

Article

The Effect of Temperature and Concentration on the Kinematic Viscosity of Starch Gels from Andean Potato Varieties

Alejandro Coloma ^{1,2}, Edgar Gallegos Rojas ^{1,2}, Herbert Callo ^{1,2} , Leandro Valencia ^{1,2}, Justo Gallegos Rojas ¹, Arturo Zaira-Churata ³, Jorge Apaza-Cruz ⁴, Nancy Curasi Rafael ^{2,5} , Cristina Valencia-Sullca ⁶  and Ulises Alvarado ^{1,2,*} 

- ¹ Escuela Profesional de Ingeniería Agroindustrial, Facultad de Ciencias Agrarias, Universidad Nacional del Altiplano, Av. Floral 1153, Puno 21001, Peru; acoloma@unap.edu.pe (A.C.); edgallegosr@unap.edu.pe (E.G.R.); herbert.callo@unap.edu.pe (H.C.); leandrovalencia@unap.edu.pe (L.V.); sipia50@gmail.com (J.G.R.)
 - ² Instituto de Investigación e Innovación en Producción, Seguridad Alimentaria y Agroindustria—IPSA, Universidad Nacional del Altiplano, Av. Floral 1153, Puno 21001, Peru; ncurasi@upeu.edu.pe
 - ³ Escuela Profesional de Nutrición Humana, Facultad de Ciencias de la Salud, Universidad Nacional del Altiplano, Av. Floral 1153, Puno 21001, Peru; azaira@unap.edu.pe
 - ⁴ Escuela Profesional de Ingeniería Electrónica, Universidad Nacional del Altiplano, Av. Floral 1153, Puno 21001, Peru; jlapaza@unap.edu.pe
 - ⁵ Escuela Profesional de Ingeniería Ambiental, Facultad de Ingeniería y Arquitectura, Universidad Peruana Unión, Carretera Arequipa Km 6, Juliaca 21100, Peru
 - ⁶ Institute of Chemistry and Biology of Membranes and Nano-Objects (CBMN), UMR 5248, CNRS, University of Bordeaux, Bordeaux INP, IECB, Allée Geoffroy Saint-Hilaire, F-33600 Pessac, France; cristina.valencia-sullca@u-bordeaux.fr
- * Correspondence: ualvarado@unap.edu.pe; Tel.: +51-99-3370-388

Abstract

Native Andean potatoes (*Solanum tuberosum* subsp. *andigenum*) are a valuable phylogenetic resource due to their compositional diversity and adaptation to high-altitude environments. Their starch is a key functional polysaccharide widely used in food systems; however, information on the kinematic viscosity of dilute gels under moderate thermal conditions remains limited. This study evaluated the effects of temperature (26, 36, and 46 °C) and starch concentration (1–3% w/v) on the kinematic viscosity of gels from three Andean potato varieties: Imilla Negra, Compis, and Peruanita. Starch was extracted from fresh tubers (Puno, Peru) using a wet extraction method, and gels were prepared by heating dispersions at 85 °C for 5 min under controlled conditions. Viscosity (0.61–34.47 cSt) decreased with increasing temperature and increased with concentration, confirming the sensitivity of these systems to thermal and compositional factors. The Arrhenius model adequately described temperature dependence, with activation energies of 15.19–29.75 kJ·mol^{−1}, showing an increasing trend with concentration. At 3% and 26 °C, viscosity followed Compis > Imilla Negra > Peruanita, indicating varietal differences in thickening capacity. These results provide useful rheological data for the design and optimisation of food processes involving dilute Andean potato starch dispersions.

Keywords: Andean potato; concentration; kinematic viscosity; starch gel; temperature



Academic Editor: Janusz Kapusniak

Received: 24 January 2026

Revised: 6 April 2026

Accepted: 13 May 2026

Published: 18 May 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The Andean potato (*Solanum tuberosum* subsp. *andigenum*) originates from the central Andes, mainly in Peru and Bolivia, which are recognised as major centres of potato genetic diversity. High-Andean agriculture has conserved more than 3500 potato varieties, characterised by wide morphological, physiological and compositional variability, many of

which are adapted to seasonal frosts, high ultraviolet radiation levels and nutrient-poor soils [1,2]. This extensive genetic reservoir represents a valuable phylogenetic heritage and a strategic resource for food sustainability and the economic resilience of Andean agricultural communities [3]. Furthermore, the Andean potato is considered a key crop for supporting population growth and mitigating future food insecurity risks [4].

Starch is a plant polysaccharide composed exclusively of D-glucose monomers linked by α -glucosidic bonds [5]. It constitutes the major component of potato dry matter, accounting for approximately 66–80% of the tuber dry weight [6–8]. At the molecular level, starch consists of two glucose polymers: amylose (15–35%), which is a mostly linear polymer formed by α (1–4) linkages that have a high affinity for forming helical complexes (e.g., with iodine), and amylopectin (65–85%), which is a highly branched macromolecule comprising α (1–4) linkages in the chains and α (1–6) branch points [9,10]. Beyond its nutritional value, native potato starch is a functional biopolymer of considerable interest to the agro-industrial sector due to its hydration capacity and ability to modify the consistency of aqueous food systems [11]. Characterising pasting parameters such as peak viscosity and visco-thermal stability [10,12] is essential for evaluating the technological performance of starch as a thickening and gelling agent in aqueous dispersions, particularly in processes where flow behaviour directly affects operational efficiency and the design of processing equipment [12].

When heated in excess water, starch granules hydrate and swell during gelatinisation, leading to increased resistance to flow in the resulting dispersion [13]. The extent of this transformation, as well as the associated rheological response, is influenced by intrinsic factors such as the amylose-to-amylopectin ratio, granule size and degree of phosphorylation, in addition to extrinsic variables including temperature, concentration and prior processing conditions [14,15]. The presence of phosphate groups in potato starch and its relatively high swelling capacity contribute to elevated viscosity compared with several other botanical sources [16]. In addition, starch dispersions and gels are commonly reported to exhibit non-Newtonian behaviour, particularly shear-thinning characteristics, depending on concentration, temperature and shear conditions, which should be considered when interpreting viscosity measurements in dilute and semi-dilute systems [17,18].

Despite the extensive literature on potato starch, comparative studies focusing specifically on the kinematic viscosity of dilute ($\leq 3\%$ *w/v*) starch gels derived from native high-altitude Andean varieties and evaluated under moderate temperature conditions remain limited. Apparent kinematic viscosity provides relevant information for modelling dilute starch dispersions used in pumping, transport and mild thermal processes, yet systematic data for genotypes cultivated in the Puno Altiplano are scarce [19]. Furthermore, most rheological studies have focused on dynamic or steady-shear viscosity measurements, while the use of capillary viscometry provides an alternative approach for characterising apparent viscosity under defined flow conditions [20]. Given the inherent compositional variability of native varieties, their technological performance under moderate thermal regimes may differ, with implications for equipment sizing, pumping efficiency and formulation stability in Andean agro-industrial systems.

Most previous studies on potato starch rheology have focused on commercial cultivars, concentrated pastes or high-temperature processing conditions and frequently report dynamic or steady-shear viscosities rather than apparent kinematic viscosity [16]. Moreover, limited attention has been given to the interpretation of apparent kinematic viscosity in dilute starch systems, particularly regarding the assumptions associated with flow behaviour under capillary conditions [20]. In this context, the present study evaluates the effect of temperature (26 °C, 36 °C and 46 °C) and concentration (1%, 2% and 3% *w/v*) on the kinematic viscosity of starch gels extracted from the three native Peruvian potato

varieties: Imilla Negra, Compis and Peruanita (locally known as Banderita). These varieties were selected based on their adaptation to high-altitude conditions, their relevance in regional supply chains and their potential for agro-industrial transformation. The study focuses on dilute systems and interprets viscosity values as apparent properties obtained under controlled laminar capillary flow conditions. The findings provide comparative rheological data under controlled moderate conditions to support preliminary process design involving dilute native Andean potato starch dispersions.

2. Materials and Methods

2.1. Plant Material

Ten kilograms of each Andean potato variety (Imilla Negra, Compis and Peruanita) were purchased from the Unión y Dignidad market in Puno, Peru. The tubers used were of a standard commercial size and exhibited the following morphological characteristics: the Imilla Negra variety is round with deep eyes, black skin and white flesh; the Compis variety is also round with deep eyes, pink skin and white flesh. The Peruanita variety, on the other hand, is oval in shape with shallow eyes, red skin bearing yellow stripes and white flesh (Figure 1). All samples were washed under running water to remove surface soil, and any sprouts were removed manually. The cleaned potatoes were then stored at 5 ± 1 °C under controlled refrigeration conditions until further processing.

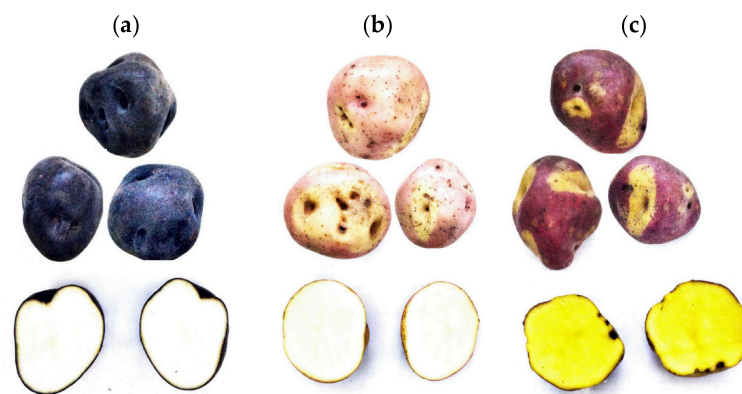


Figure 1. Andean potato varieties: (a) Imilla Negra, (b) Compis and (c) Peruanita.

2.2. Starch Extraction

Starch was extracted using the water soaking method described by Ali et al. [18]. For each potato variety, 1.3 kg of tubers were selected, discarding any damaged or deteriorated ones. The healthy tubers were then washed, peeled and cut into small pieces before being ground in a blender (Oster BLSTMG-A158-06, Oster, Mexico City, Mexico) to obtain a fine pulp. The pulp was transferred to a container and mixed with cold water (16 ± 1 °C, corresponding to laboratory ambient temperature in Puno, Peru) at a pulp-to-water ratio of 1:5. The mixture was then filtered through gauze to separate the starchy liquid from the fibrous residue. The filtrate was left to stand for 12 h to allow starch sedimentation. The supernatant was then decanted, leaving the wet starch, which was subsequently dried in an oven (P-Selecta Digitheat, Barcelona, Spain) at 60 °C for 30 min. The dried starch was ground, passed through a fine sieve if necessary, and then stored in sealed zip-lock bags until analysis.

2.3. Starch Gel Preparation

Starch gels were prepared at three concentrations (1%, 2% and 3% *w/v*) for each potato variety. These concentrations were selected based on preliminary trials to ensure stable laminar flow within the operational range of the Cannon-Fenske capillary viscometer.

Accurate amounts of starch (1 g, 2 g or 3 g) were dispersed in approximately 50 mL of distilled water in 100 mL volumetric flasks (Euro Lab, ISONext, Berlin, Germany). Each mixture was heated in a water bath at 85 °C for 5 min with continuous stirring to ensure complete gelatinisation of the starch. Once homogeneous, the dispersions were diluted to a final volume of 100 mL with distilled water. The samples were then allowed to cool to laboratory temperature (16 ± 1 °C) prior to further analysis. All preparations were carried out under consistent thermal and mixing conditions to ensure reproducibility of the gel structure prior to viscosity measurements.

2.4. Determination of Kinematic Viscosity

The kinematic viscosity was measured using a Cannon-Fenske capillary viscometer (Shibata Scientific Technology Ltd., Tokyo, Japan). Measurements were carried out under laminar capillary flow conditions. Given the dilute nature of the starch dispersions (1–3% *w/v*), the system was treated as exhibiting apparent Newtonian behaviour within the shear-rate range imposed by the viscometer. It is acknowledged that starch dispersions and gels may exhibit non-Newtonian (shear-thinning) behaviour under different shear conditions or at higher concentrations. Therefore, the viscosity values obtained in this study should be interpreted as apparent kinematic viscosity under specific capillary flow conditions, rather than intrinsic rheological properties of the system.

Before use, the viscometer was thoroughly cleaned and dried. The viscometer constant was determined by establishing a relationship between the reported kinematic viscosity of water [17] and the experimentally measured efflux time for distilled water (Table 1). For each measurement, the starch gel sample was placed in the viscometer, which was then submerged in a thermostatically controlled water bath (CNWTC/OEM, HH-S1, Shanghai, China) at a fixed temperature. After a 5 min stabilisation period, the time taken for the meniscus to pass between the calibration marks was recorded [21]. All measurements were performed in triplicate. Apparent kinematic viscosity (ν) was calculated as follows:

$$\nu = C \times t$$

where C is the viscometer constant ($\text{cSt}\cdot\text{s}^{-1}$) and t is the efflux time (s).

Table 1. Viscometer constant at different temperatures.

Temperature (°C)	Flow Time of Water (s)	Kinematic Viscosity of Water (cSt)	Viscometer Constant ($\text{cSt}\cdot\text{s}^{-1}$)
26	2.91	0.868	0.298
36	2.60	0.712	0.274
46	2.50	0.600	0.224

Density was not independently measured. However, considering the low solids content of the dispersions, density variations are expected to be minimal. Thus, the results are expressed and discussed in terms of apparent kinematic viscosity. This assumption represents a limitation of the study and has been considered in the interpretation of the results.

2.5. Effect of Temperature on Kinematic Viscosity

The effect of temperature on kinematic viscosity was evaluated using an Arrhenius-type model [22]:

$$\nu = \nu_0 \exp\left(\frac{E_a}{RT}\right)$$

where

ν : kinematic viscosity (cSt);

ν_0 : pre-exponential (empirical) constant (cSt);

E_a : flow activation energy ($\text{kJ}\cdot\text{mol}^{-1}$);

R : universal gas constant ($0.008314 \text{ kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$);

T : absolute temperature (K).

The activation energy (E_a) was obtained by plotting the natural logarithm of viscosity ($\ln \nu$) against the inverse of the absolute temperature ($1/T$). The resulting straight line had a slope equal to E_a/R , and the activation energy for each starch concentration was then calculated using this value. The Arrhenius model was used as an empirical approach to describe temperature dependence and does not imply a mechanistic interpretation of the system.

2.6. Effect of Concentration on Kinematic Viscosity

The effect of starch concentration on kinematic viscosity was evaluated using an empirical power-law relationship described by Villacorta et al. [22].

$$\nu = a \cdot C^b$$

where:

ν : kinematic viscosity (cSt);

a : proportionality constant (cSt);

b : dimensionless exponent;

C : starch concentration (% w/v).

The power-law model was used as a descriptive approach to characterise the dependence of apparent kinematic viscosity on starch concentration, without implying a mechanistic interpretation of parameter b . Therefore, the model parameters should be interpreted as fitting coefficients rather than intrinsic physicochemical constants.

2.7. Combined Effect of Temperature and Concentration on Kinematic Viscosity

The combined effect of temperature and concentration on kinematic viscosity was studied using the model proposed by Ortega-Quintana et al. [23].

$$\nu = \nu_1 C^n e^{\frac{E_a}{RT}}$$

where:

ν : kinematic viscosity (cSt);

ν_1 : empirical constant (cSt);

C : starch concentration (% w/v);

n : dimensionless proportionality exponent;

E_a : flow activation energy ($\text{kJ}\cdot\text{mol}^{-1}$);

R : universal gas constant ($0.008314 \text{ kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$);

T : absolute temperature (K).

This model was applied as an empirical approach to describe the combined influence of temperature and concentration on apparent kinematic viscosity. Therefore, the parameters (ν_1 , n , and E_a) should be interpreted as fitting coefficients rather than intrinsic physicochemical properties of the system. Given the limited number of experimental conditions evaluated, the model is intended to provide a descriptive representation of the data within the studied range, and extrapolation beyond these conditions should be performed with caution.

2.8. Statistical Analysis

Analysis of variance (ANOVA) was used to compare the mean values of the response variables among treatments at a 95% confidence level. All statistical analyses were performed using Statgraphics Centurion XIX (Statgraphics Technologies, Inc., The Plains, VA, USA), and results are reported as mean $\pm$ standard deviation of three independent replicates.

3. Results and Discussion

Effect of Starch Gel Concentration on Kinematic Viscosity at Three Temperatures

Table 2 shows the impact of temperature and starch concentration on the apparent kinematic viscosity of starch gels derived from three Andean potato varieties. The results indicate that, while kinematic viscosity increases with starch concentration, it decreases with temperature. For the Compis variety, for example, the kinematic viscosity is approximately 21.5 times higher at a starch concentration of 3% than at 1% at 26 °C. However, this difference decreases as the temperature rises to 46 °C. This increase in viscosity with concentration can be attributed to the higher solids content in the dispersion, which increases resistance to flow under capillary conditions [24]. At a concentration of 3% and a temperature of 26 °C, the kinematic viscosity of the Compis variety is 9.6 times greater than that of the Peruanita variety and 5.1 times greater than that of the Imilla Negra variety. These results are consistent with previous studies reporting a reduction in viscosity with increasing temperature [25]. The decrease in viscosity with temperature may be attributed to increased molecular mobility and reduced intermolecular interactions in the dispersion system [26]. It should be noted that the values reported correspond to apparent kinematic viscosity under capillary flow conditions and therefore reflect the combined influence of temperature, concentration and variety within the studied experimental range.

Table 2. Effect of temperature and starch concentration on the apparent kinematic viscosity (cSt) of starch gels from three Andean potato varieties.

Variety	Starch Concentration (%)	Temperature (°C)		
		26	36	46
Imilla Negra	1	1.10 $\pm$ 0.02 ^a	0.80 $\pm$ 0.02 ^a	0.65 $\pm$ 0.01 ^a
	2	3.04 $\pm$ 0.19 ^b	2.54 $\pm$ 0.05 ^b	2.07 $\pm$ 0.09 ^b
	3	12.91 $\pm$ 0.39 ^c	9.63 $\pm$ 0.66 ^c	6.09 $\pm$ 0.38 ^c
Compis	1	1.60 $\pm$ 0.08 ^a	1.19 $\pm$ 0.09 ^a	0.98 $\pm$ 0.01 ^a
	2	4.87 $\pm$ 0.31 ^b	4.08 $\pm$ 0.40 ^b	2.95 $\pm$ 0.20 ^b
	3	34.47 $\pm$ 0.75 ^c	25.09 $\pm$ 0.71 ^c	20.08 $\pm$ 0.81 ^c
Peruanita	1	0.91 $\pm$ 0.02 ^a	0.71 $\pm$ 0.08 ^a	0.61 $\pm$ 0.03 ^a
	2	1.07 $\pm$ 0.03 ^b	0.87 $\pm$ 0.08 ^a	0.65 $\pm$ 0.04 ^a
	3	3.38 $\pm$ 0.05 ^c	2.66 $\pm$ 0.12 ^b	2.11 $\pm$ 0.05 ^b

Values are expressed as mean $\pm$ standard deviation (n = 3). Different letters within the same temperature indicate significant differences ($p < 0.05$).

Figure 2 shows the correlation between the natural logarithm of apparent kinematic viscosity ($\ln \nu$) and the inverse of the absolute temperature ($1/T$) across different starch concentrations and the three varieties evaluated. The results indicate that $\ln \nu$ increases as $1/T$ increases, suggesting a temperature dependence of the apparent kinematic viscosity under the studied conditions. This effect is most pronounced in Compis, followed by Imilla Negra and Peruanita. These observations are consistent with previous studies reporting variability in the thermal and rheological behaviour of starches from different botanical sources and growing conditions. Zheng et al. [27] reported significant differences in the gelatinisation properties of rice starches both between varieties grown in the same region

and within the same variety grown in different regions. Such variability has been associated with factors including starch concentration, granule size, phosphorus and amylose content, amylose-lipid interactions, and amylopectin molecular structure [12]. However, these compositional parameters were not determined in the present study and are mentioned only as potential explanatory factors based on literature reports.

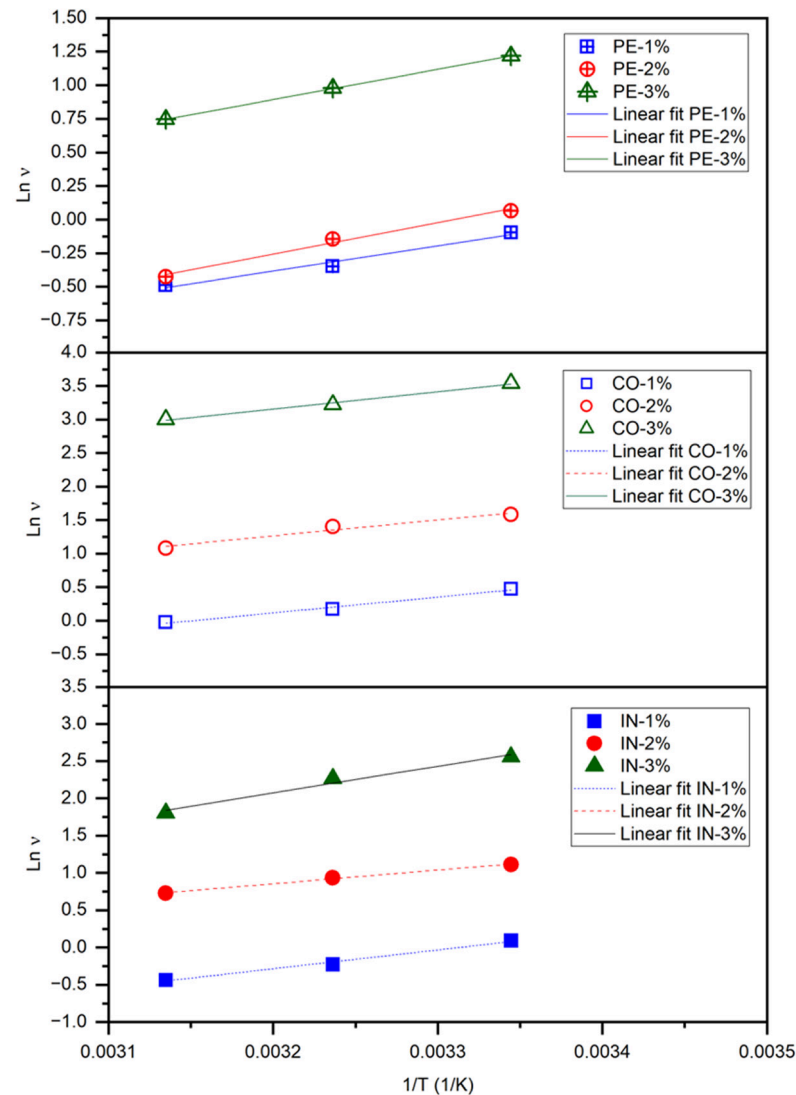


Figure 2. Correlation between $\ln v$ and the inverse of absolute temperature ($1/T$) at different starch concentrations for the varieties Imilla Negra (IN), Compis (CO) and Peruania (PE).

The relationship between starch concentration and kinematic viscosity is relevant for industrial processes involving the formulation and handling of fluid foods [28], as well as for the development of edible films and coatings [29]. In dilute systems such as those evaluated here (1–3% w/v), viscosity changes primarily reflect the combined effects of temperature and concentration under capillary flow conditions. At temperatures above 60–70 °C, starch granules undergo gelatinisation, which is typically associated with swelling and disruption of ordered structures [30]. In the present work, gels were gelatinised before viscosity measurements; therefore, the results reflect the behaviour of already formed dispersions rather than the gelatinisation process itself. From an industrial perspective, the amylose-to-amylopectin ratio may be modified through genetic selection or processing strategies, enabling adjustments in functional properties such as viscosity

and thermal stability [31]. Nevertheless, the present results should be interpreted within the studied experimental range and in terms of apparent kinematic viscosity.

In summary, the variation in starch viscosity with temperature and concentration suggests the technological relevance of native Andean potato starch for applications requiring controlled flow behaviour.

Table 3 shows the pre-exponential factor (ν_0) and activation energy (E_a) for different starch concentrations and Andean potato varieties. The Arrhenius model provided a satisfactory empirical description of the effect of temperature on the apparent kinematic viscosity of the starch gels, as evidenced by the high R^2 values obtained. The pre-exponential factor ranged from 0.00017 ± 0.00023 cSt for Imilla Negra at 3% starch to 0.00625 ± 0.00220 cSt for Compis at 3% starch. No consistent monotonic trend of ν_0 with concentration was observed across all varieties. For Imilla Negra, activation energy values ranged from 15.19 ± 1.01 kJ·mol^{−1} at 2% starch to 29.75 ± 3.65 kJ·mol^{−1} at 3% starch. Within the studied range, E_a values showed variable trends depending on the starch concentration and potato variety. In some cases, an apparent increase in E_a with concentration was observed; however, this tendency was not consistent across all samples and should therefore be interpreted with caution. A higher E_a reflects a stronger dependence of viscosity on temperature, rather than a direct measure of gel structure [32]. Similar behaviour has been reported in other food dispersions, including soursop pulp [22] and Tommy Atkins mango pulp [23]. It should be emphasised that the Arrhenius model provides an empirical description of temperature dependence and does not imply a specific mechanistic interpretation of the microstructure of the starch system.

Table 3. Effect of starch gel concentration from three varieties of potato on the pre-exponential factor and activation energy.

Variety	Starch Concentration (%)	ν_0 (cSt)	E_a (kJ·mol ^{−1})	R^2
Imilla Negra	1	0.00023 ± 0.00001 ^a	21.03 ± 0.20 ^b	0.99
	2	0.00710 ± 0.00240 ^b	15.19 ± 1.01 ^a	0.99
	3	0.00017 ± 0.00023 ^a	29.75 ± 3.65 ^c	0.97
Compis	1	0.00063 ± 0.00033 ^a	19.65 ± 1.41 ^a	0.98
	2	0.00193 ± 0.00100 ^a	19.75 ± 1.25 ^a	0.96
	3	0.00625 ± 0.00220 ^b	21.48 ± 0.77 ^a	0.99
Peruanita	1	0.00172 ± 0.00069 ^b	15.66 ± 0.82 ^a	0.95
	2	0.00049 ± 0.00028 ^a	19.47 ± 1.44 ^b	0.98
	3	0.00183 ± 0.00027 ^b	18.72 ± 0.34 ^b	1.00

ν_0 : pre-exponential (empirical) constant (cSt); E_a : flow activation energy (kJ·mol^{−1}); R^2 , coefficient of determination. Values are expressed as mean $\pm$ standard deviation ($n = 3$). Means in the same column not sharing the same letter are significantly different ($p < 0.05$).

The variability in ν_0 and E_a among varieties may be associated with compositional differences reported in the literature for native potato starches, such as amylose content, phosphorus content and molecular structure [12]. However, these parameters were not experimentally determined in the present study and are therefore proposed only as possible explanatory factors. Overall, the results suggest that the temperature dependence of apparent kinematic viscosity varies among Andean potato varieties and starch concentrations within the studied conditions.

Figure 3 shows the relationship between kinematic viscosity and starch concentration for the Imilla Negra, Compis, and Peruanita varieties at different temperatures. A power-law model was used to fit the experimental data. The results indicate that higher starch concentrations are associated with higher apparent kinematic viscosity in all three varieties. This behaviour is consistent with findings reported for other food dispersions,

such as soursop pulp [22] and Tommy Atkins mango pulp [23], where viscosity increases with solids content. In dilute systems, increasing concentration raises the effective solids fraction, which contributes to higher resistance to flow under capillary conditions [33]. It should be noted that the values reported correspond to apparent kinematic viscosity under capillary flow conditions and therefore reflect the influence of concentration within the studied experimental range. The power-law model applied in this study provides an empirical description of the dependence of viscosity on concentration and does not imply a specific mechanistic interpretation of parameter b or of gel microstructure. Accordingly, the model parameters should be interpreted as fitting coefficients rather than intrinsic physicochemical properties.

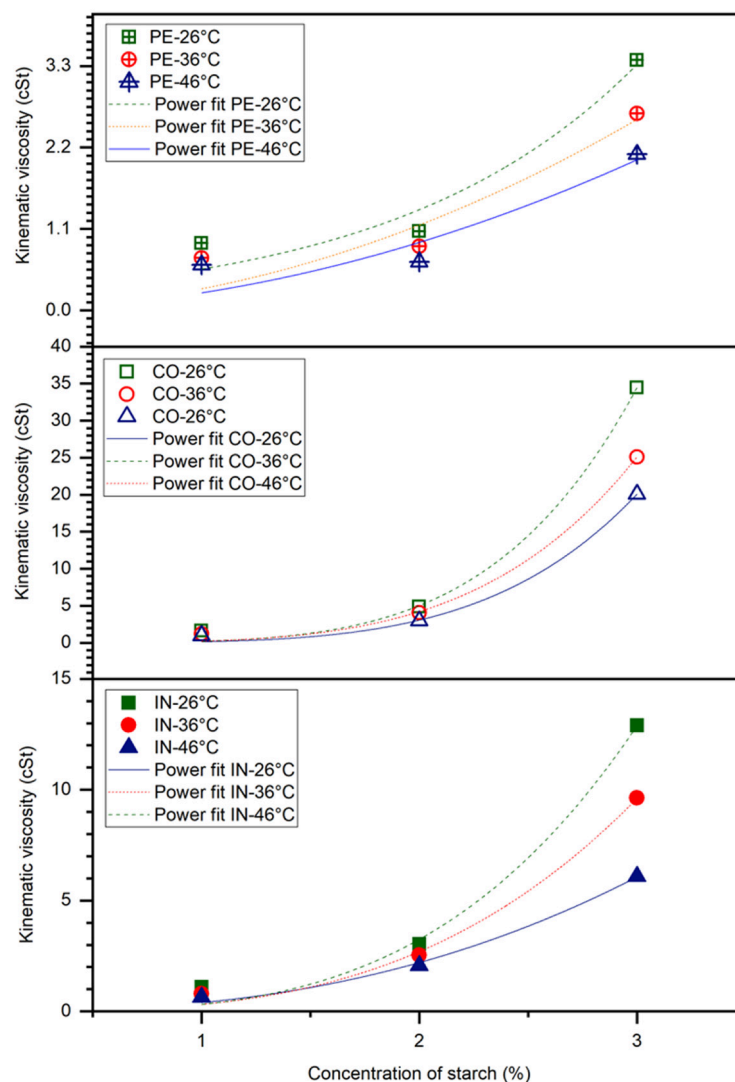


Figure 3. Relationship between apparent kinematic viscosity and starch concentration in Imilla Negra (IN), Compis (CO) and Peruanita (PE) potatoes at different temperatures.

Starch composition, including amylose and amylopectin content, has been reported to influence the functional behaviour of starch-based systems [34]. However, the amylose and amylopectin contents of the starches evaluated in the present study were not experimentally determined; therefore, any compositional explanation is based solely on literature reports. Previous studies have also shown that thermal processing and storage conditions can influence the physicochemical properties of potato starch [33], which may affect its technological performance in food systems [35]. Overall, the results suggest a strong de-

pendence of apparent kinematic viscosity on starch concentration and temperature across the three Andean varieties evaluated.

Table 4 shows the proportionality constants obtained by fitting the experimental data to the power-law model for each temperature and Andean potato variety. The value of constant “a” reached up to 0.38831 ± 0.03683 , while constant “b” reached up to 4.75926 ± 0.10688 . No consistent monotonic trend of parameters a and b with increasing temperature was observed across all varieties. The values of a and b varied depending on both temperature and potato variety. It should be noted that the power-law model provides an empirical description of concentration dependence and does not imply a direct physical interpretation of parameters a and b.

Table 4. Power-law parameters (a and b) for the three Andean potato varieties at different temperatures.

Variety	Temperature (°C)	a	b	R ²
Imilla Negra	26	0.31024 ± 0.05557^a	3.40145 ± 0.18292^b	0.99
	36	0.30869 ± 0.03738^a	3.13244 ± 0.16984^b	0.99
	46	0.38831 ± 0.03683^a	2.50275 ± 0.11917^a	0.99
Compis	26	0.18587 ± 0.02641^b	4.75926 ± 0.10688^b	0.99
	36	0.22687 ± 0.00371^b	4.29977 ± 0.00346^a	0.99
	46	0.12140 ± 0.01452^a	4.65330 ± 0.08593^b	0.99
Peruanita	26	0.35186 ± 0.02108^b	2.03242 ± 0.04756^a	0.85
	36	0.29122 ± 0.06212^{ab}	1.99853 ± 0.16016^a	0.89
	46	0.23521 ± 0.03216^a	1.96896 ± 0.10888^a	0.94

a, proportionality constant (cSt); b, dimensionless exponent; R², coefficient of determination. Means in columns not sharing the same letter are significantly different ($p < 0.05$).

Table 5 summarises the combined effect of temperature and concentration on the apparent kinematic viscosity of starch gels from the three Andean potato varieties. The parameter ν_1 ranged from 0.00014 to 0.00058 cSt, while the parameter n ranged from 2156.678 to 2644.809. The activation energy values (E_a) ranged from 0.0089 to 0.0221 kJ·mol^{−1}. Given the empirical nature of the combined model, these parameters should be interpreted strictly as fitting coefficients rather than intrinsic physicochemical constants. In particular, the relatively high values of parameter n and the low values of E_a reflect the mathematical fitting of the model to the experimental data rather than a direct physical interpretation of the system behaviour. It should be noted that the E_a values obtained from the combined model (Table 5, range: 0.0089–0.0221 kJ·mol^{−1}) differ substantially from those derived from the individual Arrhenius fits (Table 3, range: 15.19–29.75 kJ·mol^{−1}). This discrepancy is attributable to the different mathematical structure of the combined model, in which the concentration term and the exponential temperature term interact simultaneously during regression, altering the scale of the fitted E_a parameter. Therefore, the E_a values in Table 5 should not be compared directly with those in Table 3 and must be interpreted solely as fitting coefficients within the combined empirical model. The model showed an acceptable fit to the experimental data, although variability among varieties was observed. The results reveal that the parameters used to describe the combined effect of temperature and concentration vary depending on the potato variety. These findings are consistent with previous studies on concentrated soursop juice and mango pulp, such as those reported by Villacorta et al. [22] and Ortega et al. [23], which also described a strong dependence of rheological behaviour on temperature and concentration. Nevertheless, the applicability of the model should be considered within the studied experimental range, and caution is recommended when extrapolating beyond these conditions.

Table 5. Combined effect of temperature and concentration on the kinematic viscosity of starch gels from three Andean potato varieties.

Variety	ν_1 (cSt)	n	E_a (kJ·mol ^{−1})	R^2
Imilla Negra	0.00014	2644.81	0.0176	0.96
Compis	0.00038	2441.32	0.0221	0.92
Peruanita	0.00058	2156.68	0.0089	0.73

ν_1 : empirical constant (cSt); n : dimensionless proportionality exponent; E_a : flow activation energy (kJ·mol^{−1}); R^2 : coefficient of determination.

4. Conclusions

The results of this study indicate that temperature and starch concentration significantly influence the apparent kinematic viscosity of starch gels obtained from the three Andean potato varieties evaluated. Kinematic viscosity increased with starch concentration (1–3% *w/v*) and decreased with increasing temperature (26–46 °C) in all varieties studied. A positive correlation was observed between the natural logarithm of kinematic viscosity and the inverse of absolute temperature, suggesting the suitability of the Arrhenius model as an empirical approach to describe the temperature dependence of viscosity under the studied conditions. The Arrhenius model showed a strong fit to the experimental data, with coefficients of determination (R^2) generally higher than 0.96. The calculated activation energy values suggest that the temperature sensitivity of viscosity varied among varieties and concentrations. Similarly, the power-law model provided a satisfactory empirical description of the relationship between viscosity and starch concentration. Among the varieties evaluated, Compis exhibited the highest kinematic viscosity values across the concentration range, particularly at 3% starch and 26 °C, suggesting a greater thickening capacity compared with Imilla Negra and Peruanita within the studied conditions. These results suggest that starch obtained from the Compis variety may present greater potential for applications requiring higher viscosity or thickening performance in food processing systems. It should be noted that the results correspond to apparent kinematic viscosity measured under capillary flow conditions and therefore should be interpreted within the studied experimental range. Overall, the findings provide useful rheological data for the preliminary design and optimisation of processes involving dilute native potato starch dispersions and may support the utilisation and industrial valorisation of native Andean potato varieties in food formulations and processing operations.

Author Contributions: Conceptualization, A.C. and U.A.; methodology, A.C., H.C. and L.V.; formal analysis, U.A. and A.Z.-C.; investigation, L.V., E.G.R. and J.G.R.; Data curation, A.C.; writing—original draft preparation, A.C. and U.A.; writing—review and editing, U.A., C.V.-S. and J.A.-C.; visualisation, A.C. and U.A.; supervision and project administration, N.C.R. and U.A.; funding acquisition, A.C., N.C.R. and J.A.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Calliope, S.R.; Lobo, M.O.; Sammán, N.C. Biodiversity of Andean Potatoes: Morphological, Nutritional and Functional Characterization. *Food Chem.* **2018**, *238*, 42–50. [\[CrossRef\]](#)
- Martínez, P.; Peña, F.; Bello-pérez, L.A.; Núñez-santiago, C. Physicochemical, Functional and Morphological Characterization of Starches Isolated from Three Native Potatoes of the Andean Region. *Food Chem. X* **2019**, *2*, 100030. [\[CrossRef\]](#)
- Sanchez, P.D.C.; Hashim, N.; Shamsudin, R. Trends in Food Science & Technology Applications of Imaging and Spectroscopy Techniques for Non-Destructive Quality Evaluation of Potatoes and Sweet Potatoes: A Review. *Trends Food Sci. Technol.* **2020**, *96*, 208–221. [\[CrossRef\]](#)
- Li, L.; Zhu, T.; Wen, L.; Zhang, T.; Ren, M. Biofortification of Potato Nutrition. *J. Adv. Res.* **2025**, *75*, 23–34. [\[CrossRef\]](#)
- Lewandowicz, J.; Le Thanh-Blicharz, J.; Szwengiel, A. Insight into Rheological Properties and Structure of Native Waxy Starches: Cluster Analysis Grouping. *Molecules* **2024**, *29*, 2669. [\[CrossRef\]](#)
- Ligarda-Samanez, C.A.; Palomino-Rincón, H.; Choque-Quispe, D.; Moscoso-Moscoso, E.; Arévalo-Quijano, J.C.; Huamán-Carrión, M.L.; Quispe-Quezada, U.R.; Muñoz-Saenz, J.C.; Gutiérrez-Gómez, E.; Cabel-Moscoso, D.J.; et al. Bioactive Compounds and Sensory Quality in Chips of Native Potato Clones (*Solanum tuberosum* Spp. Andigena) Grown in the High Andean Region of PERU. *Foods* **2023**, *12*, 2511. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ahmed, S.; Ru, W.; Han, H.; Cheng, L.; Bian, X.; Li, G.; Jin, L.; Wu, P.; Bao, J. Food Hydrocolloids Fine Molecular Structure and Its Effects on Physicochemical Properties of Starches in Potatoes Grown in Two Locations. *Food Hydrocoll.* **2019**, *97*, 105172. [\[CrossRef\]](#)
- Almeida, R.L.J.; dos Santos Pereira, T.; de Andrade Freire, V.; Santiago, Â.M.; Oliveira, H.M.L.; de Sousa Conrado, L.; de Gusmão, R.P. Influence of Enzymatic Hydrolysis on the Properties of Red Rice Starch. *Int. J. Biol. Macromol.* **2019**, *141*, 1210–1219. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hernández-Medina, M.; Torruco-Uco, J.G.; Chel-Guerrero, L.; Betancur-Ancona, D. Caracterización Físicoquímica de Almidones de Tubérculos Cultivados en Yucatán, México. *Food Sci. Technol.* **2008**, *28*, 718–726. [\[CrossRef\]](#)
- Abera, G.; Woldeyes, B.; Dessalegn Demash, H.; Miyake, G.M. Comparison of Physicochemical Properties of Indigenous Ethiopian Tuber Crop (*Coccinia abyssinica*) Starch with Commercially Available Potato and Wheat Starches. *Int. J. Biol. Macromol.* **2019**, *140*, 43–48. [\[CrossRef\]](#)
- Velásquez-Barreto, F.; Velezmoro, C. Propiedades Reológicas y Viscoelásticas de Almidones de Tubérculos Andinos. *Sci. Agropecu.* **2018**, *9*, 189–197. [\[CrossRef\]](#)
- Vargas, G.; Martínez, P.; Velezmoro, C. Functional Properties of Potato (*Solanum tuberosum*) Starch and Its Chemical Modification by Acetylation. *Sci. Agropecu.* **2016**, *7*, 223–230. [\[CrossRef\]](#)
- Yan, X.; McClements, D.J.; Luo, S.; Liu, C.; Ye, J. Recent Advances in the Impact of Gelatinization Degree on Starch: Structure, Properties and Applications. *Carbohydr. Polym.* **2024**, *340*, 122273. [\[CrossRef\]](#)
- Li, S.; Wang, Z.; Feng, D.; Pan, Y.; Li, E.; Wang, J.; Li, C. The Important Role of Starch Fine Molecular Structures in Starch Gelatinization Property with Addition of Sugars/Sugar Alcohols. *Carbohydr. Polym.* **2024**, *330*, 121785. [\[CrossRef\]](#) [\[PubMed\]](#)
- Xie, A.; Li, X.; Zhou, D.; Bai, Y.; Jin, Z. Research on the Quantitative Relationship of the Viscosity Reduction Effect of Large-Ring Cyclodextrin on Potato Starch during Gelatinization Process and Mechanism Analysis. *Carbohydr. Polym.* **2024**, *342*, 122371. [\[CrossRef\]](#)
- Šimková, D.; Lachman, J.; Hamouz, K.; Vokál, B. Effect of Cultivar, Location and Year on Total Starch, Amylose, Phosphorus Content and Starch Grain Size of High Starch Potato Cultivars for Food and Industrial Processing. *Food Chem.* **2013**, *141*, 3872–3880. [\[CrossRef\]](#)
- Singh, P.R.; Heldman, D.R.; Erdogdu, F. *Introduction to Food Engineering*; Academic Press: Cambridge, MA, USA, 2025; ISBN 9780128231296.
- Rao, M.A. *Rheology of Fluid, Semisolid, and Solid Foods: Principles and Applications*, 3rd ed.; Springer: New York, NY, USA, 2014; ISBN 9781461492290.
- Lagarigue, S.; Alvarez, G. The Rheology of Starch Dispersions at High Temperatures and High Shear Rates: A Review. *J. Food Eng.* **2001**, *50*, 189–202. [\[CrossRef\]](#)
- Steffe, J.F. *Rheological Methods in Food Engineering*, 2nd. ed.; Freeman Press: East Lansing, MI, USA, 1996; ISBN 0963203614.
- Natto, Z. Herbs and Oral Health. In *Oral Health Care—An Important Issue of the Modern Society*; Rusu, L.-C., Ardelean, L.C., Eds.; IntechOpen: London, UK, 2022; ISBN 9781803551234.
- Villacorta, L.M.; Vásquez, C.P.; Jara, R.S. Efecto de La Temperatura y Concentración de Sólidos Solubles Sobre Las Propiedades Reológicas de La Pulpa de Guanábana (*Annona muricata* L.). *Pueblo Cont.* **2012**, *23*, 113–124.
- Ortega-Quintana, F.A.; Salcedo-Galván, E.; Arrieta-Rivero, R.; Torres-Gallo, R. Effect of Temperature and Concentration on Rheological Properties of Mango Pulp Variety Tommy Atkins. *Rev. ION* **2015**, *28*, 79–92. [\[CrossRef\]](#)
- Solarte-Montúfar, J.G.; Díaz-Murangal, A.E.; Osorio-Mora, O.; Mejía-España, D.F. Propiedades Reológicas y Funcionales Del Almidón Procedente de Tres Variedades de Papa Criolla. *Inf. Tecnol.* **2019**, *30*, 35–44. [\[CrossRef\]](#)

25. Ahmed, J.; Ramaswamy, H.S.; Ayad, A.; Alli, I. Thermal and Dynamic Rheology of Insoluble Starch from Basmati Rice. *Food Hydrocoll.* **2008**, *22*, 278–287. [[CrossRef](#)]
26. Shang, J.; Liu, C.; Li, L.; Hong, J.; Liu, M.; Liu, Z.; Zhao, B. Effect of Salt and Alkali on the Viscoelastic Behavior of Noodle Dough Sheet with Different Wheat Starch Granule Sizes. *Food Res. Int.* **2024**, *197*, 115185. [[CrossRef](#)]
27. Zheng, L.; Li, W.; Ren, F.; Yu, J.; Yang, Y.; Wang, S. Structure and Functional Properties of Starches from Xiaozhan Rice: Effects of Varieties and Growing Regions. *Food Biosci.* **2024**, *60*, 104501. [[CrossRef](#)]
28. Torres, A.; Montero, P.; Duran, M. Propiedades Físicoquímicas, Morfológicas y Funcionales Del Almidón de Malanga (*Colocasia esculenta*). *Rev. Lasallista Investig.* **2013**, *10*, 52–61.
29. Durango, A.; Soares, N.D.E.F.; Arteaga, M.R. Filmes y Revestimientos Comestibles Cmo Empaques Activos Biodegradables En La Conservacion de Alimentos. *Biotechnol. Sect. Agropecu. Agroind.* **2011**, *9*, 112–118.
30. Kunyane, K.; Phadtaisong, K.; Na Chiangmai, J.; Parittapongsachai, N.; Van Ngo, T.; Luangsakul, N.; Sungsinchai, S. Improving the Swelling Capacity of Granular Cold-Water Rice Starch by Ultrasound-Assisted Alcoholic-Alkaline Treatment. *Ultrason. Sonochem.* **2023**, *98*, 106506. [[CrossRef](#)]
31. Vargas Aguilar, P.; Hernández Villalobos, D. Harinas y Almidones de Yuca, Ñame, Camote y Ñampí: Propiedades Funcionales y Posibles Aplicaciones En La Industria Alimentaria. *Rev. Tecnol. Marcha* **2013**, *26*, 37. [[CrossRef](#)]
32. Dupuis, J.H.; Lu, Z.; Yada, R.Y.; Liu, Q. The Effect of Thermal Processing and Storage on the Physicochemical Properties and In Vitro Digestibility of Potatoes. *Int. J. Food Sci. Technol.* **2016**, *51*, 2233–2241. [[CrossRef](#)]
33. Shiotsubo, T.; Takahashi, K. Agricultural and Biological Chemistry Differential Thermal Analysis of Potato Starch Gelatinization. *Agric. Biol. Chem.* **1984**, *48*, 37–41. [[CrossRef](#)]
34. Tester, R.F.; Karkalas, J.; Qi, X. Starch—Composition, Fine Structure and Architecture. *J. Cereal Sci.* **2004**, *39*, 151–165. [[CrossRef](#)]
35. Conlon, M.A.; Kerr, C.A.; Mcsweeney, C.S.; Dunne, R.A.; Shaw, J.M.; Kang, S.; Bird, A.R.; Morell, M.K.; Lockett, T.J.; Molloy, P.L.; et al. Resistant Starches Protect against Colonic DNA Damage and Alter Microbiota and Gene Expression in Rats Fed a Western Diet 1–3. *J. Nutr.* **2012**, *142*, 832–840. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.