 0.85%. The measurements were carried out in a concentric cylinder viscometer, using a thermostatic bath for temperature control with an interval of 0.5 °C, from 15 °C to 70 °C, obtaining the shear stress (τ) corresponding to the deformation gradients. (γ). To determine the creep threshold (τ_0) of the Herschel Buckley rheological model ($\tau=K(\gamma)^n+\tau\_0$), we proceeded according to the theory of Bronshtein & Semendiaev (2018). The flow index (n) and the creep threshold (τ_0) for prickly pear juice, for concentrations of 5, 15, 25 and 40° Brix were 0.5826; 0.7302; 0.7901 and 0.8611; and 58.0935; 65.2047; 73.3424 and 94.2155; respectively, proving to be progressive and directly proportional to the concentrations; concluding that the consistency index decreases and increases in the range of working concentrations, the creep threshold and flow index are increasing and the regression coefficients (r) and determination ($r^2\times100$) show a perfect correlation between the shear stress (τ) and the strain gradient (γ).

3. Introduction

The difficulties in terms of quantity and quality in the production of fruit juices are the rheological parameters of different liquid foods and in the juice of tuna (Opuntia ficus-indica) were flow index, consistency index and creep index; which contributed in quality and acceptance, contributing to the rheological classification before, during and after the control, transformation and conservation processes of fluid foods. (Matos-Chamorro and Aguilar-Alata, 2010) Fruit juice is added to the concentrate of the same fruit that has undergone a depectinization process, a subsequent clarification and a concentration by evaporation. (Ibarz, et al., 2008) Ayala (2008) mentions that the functional properties of fruits and stalks, together with their juices, are beneficial for health and with these nutritional characteristics, fiber, hydrocolloids, pigments, calcium, potassium and vitamin C stand out, which have antioxidant properties, very important compounds for a healthy diet. Costell and Durán (2012) and Alva de la Torre (2016) mention that fruit juices have very variable rheological behavior and are of great importance in technological processes. Prickly pear fruits have pH values of 5.2; soluble solids of 13.1 °Brix and acidity of 0.085%; while aguaymanto fruits have pH values of 3.6; soluble solids of 14.1° Brix and acidity of 1.49%. (Méndez-Sanchez et al., 2017). Alva de la Torre (2016) and Flores (2008) indicate that rheology is the study of the deformation and flow of unprocessed raw materials, intermediate and semi-finished products, and finished products. Alva de la Torre (2016) and Whorlow (2002) mention that the plastic product corresponds to the Bingham model, where for certain practical purposes plastic materials are differentiated from liquids in that they do not flow when only the force of gravity acts on them. Matos-Chamorro and Aguilar-Alata (2010) mention that the fruit of the prickly pear (Opuntia ficus indica) is ovoid and native to Peru, Bolivia and Mexico; growing in various climates from sea level to 3 thousand meters, cultivated in mountains and coast at temperatures between 12 and 34 °C. (Santander-M et al., 2017) liquid foods , such as juices, smoothies and concentrates, describe different rheological models, since each of them behaves differently due to its chemical composition and proximate composition. (Alva de la Torre, 2016; Wrusch, 2015) Cheftel et al. (2015), argue that the yield threshold is the one evaluated to measure, evaluate and rheologically model liquid and pseudoplastic foods.

To obtain adequate rheological characteristics of the finished product, in the final production process of the tuna juice, concentrated tuna juice is added that has undergone a process of depectinization, clarification and finally a concentration by evaporation. (Alva de la Torre, 2016; Sherman, 2013) Alva de la Torre (2016) mentions that one of the first tasks performed in the study of the rheological properties of fluid foods is to determine the rheological model that best represents a set of experimental data on shear stress (τ) and strain gradient (γ). Kokini (2012) mention that one of the most commonly used models, of general application to fit experimental data and quantitatively express the flow behavior of time-independent inelastic fluids is the model proposed by Herschel Buckley, given by the expression: $\tau=K(\gamma)^n+\tau\_0$

Where

τ: shear stress [Pa.s].

τ_0: yield threshold [Pa.s].

K: consistency index

γ: deformation rate [s $^{(-1)]}$

The juices of most fruits are highly coveted by the inhabitants of cities in any country, due to their exquisite taste in which the rheological behavior of the prickly pear juice (Opuntia ficus indica) has a valuable help in the acceptance, control, improvement of the processes and in the design and manufacture of the different equipment with which the prickly pear juice will be treated; reducing technological problems.

4. Theoretical Framework

If a material deforms but does not flow when a stress is applied, it is a solid; if the material flows when a very small stress is applied (in mathematical terms: a stress differential), then it is a fluid. (Abdullah et al., 2020). The rheological properties of a food are closely related to its quality and acceptance by the consumer and the determination of the effect of concentration and temperature on the rheological properties is essential to perform calculations related to the flow of non-Newtonian fluids with simultaneous heat transfer that takes place in the processing of fluid foods and in particular in the concentration and sterilization processes of tomato paste (Solanum lycopersicon). (Barreiro et al.,2016). The minerals present in prickly pear (Opuntia ficus indica) are potassium, phosphorus and magnesium; it is highly recommended for people who care about their appearance because it has a very low caloric intake; it also provides a great contribution of fiber, ideal for people with constipation. (García, 2016). Barboza-Mejía et al. (2022) mention that viscosity varies considerably when changing temperature and that they have an inversely proportional relationship and that rheological models and measurements have unpredictable and very varied changes. Rheology is defined as the science of flow that studies the deformation of a body subjected to external stresses and its study is essential in many industries including plastics, paints, food, printing inks, detergents and lubricating oils; which can be reached in a formal definition of the term rheology: part of mechanics that studies the elasticity, plasticity and viscosity of matter. (Bird, et al ., 2018).Chen and Wu (2020) identified that increasing the concentration of soluble solids in Newtonian juices significantly increases the viscosity, affecting product stability and sensory acceptance; highlighting the importance of maintaining strict control over concentration levels during processing and ensuring product consistency. Andia (2019) mentions that creep is a phenomenon that describes the slow and continuous deformation of a material under a constant load over time, which occurs in solid and liquid foods when they are subjected to a stress that remains constant for a prolonged period and is especially relevant in foods that can be deformed, where the deformation rate changes over time.

4.1. Flow Rate: The flow of food fluids is the continuous movement, as time passes and the fundamentals of fluid flow are a diversity of disciplines, which we begin with the most appropriate language, where the volumetric flow or fluid flow rate is the volume of fluid that passes through a given surface in a given time and the fluid flow is the movement of a fluid subjected to different unbalanced forces; correspondingly, a part of fluid mechanics and fluid flow deals with fluid dynamics. (Barboza-Mejía and Velásquez-Barreto; 2022)

4.2. Consistency Index: It refers to the thickness of a liquid, where liquids that are thickened may be referred to as slightly thick, medium thick, or moderately thick, in which viscosity (dynamic) in fluids is determined to describe the consistency of fluids and viscosity is defined as the frictional resistance developed by a fluid subjected to shear or compression stress through deformation (Chen and Wu, 2020).

4.3. Yield Threshold: The yield strength is an indication of the maximum tensile strength that can be developed in a material without causing plastic deformation and the yield point, or yield strength, is the point on a stress-strain curve where elastic behavior ends and plastic behavior begins; therefore, yield describes the beginning of the breaking down of fibers in the sample being tested. (Chen and Wu, 2020)

5. Method

The study is based on fruit juices in their natural state (without the addition of thickeners, clarifiers or other inputs). Prickly pear juice (Opuntia ficus indica) has been chosen because it is a seasonal fruit and a fruit resource that is in demand every day and is becoming more and more interesting to society, even more so because it offers nutritional and healthy characteristics in liquid form. The spatial scope is defined by the technological forms in which prickly pear juice can be processed and in the temporal scope by the seasonality of the raw material, which could be a problem to be solved by means of sustainable technology.

Universe and study sample. The juice of the red-violet variety prickly pear (Opuntia ficus indica) has been considered. The tuna fruit was received, washed, classified (manually by color), peeled and seeded in a stainless-steel container. The seeded tuna pulp was mixed with 25% cold boiled water (w/w) and was liquefied; obtaining the tuna juice that was depeptidized. Suspended particles were removed from the depeptidized tuna juice, with the sole purpose of obtaining a clarified and homogeneous tuna juice; the sample was not greater than one liter or less than 0.25 liters.

5.1. Instruments used: The soluble solids content of the prickly pear juice was determined using an ABBE-ZEISS refractometer at a temperature of 20 °C; the pH of the prickly pear juice concentrate was determined using a pH meter, resulting in a pH of 3.64 at 20 °C. Its acidity was assessed by titration with NaOH solution until the phenolphthalein change, on a diluted solution of the prickly pear juice, reaching an acidity of 0.85%.

5.2. Materials and Packaging: Thermometer, stopwatch, 125 ml, 250 ml Erlenmeyer flask, 100 ml, 250 ml beakers, 10, 25, 50, 100 ml flasks, funnels, digital thermometer, stainless steel tables, fan with source, 10 L couler, piscetarian, stopwatch, 10-20 kg plastic crates, plastic containers, others that mention the procedures of the techniques and according to the tests and notebook of notes. All rheological measurements were carried out with a Roto visco RV 12 concentric cylinder viscometer (Hooke); its characteristics are described in a work by Andia (2019). Once the values of the deformation gradients corresponding to the different values of the shear stresses have been obtained, the appropriate fluidity curve can be constructed, from which it is possible to find the equation that describes the rheological behavior of the fluid used. (Barreiro et al., 2016)

5.3. The Analysis Unit: The previously treated prickly pear juice (Opuntia ficus indica) was divided into two portions of 0.5 liters each. The first was taken as a standard or auxiliary sample. The second sample was used to be subjected to different temperature and concentration conditions, used on this occasion. It should be noted that the temperature and concentrations used were: 20°C and 5, 15, 25 and 40° Brix, respectively.

5.4. Data Collection Techniques: Shear stress data (τ) versus strain gradient (γ) were read directly from the equipment used. The observed and collected data were tabulated, plotted and graphed, describing the behavior of the tuna juice, subjected to various process conditions.

5.5. Procedure: All rheological measurements were performed with a rotavis concentric cylinder viscometer or a concentric cylinder viscometer. For this process it was necessary to use a thermostatic bath that allowed temperature control within a range of 0.5°C, from 15°C to 70 C. After obtaining the values of the deformation gradients, corresponding to the different values of the shear stresses; they were graphed to obtain the respective rheograms, through which it was possible to characterize the tuna juice and determine the rheological model. Eirini et al., (2018) mention that rheological models can be used for the rheological characterization of fluid products and all kinds of foods, and can be performed and done with mathematical models that express, with an equation, the relationship between the shear stress (τ) and the velocity gradient (γ).

Rheological Model: The rheological model that came closest to the study was that of Herschel Buckley, given by the expression: $\tau=K(\gamma)^n+$τ_0

Where

τ: Shear stress [Pa.s].

τ_0: Yield threshold [Pa.s].

K: Consistency index

γ: Deformation rate [s $^{(-1)]}$

n: Flow rate

To determine the rheological model we have applied the procedure indicated by Bronshtein & Semendiaev (2018): 1) The way to calculate the yield threshold (τ_0) is by considering three random independent values and their corresponding values dependent on the database and using the relationship: $\tau_0=(A\times B-I^2)/(A+B-2I)$; 2) The first value (A) is the value of the dependent variable, which corresponds to the first value of the independent variable (γ_1); the second value (B) will be the value of the dependent variable that corresponds to the last data of the independent variable (γ_2)and the third value (I), is the value of the dependent variable that corresponds to the geometric mean of the independent variables $\gamma_1$and γ_2: $\gamma_3=\sqrt{(\gamma_1\times\gamma_2)}$; 3) If the value of I, corresponding to γ_3, is not in the table; it must be interpolated by the Lagrange method with four points, considering two points before and two points after the value of γ_3; 4) The value of τ_0 It is replaced in the Herschel Buckley rheological model : $\tau=K(\gamma)^n+\tau_0$; 5) The Herschel Buckley rheological model is mathematically linearized, to which the least squares method (MMC) is applied, adopting the form: $\ln(\tau-\tau_0)=\ln K+n\times\ln\gamma$; which is a linear equation of the form: $y=A+Cx$; where: $y=\ln(\tau-\tau_0)$, $x=\ln\gamma$and $A=\ln K$; 6) The statistical process of linear regression can be performed on a computer or scientific calculator, entering the ordered pairs (x,y)in the form: $[\ln\gamma ,\ln(\tau-\tau_0)]$; 7) Once all the ordered pairs have been entered, the values of lnK and n, and 8) The value of nis the value of the slope of the linear equation; that is, the value of " C" of the linear equation $y=A+Cx$; the value of Ais lnKand, therefore $K=e^A$, and from the same regression analysis we evaluate the correlation coefficient, the rPearson's coefficient of determination ($r^2\times100$); thus determining the Herschel Buckley rheological model .

6. Results

After obtaining the juice of prickly pear (Opuntia ficus indica), partially depectinized and standardizing its concentrations (5, 15, 25 and 40 °Brix), the rheological tests were carried out in a rheometer or viscometer of concentric cylinders of rota visco at a temperature of 20 °C. Prior to the rheological tests of the depectinized juice of prickly pear (Opuntia ficus indica), the equipment was calibrated with sugar water at a concentration of 5%, which reported viscosity values very close to those reported by the bibliography. By virtue of that some preliminary tests were carried out, in which the deformation $\gamma(s^{-1})$) and shear stress data were measured τ (Pa), the same ones that are shown in tables 1, 2, 3 and 4 and their behavior in figures 1, 2, 3 and 4; respectively.

Obtaining rheological models and statistical coefficients

Calculation of creep factor ($\tau_0=(A\times B-I^2)/(A+B-2I)$), consistency index (K), flow index, (n)Pearson $r^2\times100$regression coefficient ( ) and coefficient of determination (r)

For temperature T=20 °Cand concentration of C=5 °Brix

$\gamma_1=410{,}21$; A=90,54

$\gamma_2=26\ 201{,}64$; B=610,89

$\gamma_3=\sqrt{(410{,}21\times26\ 201{,}64)}=3\ 278{,}44$

For this value of $\gamma_3=3\ 278{,}44$; we obtain (by Lagrange interpolation): I=192,02. Replacing the corresponding values; we have:

$\tau_0=(90{,}54\times610{,}89-192{,}02^2)/(60{,}54+610{,}89-2(192{,}02))=58{,}0935$

The value of τ_0is replaced in the rheological model: $\tau=K(\gamma)^n+58{,}0935$, it is linearized $\ln(\tau-58{,}0935)=\ln K+n\times\ln\gamma$and linear regression is performed; obtaining the values of K=1,3742; n=0,5826; r=0,9883 and $r^2\times100=97{,}67$ %; determining from the Herschel Buckley rheological model: $\tau=1{,}3742(\gamma)^{(0{,}5826)}+58{,}0935$

For temperature T=20 °Cand concentration of C=15 °Brix

$\gamma_1=408{,}71$; A=111,75

$\gamma_2=26\ 204{,}05$; B=1 043,78

$\gamma_3=\sqrt{(408{,}71\times26\ 204{,}05)}=3\ 272{,}5218$

For this value of $\gamma_3=3\ 272{,}5218$; we obtain (by Lagrange interpolation): I=278,6246. Replacing the corresponding values; we have:

$\tau_0=(111{,}75\times1043{,}78-278{,}6246^2)/(111{,}75+1043{,}78-2(278{,}6246))=65{,}2047$

The value of τ_0is replaced in the rheological model:

τ=K(γ)^n+65,2047, it is linearized ln(τ-65,2047)=lnK+n×lnγand linear regression is performed; obtaining the values of K=0,5776; n=0,7302; r=1,00and r^2×100=100,00 %; determining from the Herschel Buckley rheological model: $\tau=0{,}5776(\gamma)^{(0,7302)}+65{,}2047$

For temperature T=20 °Cand concentration ofC=25 °Brix

γ_1=412,28; A=159,62

γ_2=26 210,21; B=2 363,22

γ_3=√(412,28×26 210,21)=3 287,2398

For this value of γ_3=3 287,2398; we obtain (by Lagrange interpolation): I=517,8254. Replacing the corresponding values; we have:

τ_0=(159,62×2 363,22-517,8254^2)/(159,62+2 363,22-2(517,8254))=73,3424

The value of τ_0is replaced in the rheological model: τ=K(γ)^n+73,3424, it is linearized ln(τ-73,3424)=lnK+n×lnγand linear regression is performed; obtaining the values of K=0,7401; n=0,7901; r=1,00 and r^2×100=100,00 %; determining from the Herschel Buckley rheological model: $\tau=0{,}7401(\gamma)^{(0,7901)}+73{,}3424$

For temperature T=20 °Cand concentration of C=40 °Brix

γ_1=411,55; A=249,30

γ_2=26 208,02; B=5 632,12

γ_3=√(411,55×26 208,02)=3 284,1910

For this value of γ_3=3 284,1910; we obtain (by Lagrange interpolation): I=1 020,9534. Replacing the corresponding values; we have:

τ_0=(249,30×5 632,121 020,9534^2)/(249,30+5 632,12-2(1 020,9534))=94,2155

The value of τ_0 is replaced in the rheological model: τ=K(γ)^n+94,2155, it is linearized ln(τ-94,2155)=lnK+n×lnγand linear regression is performed; obtaining the values of K=0,8700; n=0,8611; r=1,00and r^2×100=100,00 %; determining from the Herschel Buckley rheological model: $\tau=0{,}8700(\gamma)^{(0,8611)}+94{,}2155$.

Table 1: Rheological data of prickly pear juice (Opuntia ficus indica) at a concentration of 5 °Brix

γ(1⁄s)	τ(Pa)
410.21	90.54
1970.04	151.91
3450.32	196.72
4970.84	234.7
8020.62	303.27
11150.72	365.47
14172.84	419.62
17419.24	475.66
20405.32	523.53
23374.42	569.16
24782.64	590.25
26201.64	610.89

Table 2: Rheological data of prickly pear juice (Opuntia ficus indica) at a concentration of 15 °Brix

γ(1⁄s)	τ(Pa)
408.71	111.75
197 6.74	212.72
3452.55	287
4968.92	354.5
8019.62	475.62
11148.55	589.12
14122.04	684.13
17421.15	780.45
20398.92	872.13
23371.33	958.42
24779.57	1002.41
26204.05	1043.78

Table 3: Rheological data of prickly pear juice (Opuntia ficus indica) at a concentration of 25 °Brix .

γ(1⁄s)	τ(Pa)
412.28	159.62
1976404	370.62
3453.45	535.27
4975.84	689.6
8023.12	972.31
11154.48	1239.01
14174.23	1482.52
17425.11	1734.18
20412.23	1956.42
23372.35	2175.23
2478 0.45	2262.13
26210.21	2363.22

Table 4: Rheological data of prickly pear juice (Opuntia ficus indica) at a concentration of 40 °Brix .

γ(1⁄s)	τ(Pa)
411.55	249.3
1969.54	692.15
3449.23	1060.82
4977.89	1423.6
8022.36	2094.76
11149.89	2754.32
14177.56	3365.76
17424.01	4000.76
20411.12	4570.3
23375.12	5123.1
24784.56	5383.7
26208.02	5632.12

Table 5: Rheological and statistical parameters of the models obtained for tuna juice at a temperature of 20°C.

°Brix	Yield threshold (T0)	Consistency index (K)	Flow rate (n)	Regression coefficient (r)	Coefficient of determination (r2 × 100)
5	5,80,935	13,742	0.5826	0,9883	97,67
15	6,52,047	0.5776	0.7302	10,000	100,00
25	7,33,424	0.7401	0.7901	10,000	100,00
40	9,42,155	0.87	0.8611	10,000	100,00

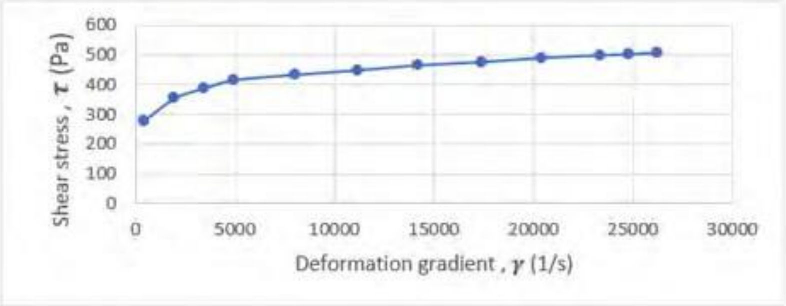

Figure 1: Shear stress behavior (τ) vs deformation gradient (γ) of prickly pear juice (Opuntia ficus indica) at a concentration of 5 °Brix.

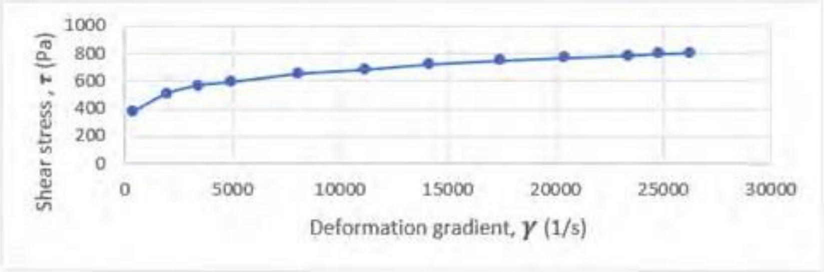

Figure 2: Shear stress behavior (τ) vs deformation gradient (γ) of prickly pear juice (Opuntia ficus indica) at a concentration of 15 °Brix

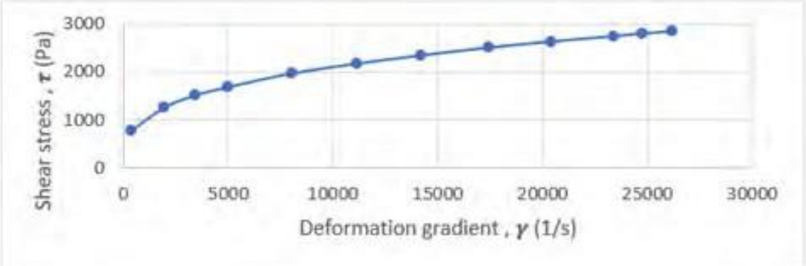

Figure 3: Shear stress behavior (τ) vs deformation gradient (γ) of prickly pear juice (Opuntia ficus indica) at a concentration of 25 °Brix

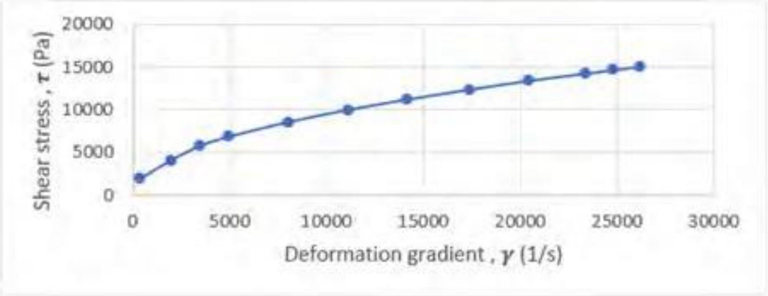

Figure 4: Shear stress behavior (τ) vs deformation gradient (γ) of prickly pear juice (Opuntia ficus indica) at a concentration of 40 °Brix

7. Discussion

Prickly pear juice (Opuntia ficus indica) showed variable rheological behavior, of great importance in food engineering processes and presenting greater importance in human consumption due to its qualities; coinciding with what was reported by Costell and Durán (2012) and Alva de la Torre (2016). The interest in consuming prickly pear juice is increasing due to the need to satisfy nutritional and protein requirements and provide relevant benefits for the health of the population of any social stratum, race and condition; coinciding with what was reported by Santander-M et al., (2017). The Herschel Buckley model was found to be ideal for adjusting the experimental data, in the rheological characterization of prickly pear juice and quantitatively expressing the flow behavior of prickly pear juice, behaving as a fluid food, inelastic and independent of time; coinciding with what was mentioned by Kokini (2012). The determination of the effect of temperature on the rheological properties of tuna juice is essential to carry out calculations related to the flow of non-Newtonian fluids using the flow index (n), whose values for concentrations of 5, 15, 25 and 40° Brix were 0.5826; 0.7302; 0.7901 and 0.8611; respectively, coinciding with what was mentioned by Barreiro et al., (2016). The flow index in tuna juice turned out to be progressively increasing and directly proportional to the concentration, coinciding with what was mentioned by Barboza-Mejía and Velásquez-Barreto (2022). The yield threshold () τ_0) was found to be directly proportional to concentrations of 5, 15, 25 and 40 ° Brix, which were determined to be 58.0935; 65.2047; 73.3424 and 94.2155; respectively, coinciding with that proposed by Chen and Wu (2020). It is concluded that the consistency index of tuna juice decreases and grows in the concentration range worked, that the yield threshold and flow index are increasing and that the regression coefficients (r) and determination ($r^2 \times 100$) show a perfect correlation between the shear stress (τ) and the deformation gradient (γ). It is recommended to carry out the study at other concentrations of tuna juices, use the temperature up to 0.5 ° C, use other types of equipment to determine more parameters than those found on this occasion and with juices from other fruits that provide other structural components. Carry out more frequent measurements in temperature intervals to obtain a more detailed profile of how the patterns change rheological with temperature and concentration; in which the accuracy of mathematical modeling and the prediction of the behavior of tuna juice can be improved.

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