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Rheological behavior and thermal sensitivity of depectinized passion fruit nectar (*Passiflora ligularis*)

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Abstract: Understanding the thermo-rheological properties of fruit-based beverages is critical for optimizing their industrial processing, stability, and sensory quality. This study evaluates the viscosity and flow behavior of depectinized passion fruit nectar (P. ligularis), standardized to 25° Brix, across a temperature range of 5 to 85°C. Apparent viscosity was measured using a Brookfield DV3T rotational viscometer with concentric cylinder geometry. The nectar displayed Newtonian flow behavior, maintaining consistent viscosity regardless of shear rate. Viscosity decreased significantly with rising temperature, from 0.00778 Pa·s at 5°C to 0.00018 Pa·s at 85°C. The Arrhenius model was applied to describe the temperature dependence of viscosity, yielding an activation energy (Ea) of 38.35 kJ/mol. The model fit was statistically robust (R^2 = 0.9913; RMSE = 0.000485 Pa·s), indicating predictable thermal behavior. Enzymatic depectinization played a key role in achieving this flow profile, eliminating structural polysaccharides that would otherwise induce non-Newtonian characteristics. These findings are industrially relevant for the design of efficient pasteurization, pumping, and packaging systems, especially for clean-label juice products. By characterizing the thermo-rheological response of this underexplored tropical nectar, this study contributes original data to the field of food engineering and supports the formulation of stable, energy-efficient fruit-based beverages.
Keywords: *Depectinized nectar, P. ligularis, Rheological properties, Viscosity modeling, Arrhenius activation energy.*

1. Introduction

The rheological behavior of fruit-based beverages plays a crucial role in their processing, transportation, storage, and overall consumer acceptance. The viscosity and flow properties of these beverages are largely influenced by factors such as temperature, soluble solids content, and the presence of hydrocolloids, particularly pectin [1, 2]. Pectin is a complex polysaccharide found in the cell walls of fruits, playing a key role in determining the texture, stability, and gelling properties of food products [3].

Among fruit-derived beverages, passion fruit nectar (*P. ligularis*) has gained increasing attention due to its distinctive sensory characteristics and potential health benefits [4]. However, despite their growing commercial importance, limited research has been conducted on their rheological properties,

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particularly after depectinization, a process often employed to improve clarity and stability in fruit juices [5].

The processing of fruit juices and nectars typically involves heat treatments such as pasteurization, which can significantly alter viscosity due to changes in molecular interactions, particularly in polysaccharide-rich systems [6, 7]. Understanding the relationship between temperature and viscosity is essential for optimizing these processes, ensuring product consistency, and minimizing energy consumption. Although there are significant reports on the management of these variables, further research is necessary to develop more effective control strategies [8, 9]. The variability specific to each fruit type requires checking these relationships.

The Arrhenius model is widely used to describe the temperature dependence of viscosity, providing an estimate of the activation energy (E_a) required for changes in flow behavior. This parameter is particularly relevant in industrial applications such as pumping, filling, and packaging, where viscosity variations affect processing efficiency and equipment performance [10].

Previous studies on fruit-derived hydrocolloids have demonstrated that the activation energy is highly dependent on the molecular composition and degree of esterification of pectins, which in turn determines their response to temperature changes [11]. Thus, there are reports in Marsiglia-Fuentes, et al. [12], *Achras sapota* fruits [13], apple [14], *Opuntia ficus indica* [15] and also fruit syrups as an additive to desserts [16].

Depectinization is applied in combination in the processing of fruit nectars to improve product clarity, reduce turbidity, and prevent gelation during storage [17]. These improvements are crucial for optimizing fluid dynamics in pumping, pasteurization, and packaging operations [14, 17, 18]. Furthermore, while pectin extracted from citrus fruits and apples has been extensively characterized [1, 2] less attention has been paid to the rheological properties of nectars derived from underutilized fruits such as *P. ligularis*, despite increased interest in identifying new tropical fruits with potential for nectar formulation [19-21]. It should also be noted that pectin plays important roles in other types of nectars or beverages and is not necessarily a problem [22].

Recent research highlights that pectin extraction and modification can influence not only the viscosity of fruit-based products but also their antioxidant capacity and functional properties [3, 23, 24]. Furthermore, industrial-scale depectinization, often achieved through enzymatic or acid hydrolysis, alters the structural integrity of nectar, resulting in significant modifications to its flow behavior and temperature sensitivity [25]. This makes it crucial to assess whether depectinized *P. ligularis* nectar behaves as a Newtonian or non-Newtonian fluid under various thermal conditions, which has direct implications for its processing and shelf-life stability [26]. In the case of *Passiflora* nectar, the systematic characterization of its viscosity and activation energy over a controlled temperature range can provide valuable information for its handling and industrial processing [4] however, it is not so clearly defined for *P. ligularis* where Newtonian fluids have a constant viscosity regardless of the shear rate, which would simplify process modeling and equipment selection, while non-Newtonian fluids require additional considerations to adjust flow behavior [27]. Specifically, this study seeks to address this knowledge gap by evaluating the rheological properties of *P. ligularis* nectar depectinized at 25 °Brix over a temperature range of 5 to 85 °C.

By investigating the impact of temperature on viscosity and flow characteristics, this study provides a comprehensive understanding of how thermal processing conditions influence the stability and processability of *P. ligularis* nectar. Furthermore, the results will expand scientific knowledge on temperature-dependent viscosity in fruit-based beverages, filling a critical gap in the literature on the rheology of depectinized *P. ligularis* nectar and its implications for food engineering applications.

2. Materials and Methods

Raw Material and Sample Preparation: Passion fruit (*P. ligularis*) nectar was obtained from fresh fruits sourced from a local market in the district of Miraflores, Lima, Peru. The fruits were manually peeled, and the pulp was separated by gently pressing the arils through a sanitized fine-mesh sieve using a sterile spatula, allowing the juice and pulp to pass through while retaining the seeds. The extracted pulp was sieved through a 1 mm mesh to remove seeds and coarse particles. The nectar was standardized to 25 °Brix using food-grade sucrose (Sigma-Aldrich®, St. Louis, MO, USA), and pH was adjusted to 3.5 ± 0.1 using citric acid (Sigma-Aldrich®, St. Louis, MO, USA).

Enzymatic depectinization was performed using Pectinase enzyme (Pectinex® Ultra SP-L, Novozymes A/S, Bagsværd, Denmark) at a concentration of 0.2% w/w of nectar. The enzymatic reaction was conducted at 45°C for 60 minutes under continuous stirring. The treated nectar was immediately subjected to thermal treatment at 90°C for 5 minutes to inactivate the enzyme, followed by rapid cooling to room temperature (25°C). The nectar was standardized to 25 °Brix by gradually adding food-grade sucrose under constant agitation, with Brix values monitored using a digital refractometer (Atago PAL-1). Pectinase (Pectinex® Ultra SP-L, Novozymes) was selected due to its high specificity for degrading pectin, which is the primary polysaccharide contributing to turbidity and viscosity in fruit nectars. Other enzymes, such as cellulases or hemicellulases, were not used, as their substrates are not predominant in passion fruit pulp.

Rheological measurements were conducted using a Brookfield DV3T rotational viscometer equipped with a concentric cylinder (SC4-18 spindle). The apparent viscosity of the nectar was determined as a function of shear rate under controlled temperature conditions. Viscosity measurements were performed at temperatures ranging from 5°C to 85°C, with a shear rate range of 10 to 200 s^{-1}. Each sample was equilibrated at the target temperature for 5 minutes prior to measurement. This temperature range (5–85°C) was selected to simulate conditions from cold storage to pasteurization processes, which are commonly used in fruit nectar production and distribution chains.

To determine the flow behavior of the nectar, the relationship between shear stress (τ) and shear rate ($\dot{\gamma}$) was analyzed. The experimental data were fitted to the power-law model for non-Newtonian fluids (Eq. 1):

$$\tau = K\dot{\gamma}^{n} \text{ (eq. 1)}$$

where K is the consistency coefficient ($Pa{\cdot}s^n$), and n is the flow behavior index (dimensionless). A Newtonian fluid is characterized by $n \approx 1$, while values of $n < 1$ or $n > 1$ indicate shear-thinning or shear-thickening behavior, respectively.

Activation Energy and Temperature Dependency: The temperature dependence of viscosity was modeled using the Arrhenius equation (Eq. 2):

$$\eta = \eta_0 exp\left(\frac{E_a}{RT}\right) \text{ (Eq.2)}$$

where:

- η is the viscosity (Pa·s),
- η_0 is the pre-exponential factor (Pa·s),
- E_a is the activation energy (kJ/mol),
- R is the universal gas constant (8,314 J/mol·K),
- T is the absolute temperature (K).

The activation energy (E_a) was obtained from the slope of the ln(η) vs. 1/T plot.

Statistical Analysis**:** All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation (SD). The normality of data distribution was verified using the Shapiro-Wilk test, and homogeneity of variances was assessed using Levene's test. Significant differences between temperature conditions were evaluated using analysis of variance (ANOVA) followed by Tukey's post-hoc test for multiple comparisons at a significance level of $p < 0.05$. Data analysis was performed using

Minitab® 19. Finally, a non-linear regression analysis was performed to determine the optimum viscosity point and function of the tested temperature.

3. Results

3.1. Flow Behavior of Depectinized Passion Fruit Nectar

The rheological analysis of depectinized passion fruit (*P. ligularis*) nectar at 25 °Brix was conducted across a temperature range of 5°C to 85°C. The shear stress versus shear rate data exhibited a linear relationship at all tested temperatures, indicating Newtonian flow behavior. This suggests that the nectar's viscosity remains constant irrespective of the applied shear rate. Similar Newtonian behavior has been observed in other fruit juices, such as clarified pear and peach juices. The flow behavior index (n) ranged from 0.98 to 1.02 across all tested temperatures, confirming Newtonian flow. The consistency index (K) remained stable and low, supporting the classification of the nectar as a Newtonian fluid. It is important to note that, in Newtonian fluids, the increase in shear stress with shear rate is expected and linear, as described by Newton's law ($\tau = \eta \cdot \dot{\gamma}$). The apparent viscosity, however, remains constant at a given temperature regardless of the applied shear rate, which was confirmed in our data across the full deformation gradient range.

Table 1.
Shear stress values $\tau(\frac{\text{dyne}}{\text{cm}^2})$ against the deformation gradient $D(s^{-1})$ for depectinized passion fruit juice (*P. ligularis*), at 25 °Brix depending on different process temperatures (T), °C.

	Process Temperature (T), °C								
	5	**9**	**12**	**18**	**25**	**40**	**60**	**70**	**85**
$D(s^{-1})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$	$\tau(\frac{dyne}{cm^2})$
8	62.38	46.15	38.47	26.50	13.70	5.70	4.67	3.40	2.30
18	140.12	104.00	87.00	58.91	30.52	12.50	9.46	6.60	4.08
32	250.68	186.02	153.00	105.20	54.00	22.00	16.20	11.10	6.60
48	373.70	278.01	229.70	157.70	81.00	32.90	23.90	16.20	9.50
65	504.13	375.95	310.95	213.45	110.20	44.45	32.00	21.60	12.55
102	796.14	590.00	487.82	335.00	172.00	69.60	49.82	33.50	19.22
220	1711.90	1271.91	1051.90	721.90	370.00	150.02	106.50	71.30	40.50
270	2100.02	1560.02	1291.02	885.91	454.00	183.91	130.51	87.30	49.51
400	-	2312.00	1912.16	1312.35	672.00	272.35	193.00	128.95	72.95
580	-	-	2772.80	-	1430.02	394.80	274.00	186.60	105.40
790	-	--	-	-	-	538.00	380.27	253.87	143.27
940	-	-	-	-	-	-	452.31	301.91	170.31

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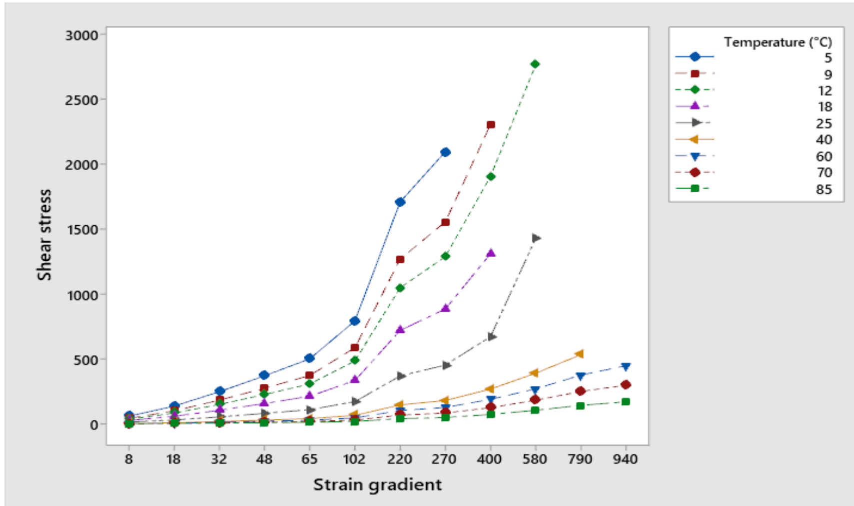

Figure 1.
Rheogram of depectinized passion fruit nectar at 25 °Brix across various temperatures.

With this information, the analysis of variance was carried out, which was significant for Shear stress $\tau(\frac{dyne}{cm^2})$ Depending on the variability of the deformation gradient level ($D(s^{-1})$) and temperature (°C), significance is obtained independently for each of these two factors and also for the interaction of both.

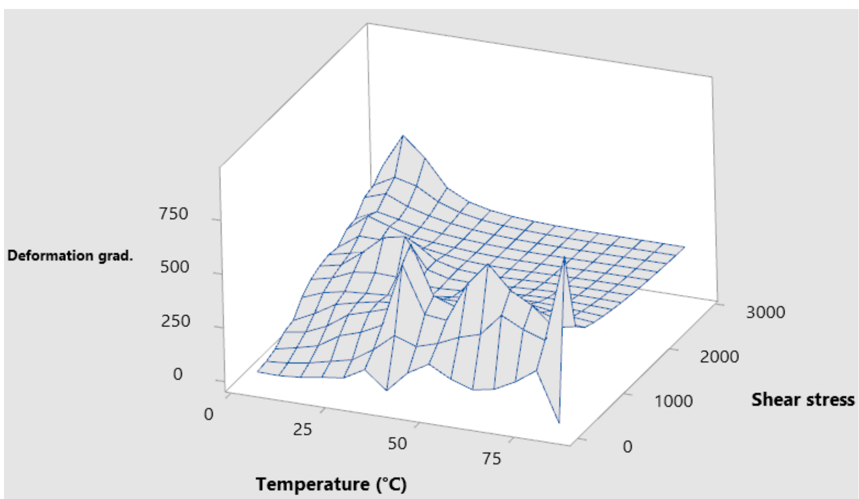

Figure 2.
3D surface plot of shear stress $[\boldsymbol{\tau}(\frac{\boldsymbol{dyne}}{\boldsymbol{cm^2}})]$ based on the deformation gradient $[D(s^{-1})]$ levels vs. temperature (°C).

The results of the comparisons using the Tukey test revealed three homogeneous groupings of strain levels (Table 2). The interesting aspect of this determination is that, for the strain gradients, there was consensus on the levels of 790, 940, and 220 ($D(s^{-1})$), which were common to the three homogeneous groups. Meanwhile, the comparisons of the temperature levels allowed grouping into two homogeneous groups of shear stress $[\boldsymbol{\tau}(\frac{\boldsymbol{dyne}}{\boldsymbol{cm^2}})]$. There was consensus on core temperatures of 18°C and

25°C, which provide a good reference for the values that would optimize the desirable conditions for *passion* fruit juice (Table 3).

Table 2.
Shear stress values grouping $\tau(\frac{dyne}{cm^2})$ against the deformation gradient $D(s^{-1})$ for depectinized passion fruit juice (*P. ligularis*).

Deformation gradient ($D(S^{-1})$	N	Mean	Homogeneous groups (*)		
580	6	1022.81	A		
400	8	919.14	A		
270	9	749.13	A	B	
790	4	662.12	A	B	C
940	3	661.68	A	B	C
220	9	610.66	A	B	C
102	9	283.68		B	C
65	9	180.59		B	C
48	9	133.62			C
32	9	89.42			C
18	9	50.35			C
8	9	22.59			C

Note: (*) Tukey's comparison test (α=0,05). Means that do not share a letter are significantly different.

Table 3.
Shear stress values grouping $\tau(\frac{dyne}{cm^2})$ against the temperature (°C) gradient for depectinized passion fruit juice (*P. ligularis*).

Temperature (°C)	N	Mean	Homogeneous groups (*)	
5	8	926.194	A	
12	10	876.099	A	
9	9	858.246	A	
18	9	535.231	A	B
25	10	381.361	A	B
40	11	176.282		B
60	12	139.387		B
70	12	93.527		B
85	12	53.016		B

Note: (*) Tukey's comparison test (α=0,05). Means that do not share a letter are significantly different.

3.2. Effect of Temperature on Viscosity

Temperature demonstrated a significant inverse effect on the viscosity of the nectar. As the temperature increased from 5°C to 85°C, viscosity decreased exponentially. Similar trends have been reported in other fruit-based products, including mango and papaya nectar blends, where viscosity decreased with rising temperature.

Table 4.
Dynamic viscosity data and relative and absolute temperatures for depectinized passion fruit (*P. ligularis*) juice.

Temperature. T (°C)	Temperature (T) K	Viscosity. n (cp.)
5	278.15	7.77792
9	282.15	5.77860
12	285.15	4.78000
18	291.15	3.28051
25	298.15	1.68606
40	313.15	0.68055
60	333.15	0.47894
70	343.15	0.32030
85	358.15	0.18029

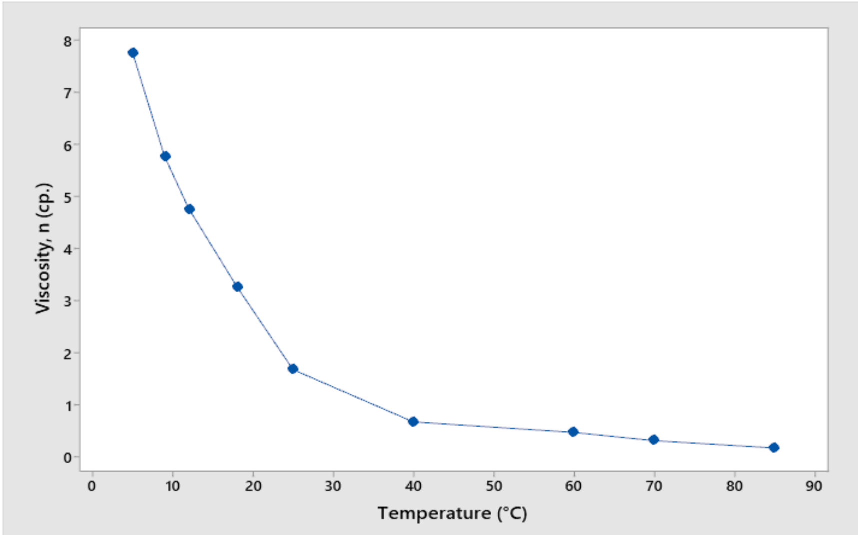

Figure 3.
Viscosity of nectar passion fruit juice (*P. ligularis*), n (cp) at 25 °Brix, on melting temperature, T (°C).

3.3. Arrhenius Model Application and Activation Energy

The Arrhenius equation (eq. 2) was employed to quantify the temperature dependence of viscosity. Plotting the natural logarithm of viscosity against the reciprocal of temperature yielded a linear relationship, confirming the model's applicability. The calculated activation energy (E_a) for the nectar was 9,161 kcal/mol, indicating moderate sensitivity to temperature changes. This value is within the range reported for other fruit juices, such as mango juice, which exhibited activation energies around 10.93 kJ/mol.

Arrhenius equation $\frac{d(\ln n)}{dT} = \frac{\Delta H}{RT^2}$. Integrated, we have:

$$\ln n = -\frac{Ea}{R} \times \frac{1}{T} + \ln A \Rightarrow n = A \times e^{-\frac{Ea}{T}}$$ (Arrhenius deduction)

Where:
n = viscosity
E_a = Activation energy or enthalpy increase (cal.).
T = Absolute temperature (K)
R = Universal gas constant (1,9872 cal./mol K)

Applying the Arrhenius equation to the data shown in Table 4, the following statistical values are obtained.

The slope of the curve was $-E_a/R$ es 4610,0136; of which the Arrhenius Activation Energy (E_a) turns out to be equal to 9,161 cal./mol, or what is the same: 9,161 kcal/mol.

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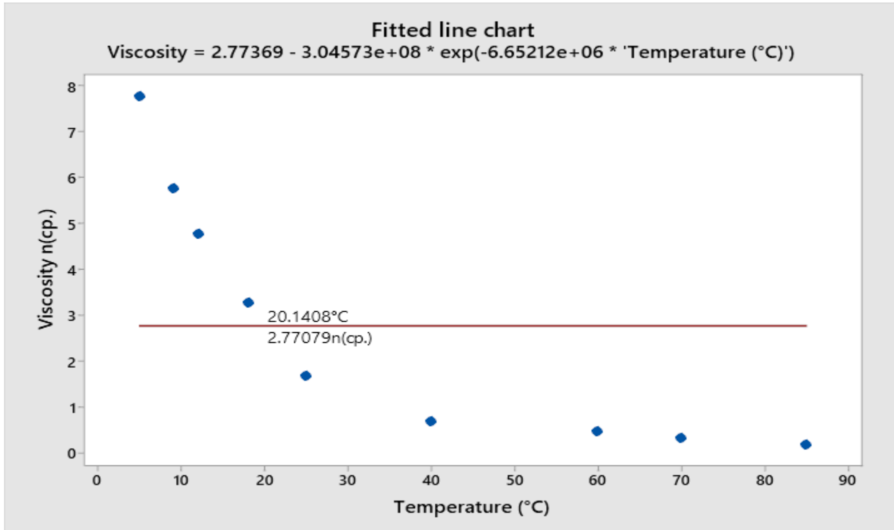

Figure 4.
Arrhenius plot of ln(viscosity) vs. inverse temperature (1/T) for nectar.

The nonlinear regression was performed using the Gauss-Newton algorithm, which converged after 12 iterations. The Arrhenius equation was used for the calculation, refining the values based on the initial estimate of the parameter E_a/R = 4610.0136. Based on this formula [$ln(n)=a+b/T$] (where n is the viscosity (cp); T is the temperature (°C); b = the calculated E_a/R), the final values were refined to a = 14,6814.

Fig. 4 shows that the fitted line model reports an inflection point at the intersection between 20.14°C and 2.77 n(cp), which determines the ideal temperature point for the best viscosity performance of depectinized passion fruit juice (*P. ligularis*).

The fit yielded an R^2 of 0.9913 (closer to 1.000 indicates a better model fit) and a root mean square error (RMSE) of 0.485 cp (0.000485 Pa·s), indicating excellent model performance. Lower RMSE indicates a better fit between the model and the experimental data, as it resulted in a small margin of error within the range of experimental viscosities, which were between 0.18 and 7.78 cp.

3.4. Industrial Implications

Understanding the Newtonian behavior and temperature sensitivity of depectinized passion fruit nectar is crucial for optimizing industrial processes. The predictable decrease in viscosity with increasing temperature can inform the design of thermal treatments, such as pasteurization, ensuring microbial safety without compromising product quality. Additionally, knowledge of energy activation aids in selecting appropriate equipment and processing conditions to maintain energy efficiency and product consistency. These insights are valuable for the beverage industry, where precise control over rheological properties is essential for consumer acceptance and process optimization.

4. Discussion

The results of the rheological analysis confirmed that depectinized *P. ligularis* nectar exhibits Newtonian flow behavior across all tested temperatures. This behavior is characteristic of many clarified fruit juices and nectars, where the absence of insoluble solids or high-molecular-weight polymers (such as pectin) prevents the formation of complex fluid structures that would otherwise induce shear-thinning or shear-thickening behavior [10].

Comparable Newtonian behavior has been reported in clarified peach and pear juices, suggesting that the enzymatic removal of pectin effectively eliminates structural interactions that contribute to non-Newtonian properties [5]. However, in contrast to other fruit-based liquids such as mango or papaya nectar, which often exhibit pseudoplastic behavior due to their fibrous and polysaccharide-rich composition, *P. ligularis* nectar demonstrates stable viscosity independent of shear rate. This makes it highly suitable for processing operations requiring consistent flow properties, such as pumping, pasteurization, and filling [27].

The inverse exponential relationship observed between viscosity and temperature is consistent with the expected behavior of liquid foods. This trend aligns with previous studies on fruit-based products, where the weakening of hydrogen bonds and Van der Waals forces at higher temperatures facilitates molecular mobility, thereby reducing resistance to Flow [3, 4, 11, 28].

A similar viscosity-temperature relationship has been observed in mango and papaya nectar blends, where viscosity was found to decrease due to the breakdown of polysaccharide networks at elevated temperatures. However, the relatively low viscosity values obtained for depectinized *P. ligularis* nectar suggest that the removal of pectin significantly contributes to this reduction, as pectic substances are known to enhance viscosity in fruit-based systems [4, 14, 26].

For instance, during pasteurization, high temperatures can facilitate flow through heat exchangers, reducing the energy required for pumping and minimizing mechanical stress on processing equipment [29].

The successful application of the Arrhenius model to describe the temperature dependence of viscosity further validates the thermally activated nature of flow behavior in *P. ligularis* nectar. The calculated activation energy (E_a = 9.161 kcal/mol) indicates moderate sensitivity to temperature changes, which is comparable to values reported for other fruit-based beverages such as mango juice ($E_a \approx 10.93$ kJ/mol) and apple juice ($E_a \approx 8.5$–12.3 kJ/mol) [7, 10, 30].

Activation energy serves as a critical parameter in food rheology, providing insights into the extent to which temperature variations affect viscosity. The moderate E_a observed in this study suggests that depectinized *P. ligularis* nectar maintains relatively stable viscosity across a broad temperature range, making it adaptable to various processing conditions [4, 5, 27].

Moreover, the nonlinear regression analysis revealed an inflection point at 20.14°C and 2.77 cp, indicating an optimal temperature for maintaining desirable viscosity levels. This suggests that, under typical storage and processing conditions, the nectar retains a viscosity profile that balances ease of handling with consumer-preferred texture. Such findings are particularly relevant for industrial applications where viscosity must remain within controlled limits to ensure consistent product quality, efficient packaging, and prolonged shelf stability [3, 17, 23].

Understanding the rheological and thermal behavior of depectinized *P. ligularis* nectar has significant implications for the food and beverage industry. The Newtonian flow properties observed in this study indicate that the nectar can be easily processed using standard pumping and filling equipment without the need for specialized shear-dependent flow control mechanisms. This simplifies the design of processing pipelines and reduces operational complexities, making it an attractive ingredient for large-scale beverage production [5, 8, 11, 19].

By carefully adjusting processing temperatures based on the observed activation energy, manufacturers can optimize heat transfer efficiency while minimizing undesirable changes in viscosity and mouthfeel [19, 26]. Additionally, the moderate temperature sensitivity suggests that the nectar is relatively resistant to excessive thickening or thinning under normal storage conditions, ensuring a stable consumer experience [11, 17, 22].

The insights gained from this study can also aid in the formulation of multi-component beverages. For instance, incorporating *P. ligularis* nectar into blended juice products may help achieve target viscosity levels without relying on additional hydrocolloids or stabilizers. This could enhance the clean-label appeal of fruit-based drinks while maintaining desirable textural attributes [1, 2, 24, 29].

Overall, the findings highlight the importance of rheological characterization in the development of fruit-based beverages. By leveraging temperature-dependent viscosity models and activation energy calculations, food technologists can design optimized processing strategies that balance efficiency, quality, and consumer preference.

This study successfully characterized the rheological behavior of depectinized passion fruit nectar (*P. ligularis*) at 25 °Brix, demonstrating Newtonian flow properties across a temperature range of 5°C to 85°C. The viscosity exhibited a significant inverse correlation with temperature, and the Arrhenius model effectively described this dependency, yielding an activation energy of 9.161 kcal/mol.

Institutional Review Board Statement:

The authors unanimously agree that all ethical considerations at the national and international levels have been met.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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References

[1] S. Ishii and T. Yokotsuka, "Susceptibility of fruit juice to enzymic clarification by pectin lyase and its relation to pectin in fruit juice," *Journal of Agricultural and Food Chemistry*, vol. 21, no. 2, pp. 269-272, 1973. https://doi.org/10.1021/jf60186a027

[2] X. Ye *et al.*, "Preparation of bioactive gelatin film using semi-refined pectin reclaimed from blueberry juice pomace: Creating an oxidation and light barrier for food packaging," *Food Hydrocolloids*, vol. 129, p. 107673, 2022. https://doi.org/10.1016/j.foodhyd.2022.107673

[3] D. Konrade, S. Gaidukovs, F. Vilaplana, and P. Sivan, "Pectin from fruit-and berry-juice production by-products: Determination of physicochemical, antioxidant and rheological properties," *Foods*, vol. 12, no. 8, p. 1615, 2023. https://doi.org/10.3390/foods12081615

[4] S. Kulkarni and P. Vijayanand, "Effect of extraction conditions on the quality characteristics of pectin from passion fruit peel (Passiflora edulis f. flavicarpa L.)," *LWT-Food Science and Technology*, vol. 43, no. 7, pp. 1026-1031, 2010. https://doi.org/10.1016/j.lwt.2009.11.006

[5] C. Arrieta-Durango, L. Henao-Rivas, and R. Andrade-Pizarro, "Rheological behavior of passion fruit (Passiflora edulis) peel extract," *Gels*, vol. 8, no. 9, p. 566, 2022. https://doi.org/10.3390/gels8090566

[6] R. Buffo, G. Reineccius, and G. Oehlert, "Factors affecting the emulsifying and rheological properties of gum acacia in beverage emulsions," *Food Hydrocolloids*, vol. 15, no. 1, pp. 53-66, 2001. https://doi.org/10.1016/S0268-005X(00)00050-3

[7] A. Franzol, T. Banin, T. Brazil, and M. Rezende, "Assessment of kinetic stability of cosmetic emulsions formulated with different emulsifiers using rheological and sensory analyses," *Journal of Sol-Gel Science and Technology*, vol. 99, pp. 469-481, 2021. https://doi.org/10.1007/s10971-021-05587-x

[8] L. de Lacerda de Oliveira, B. A. Ortega Sanchez, I. C. Celestino, S. M. Costa Celestino, E. R. de Alencar, and A. M. Costa, "Shelf life and retention of bioactive compounds in storage of pasteurized Passiflora setacea pulp, an exotic fruit from Brazilian savannah," *LWT*, vol. 159, p. 113202, 2022. https://doi.org/10.1016/j.lwt.2022.113202

[9] A. I. ElManawy, A. Maratab, A. F. Ghazal, F. Li, X. Li, and X. Zhang, "Shelf-life assessment techniques for fruit and vegetables: Recent trends and future prospects," *Postharvest Biology and Technology*, vol. 226, p. 113521, 2025. https://doi.org/10.1016/j.postharvbio.2025.113521

[10] M. Sterczyńska, M. Zdaniewicz, and K. Wolny-Kołładka, "Rheological and microbiological characteristics of hops and hot trub particles formed during beer production," *Molecules*, vol. 26, no. 3, p. 681, 2021. https://doi.org/10.3390/molecules26030681

[11] Y. Liu *et al.*, "Influence of temperatures on physicochemical properties and structural features of tamarind seed polysaccharide," *Molecules*, vol. 29, no. 11, p. 2622, 2024. https://doi.org/10.3390/molecules29112622

[12] R. Marsiglia-Fuentes, J. M. Franco, and L. A. García-Zapateiro, "Preparation and characterization of dressing-type emulsions formulated with hydrocolloids from the mango (Mangifera indica) peel," *Applied Food Research*, vol. 4, no. 2, p. 100582, 2024. https://doi.org/10.1016/j.afres.2024.100582

[13] J. Menezes and K. Athmaselvi, "Study on effect of pectin based edible coating on the shelf life of sapota fruits," *Biosciences Biotechnology Research Asia*, vol. 13, no. 2, pp. 1195-1199, 2016. http://dx.doi.org/10.13005/bbra/2152
[14] O. Marín-Machuca, J. A. Iannacone, F. A. Alvarado-Zambrano, A. O. Vásquez-Aranda, R. A. Alvarado-Zambrano, and A. Quispe Quispe, "Effects of concentration and temperature on the thermophysical properties of apple juice," *Paideia XXI*, vol. 11, no. 1, pp. 113-125, 2021. https://doi.org/10.31381/paideia.v11i1.3791
[15] C. B. Díaz-Cachay, "Rheological characterization of prickly pear juice (Opuntia ficus-indica)," *Annals of Clinical Medicine and Case Reports*, vol. 14, no. 9, pp. 1–8, 2018.
[16] O. Marín-Machuca, J. Iannacone, F. A. Alvarado-Zambrano, A. O. Vásquez-Aranda, J. E. Candela-Diaz, and A. Quispe-Quispe, "Physicochemical rheology of fruit syrup (Honey) for nougat," *Biotempo*, vol. 18, no. 1, pp. 101-108, 2021. https://doi.org/10.31381/biotempo.v18i1.3932
[17] H. Mirhosseini, C. P. Tan, A. Aghlara, N. S. Hamid, S. Yusof, and B. H. Chern, "Influence of pectin and CMC on physical stability, turbidity loss rate, cloudiness and flavor release of orange beverage emulsion during storage," *Carbohydrate Polymers*, vol. 73, no. 1, pp. 83-91, 2008. https://doi.org/10.1016/j.carbpol.2007.11.002
[18] C. Badia-Olmos, L. Laguna, A. Rizo, and A. Tárrega, "Dysphagia thickeners in context of use: Changes in thickened drinks viscosity and thixotropy with temperature and time of consumption," *Journal of Texture Studies*, vol. 53, no. 3, pp. 383-395, 2022. https://doi.org/10.1111/jtxs.12685
[19] J. Aschemann-Witzel *et al.*, "Sustainable use of tropical fruits? Challenges and opportunities of applying the waste-to-value concept to international value chains," *Critical Reviews in Food Science and Nutrition*, vol. 63, no. 10, pp. 1339-1351, 2023. https://doi.org/10.1080/10408398.2021.1963665
[20] L. d. A. P. Rodrigues, D. D. G. Nunes, K. V. S. Hodel, J. D. Viana, E. P. Silva, and M. B. P. Soares, "Exotic fruits patents trends: An overview based on technological prospection with a focus on Amazonian," *Heliyon*, vol. 9, no. 12, p. e22060, 2023. https://doi.org/10.1016/j.heliyon.2023.e22060
[21] T. Sarkar *et al.*, "Minor tropical fruits as a potential source of bioactive and functional foods," *Critical Reviews in Food Science and Nutrition*, vol. 63, no. 23, pp. 6491-6535, 2023. https://doi.org/10.1080/10408398.2022.2033953
[22] S. Aliyev, M. Khalilov, R. Saidov, G. Mammadov, and G. Allahverdiyeva, "Technology for making drinks based on pectin rich fruits and vegetables grown in Azerbaijan," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 11 (117), pp. 45-52, 2022. https://doi.org/10.15587/1729-4061.2022.256921
[23] M. Alam, B. N. Dar, and V. Nanda, "Hydrocolloid-based fruit fillings: A comprehensive review on formulation, techno-functional properties, synergistic mechanisms, and applications," *Journal of Texture Studies*, vol. 55, no. 4, p. e12861, 2024. https://doi.org/10.1111/jtxs.12861
[24] G. Dharmaprema, K. Senevirathne, Y. Jayasundara, M. D. Bandara, and H. Rathnayake, "Fruit and vegetable by-products as a source of dietary fiber: Applications, physico-chemical impact and functional attributes," *Food and Bioprocess Technology*, pp. 1-49, 2025. https://doi.org/10.1007/s11947-025-04029-8
[25] M. Alam, M. Rawat, S. Kaur, B. N. Dar, and V. Nanda, "Transformation of quality attributes of fruit leathers using diverse hydrocolloids: Recent application and future perspective," *Journal of Food Process Engineering*, vol. 47, no. 11, p. e14782, 2024. https://doi.org/10.1111/jfpe.14782
[26] L. Zhou *et al.*, "Physicochemical properties and anti-diabetic ability of polysaccharides from a thinned peach fruit," *Food & Function*, vol. 14, no. 19, pp. 8876-8892, 2023. https://doi.org/10.1039/D3FO03041E
[27] Â. Viegas, M. J. Alegria, and A. Raymundo, "Sustainable jam with apple pomace: Gelling, rheology, and composition analysis," *Gels*, vol. 10, no. 9, p. 580, 2024. https://doi.org/10.3390/gels10090580
[28] Y. Cui, J. Liu, S. Han, P. Li, D. Luo, and J. Guo, "Physical stability of chestnut lily beverages (CLB): Effects of shear homogenization on beverage rheological behavior, particle size, and sensory properties," *Foods*, vol. 11, no. 20, p. 3188, 2022. https://doi.org/10.3390/foods11203188
[29] K. S. Sandhu, M. Kaur, S. Punia, and J. Ahmed, "Rheological, thermal, and structural properties of high-pressure treated Litchi (Litchi chinensis) kernel starch," *International Journal of Biological Macromolecules*, vol. 175, pp. 229-234, 2021. https://doi.org/10.1016/j.ijbiomac.2021.02.030
[30] W. Xing *et al.*, "Development of predictive models for shelf-life of sweet cherry under different storage temperatures," *LWT*, vol. 217, p. 117442, 2025. https://doi.org/10.1016/j.lwt.2025.117442