



Rheological Properties of Hydrocolloid Stabilizers and Determination of Their Concentration in Plant-Based Milk Formulations

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Abstract— The rapid growth of plant-based milk consumption, driven by health awareness, lactose intolerance, and environmental sustainability concerns, has increased the demand for products with stable physical properties and acceptable mouthfeel. Meeting these quality expectations requires precise control of formulation parameters, particularly the type and concentration of hydrocolloid stabilizers used to govern texture and stability. This study aimed to develop and validate a non-linear regression modelling framework, guided by rheological characterization of commercial plant-based milk benchmarks, to predict optimal concentration ranges of five commonly used hydrocolloid stabilizers (gellan gum, xanthan gum, guar gum, carrageenan, and carboxymethyl cellulose). Rheological properties were evaluated using modular compact rheometer, and the relationships between stabilizer concentration and key rheological parameters—flow behavior index (n), consistency index (K), and apparent viscosity at 50 s^{-1} —were modelled using logarithmic and power-law regression. The models demonstrated strong predictive performance ($R^2 > 0.97$ for most stabilizers) and the predicted optimal concentration ranges for each stabilizer were determined as follows: carrageenan (0.0583–0.3613%), CMC (0.0148–0.1121%), guar gum (0.0718–0.1859%), xanthan gum (0.0596–0.2249%), and gellan gum (0.0581–0.1373%). The predicted concentration ranges provide practical guidance for reducing trial-and-error formulation, shortening product development time, and improving formulation reproducibility in the food industry. Nevertheless, model validation was limited to soy milk, and further studies are required to extend its applicability to other plant-based matrices.

Keywords— concentration, plant-based milk, rheology, stability, stabilizers.

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I. INTRODUCTION

The global demand for plant-based milk has increased rapidly due to growing health awareness, lactose intolerance, and concerns over environmental sustainability, positioning these products as important alternatives to conventional dairy milk [1,2]. In addition to these factors, limitations associated with cow's milk consumption—including digestive intolerance, safety concerns, and cost—have further encouraged consumers to shift toward plant-based alternatives. Plant-based milk is commonly produced from legumes, cereals, nuts, and seeds such as soy, oat, and almond, and is formulated to resemble cow's milk in appearance, texture, and functionality [3,4].

Despite their growing popularity, plant-based milk products face significant formulation challenges. Inherent differences in protein composition, lipid structure, and total solids content often result in physical instability during storage, such as sedimentation or creaming [5]. Moreover, achieving a desirable

mouthfeel and texture comparable to dairy counterparts remains difficult. Product stability and texture are critical determinants of consumer acceptance and are primarily governed by the rheological properties of the final product, making their control a major technological challenge in plant-based milk formulation [6].

Hydrocolloid stabilizers are therefore widely incorporated to improve viscosity, suspension stability, and sensory attributes of plant-based milk [7]. These stabilizers interact with water, proteins, and other components to form structured networks that retard particle sedimentation and modify flow behaviour. However, their effectiveness depends strongly on both stabilizer type and concentration [8]. Inappropriate stabilizer selection or dosage may lead to undesirable textural defects, excessive thickening, gelation, or reduced consumer acceptance, highlighting the importance of rational stabilizer concentration selection.

Rheological characterization provides a quantitative framework for evaluating flow behaviour, consistency, and apparent viscosity of liquid food systems [9]. Most plant-based milk products exhibit non-Newtonian, shear-thinning behaviour, which directly influences processing performance, pouring behaviour, and oral perception [10]. Although numerous studies have reported the rheological properties of individual hydrocolloids and plant-based milk systems, these investigations are largely descriptive and often focus on specific stabilizers or formulations. Consequently, they offer limited guidance for defining appropriate stabilizer concentration ranges applicable across different product systems.

As a result, stabilizer concentration selection in industrial practice remains largely empirical, relying on time-consuming trial-and-error approaches that are resource-intensive and difficult to reproduce consistently at industrial scale [11]. Despite the growing availability of rheological data, predictive modelling tools that translate rheological measurements into actionable formulation guidelines remain scarce, particularly those validated against commercially accepted product benchmarks.

Therefore, this study aimed to integrate rheological characterization of commercial plant-based milk products with non-linear regression modelling of hydrocolloid stabilizer systems to predict optimal stabilizer concentration ranges. By anchoring model predictions to rheological benchmarks derived from market-accepted products, the proposed framework seeks to reduce reliance on empirical formulation trials, improve formulation efficiency, and enhance reproducibility in plant-based milk development.

II. MATERIAL AND METHODS

A. Material

This study utilized various types of commercially available plant-based milk and stabilizers, along with ingredients for homemade soy milk preparation. The milk samples included soy milk, oat milk, almond milk, pistachio milk, mung bean-based beverages, and full-cream UHT cow's milk. All beverage samples were obtained from local supermarkets in Jakarta, Indonesia. The stabilizers used in this study included gellan gum, xanthan gum, guar gum, carrageenan, and carboxymethyl cellulose (CMC), which were procured from a local food additive supplier. Ingredients for homemade soy milk preparation included dried soybeans sourced from an organic food store in Jakarta, along with granulated sugar, vanillin salt, and water.

The equipment used in this study consisted of tools for the production of plant-based milk and tools for analysis. In the plant-based milk preparation stage, the equipment included beakers of various sizes (Duran, Germany), a Guardian 5000 hot plate stirrer (Ohaus, Germany), a T25 Digital Ultra Turrax high-speed mixer (Ika, Malaysia), a 200-mesh nylon filter cloth (Sumber Filtech Mandiri, Indonesia), a pot, and glass bottles.

The analytical instruments used were a Digital Pocket Refractometer (Atago, Japan) and a Modular Compact Rheometer MCR 92 (Anton Paar, Austria), which was connected to RheoCompass software for data processing and rheological analysis.

B. Methods

Characterization of rheological properties of commercial plant-based milk

This stage aimed to assess the actual rheological characteristics of plant-based milk products available in the market as a benchmark for stable and consumer-accepted formulations. The procedure included stratified random sampling [12] based on plant sources (e.g., soy, oat, almond and other milk). The samples consisted of five Soy milk products, four oat milk products, three almond milk products, one mung bean and one pistachio milk product, as well as one UHT cow's milk sample used as a reference. Packaging label identification, °Brix measurement using a refractometer, and rheological analysis were performed. Packaging label identification included collecting information on product composition, particularly the types of stabilizers listed.

Prior to rheological measurement, all plant-based milk samples were gently homogenized by mechanical stirring or shaking to ensure uniform particle distribution and to disrupt any aggregates formed during storage. The samples were then filtered through a coarse sieve (100–200 µm) to remove large particles that could interfere with viscosity measurements. Subsequently, samples were allowed to equilibrate at the measurement temperature to minimize the influence of temperature fluctuations on rheological parameters.

Rheological analysis was conducted using a Modular Compact Rheometer MCR 92 (Anton Paar) under controlled temperature conditions (25 ± 1 °C) to determine the flow behaviour index (n), consistency index (K), and apparent viscosity at a shear rate of 50 s^{-1} . The measurements were carried out over a shear rate range of $0.1\text{--}1000 \text{ s}^{-1}$ [15] for a duration of 300 seconds (with readings taken every 2.5 seconds).

The Power Law model was applied to interpret the rheological characteristics of the commercial plant-based milk samples. Rheological measurements were performed using continuous shear sweep tests under identical conditions for all samples. Due to the high repeatability of the rheometer, a representative measurement per formulation was considered sufficient for comparative rheological modelling.

Rheological mapping of stabilizer solutions at varying concentrations

This stage evaluated the effect of stabilizer type and concentration on solution rheology to understand their functional behaviour in liquid systems. Stabilizers used included CMC, gellan gum, xanthan gum, guar gum, and carrageenan. Each stabilizer was evaluated at four concentration levels, with overall concentrations ranging from 0.05% to 0.70% (w/w). The selection of concentration levels was based on the functional characteristics of each stabilizer,

particularly their thickening and gelling tendencies, as well as their common application ranges in plant-based beverage formulations. The specific concentration levels applied to each stabilizer are summarized in **Table 1**.

TABLE 1
 CONCENTRATION LEVELS OF HYDROCOLLOID STABILIZERS USED IN THIS STUDY

Stabilizer	Concentration levels (% w/w)
CMC	0.05; 0.10; 0.30; 0.50
Gellan gum	0.10; 0.20; 0.30; 0.50
Guar gum	0.10; 0.20; 0.30; 0.50
Carrageenan	0.10; 0.30; 0.50; 0.70
Xanthan gum	0.10; 0.30; 0.50; 0.70

Stabilizer solutions were prepared by dispersing the hydrocolloids in distilled water, followed by heating at 70 °C to ensure complete hydration. The solutions were allowed to rest before being stored at 4–10 °C prior to analysis [13]. Rheological properties (n , K , and apparent viscosity at 50 s⁻¹) were analyzed using a modular compact rheometer under the same measurement conditions as those applied for the commercial plant-based milk samples, including shear rate range and data interpretation using the Power Law model.

Prediction of stabilizer concentration for application in plant-based milk formulation

Regression modeling was conducted to predict the stabilizer concentrations required to achieve rheological characteristics similar to those of commercial plant-based milk products. Regression modeling (polynomial, exponential, power, logarithmic) was performed to predict optimal stabilizer concentrations based on commercial plant-based milk values. The best-fit model was selected using the coefficient of determination (R^2) [14]. Each regression equation was used to estimate the stabilizer concentrations that produce rheological values similar to commercial products, helping to define the ideal concentration range for each stabilizer.

Application of stabilizers in plant-based milk and their verification in soy milk

Predicted concentrations were applied to soy milk formulations for experimental verification. Soy milk was prepared from raw soybeans following a controlled laboratory-scale process. Soybeans were soaked (1:2 w/w) for 6 h, boiled, blended with water (1:10 w/w), and filtered to obtain soy extract. The extract was then mixed with the predicted concentrations of stabilizers, sugar, vanillin, and salt, homogenized at 15,000 rpm for 10 min, bottled, and pasteurized at 90 °C for 20 min [15]. The rheological characteristics of the soy milk with stabilizer addition were then determined and compared with the targeted rheological properties to verify the accuracy of the regression model predictions.

III. RESULT AND DISCUSSION

Rheological characteristics of commercial plant-based milk

Plant-based milk is an emulsion derived from plant materials and formulated to mimic cow's milk in both appearance and sensory characteristics. Due to inherent differences in protein composition, lipid structure, and total solids content compared to dairy milk, plant-based milks are more prone to physical instability such as sedimentation or phase separation. These products generally require the addition of thickening agents, particularly hydrocolloids, to enhance physical stability during storage. Hydrocolloids are incorporated to improve structural characteristics, texture, and stability, and their effects can be evaluated through rheological measurements [16,17]. Rheology studies the relationship between shear stress and shear rate in fluids, which is essential for understanding flow behaviour and texture in liquid products, including plant-based milk [18,19].

All commercial plant-based milk samples evaluated in this study exhibited non-Newtonian pseudoplastic (shear-thinning) behaviour, as indicated by flow behaviour index (n) values below 1 [20]. This behaviour is desirable for beverage applications, as it allows the product to remain viscous at low shear rates (enhancing stability during storage) while becoming less viscous under higher shear rates (facilitating pouring and oral processing). The representative flow behaviour and apparent viscosity curves of commercial Soy milk products (**Figure 1** and **Figure 2**) demonstrate this characteristic trend, which was consistently observed across all plant-based milk categories evaluated. The rheological curve of soy milk is presented as a representative example, since similar patterns were observed for all commercial plant-based milk samples and the UHT cow's milk sample.

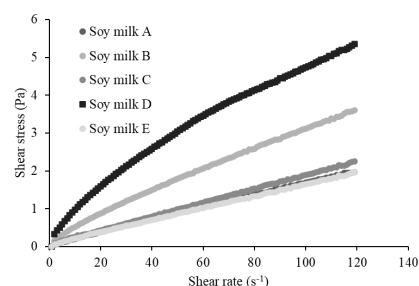


Fig. 1 Shear stress as a function of shear rate for five commercial Soy milk products (A–E), illustrating non-Newtonian shear-thinning behaviour and differences in flow resistance among formulations.

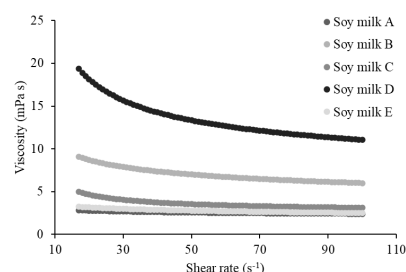


Fig. 2 Apparent viscosity as a function of shear rate for five commercial Soy milk products (A–E), showing variations in viscosity and flow behaviour.

Grouping the samples by plant source (soy, oat, almond, other plant-based variants, and dairy milk) allowed clearer interpretation of how raw material composition and formulation strategies influence rheological behaviour as shown in **Table 2**. Variations in n , K , and apparent viscosity among products also reflect differences in stabilizer type, stabilizer concentration, total solids content, and processing conditions rather than plant source alone.

TABLE 2
 RHEOLOGICAL PROPERTIES OF COMMERCIAL PLANT-BASED MILK SAMPLES

Products name	Rheological properties			°Brix
	n	K (Pa·s ⁿ)	Viscosity 50 s ⁻¹ (mPa·s)	
Soy milk A	0.9157	0.0035	2.5561	13.3
Soy milk B	0.7769	0.0165	7.0438	13.9
Soy milk C	0.8525	0.0059	3.4585	10.8
Soy milk D	0.8823	0.0043	2.7782	13.7
Soy milk E	0.6897	0.0463	13.3990	17.8
Soy milk average	0.8234	0.0153	5.8471	13.9
Oat milk A	0.9844	0.0014	1.3075	12.3
Oat milk B	0.9490	0.0042	3.6500	9.5
Oat milk C	0.9823	0.0033	3.0432	14.0
Oat milk D	0.8454	0.0070	3.8448	11.7
Oat milk average	0.9403	0.0040	2.9614	11.9
Almond milk A	0.7476	0.0141	5.2687	6.2
Almond milk B	0.7122	0.0185	6.0124	8.6
Almond milk C	0.6521	0.0294	7.6735	7.5
Almond milk average	0.7040	0.0207	6.3182	7.4
Mungbean drink	0.7719	0.0309	12.6000	10.6
Pistachio milk	0.8038	0.0105	4.8178	9.7
Other milk average	0.7879	0.0207	8.7089	10.2
Cow milk	0.9919	0.0019	1.8331	13.7

The soy milk group had average values of $n = 0.8234$, $K = 0.0153$ Pa·sⁿ, and apparent viscosity = 5.8471 mPa·s at 50 s⁻¹. Variability among samples was associated with the type and concentration of stabilizer used, total solids, and soybean content. The product with the lowest viscosity (soy milk A) used sodium bicarbonate, which is often used to adjust pH in plant-based milks. Sodium bicarbonate does not increase viscosity, but it enhances protein extraction and reduces lipoxygenase activity [21]. In contrast, a soy drink with added carrageenan and high soybean content (soy milk E) had the highest °Brix and viscosity, supporting previous findings that carrageenan improves the rheological properties of plant-based milk.

The Oat milk group had the highest average flow behaviour index (n) of 0.9403 (closer to Newtonian fluid behaviour), however, it also had the lowest consistency index (0.0040 Pa·sⁿ) and the lowest viscosity at 50 s⁻¹ (2.9614 mPa·s). This is likely due to oats' high carbohydrate content (about 60% starch) and higher amylose content (20–28%) compared to legumes [22]. These starches may gelatinize during heat treatment, so oat milk is often processed with enzymatic hydrolysis to prevent starch

gelatinization that could reduce product acceptability [23]. Some products also include calcium salts like calcium carbonate as stabilizers to improve colloidal stability. Interestingly, despite using less oat (2.48%), oat milk D had the highest viscosity likely due to added ingredients such as soy protein isolate, fibre, and stabilizers. Oat milk B in other hand, which used no stabilizer, showed the lowest viscosity.

Almond milk group displayed the lowest average flow behaviour index ($n = 0.7040$), but relatively high viscosity, possibly due to the use of gellan gum, which enhances mouthfeel [24]. Almond milk A (2% almond) exhibited the lowest viscosity, while almond milk C (4.2% almond) exhibited the highest values.

Other plant-based milk products, such as mung bean drink and pistachio milk, had the highest average viscosity (8.7089 mPa·s), with $n = 0.7879$ and $K = 0.0207$ Pa·sⁿ. The high viscosity of mung bean drinks may be due to starch gelatinization during heating, which forms gels that retain water and increase thickness. In addition, mung bean proteins like globulin and albumin may form structures during processing that enhance viscosity [25].

As a comparison, cow's milk (UHT full cream) had a flow behaviour index of 0.9919 and the lowest viscosity (1.8331 mPa·s). This sample was included to contrast the flow profile of dairy and plant-based milk. Although plant-based products are formulated to resemble dairy milk in appearance and function, differences in protein and fat composition affect their rheological properties [19].

Rheological Properties of Stabilizers at Various Concentrations

The rheological responses observed across the five hydrocolloid stabilizers can be mechanistically explained by differences in molecular structure, chain flexibility, and interaction potential with plant-based milk components. Shear-thinning behaviour ($n < 1$) was consistently observed across all stabilizers and concentrations tested, indicating progressive disruption and alignment of polymer chains under increasing shear.

To avoid redundancy, the flow and apparent viscosity curves of guar gum are presented in **Figure 3** and **Figure 4** as a representative example for the other stabilizers due to their similar rheological patterns.

Increasing stabilizer concentration resulted in higher apparent viscosity and consistency index (K), accompanied by lower n values (as shown in **Table 3**), indicating the formation of increasingly structured polymer networks. At low concentrations, the molecules move freely, but as concentration increases, entanglement between polymer chains occurs, increasing collision frequency and molecular friction, thereby enhancing solution viscosity [26,27]. Longer polymer chains contribute to thicker colloidal structures [28].

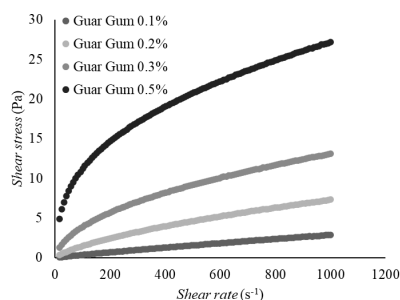


Fig. 3 Shear stress as a function of shear rate for guar gum solutions at different concentrations (0.1–0.5%), illustrating non-Newtonian shear-thinning behaviour and the concentration-dependent increase in flow resistance.

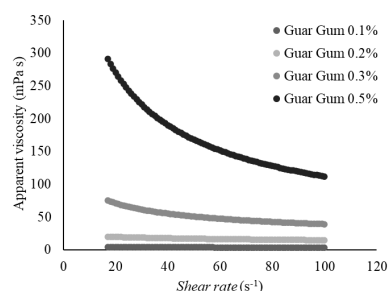


Fig. 4 Apparent viscosity as a function of shear rate for guar gum solutions at different concentrations (0.1–0.5%), showing pronounced shear-thinning behaviour and a concentration-dependent increase in viscosity.

TABLE 3
RHEOLOGICAL PROPERTIES OF STABILIZERS TESTED AT VARIOUS CONCENTRATIONS

Stabilizer type	Concen- trations (%)	Rheological Properties		
		n	K (Pa·s ^{n})	Viscosity 50 s ⁻¹ (mPa·s)
Carrageenan	0.10	0.8785	0.0101	6.0374
	0.30	0.8831	0.0192	11.7070
	0.50	0.8806	0.0325	19.5400
	0.70	0.4451	1.0021	118.6400
CMC	0.05	0.8103	0.0118	5.4753
	0.10	0.7280	0.0438	14.7910
	0.30	0.6020	0.2958	61.2850
	0.50	0.5264	0.8202	127.2500
Guar gum	0.10	0.9061	0.0056	3.8031
	0.20	0.7172	0.0531	17.0990
	0.30	0.5450	0.3093	51.1240
	0.50	0.3941	1.7931	168.2000
Xanthan gum	0.10	0.8694	0.0058	3.3852
	0.30	0.6467	0.0952	23.2400
	0.50	0.5235	0.3684	55.9880
	0.70	0.4277	0.9615	101.9200
Gellan gum	0.10	0.7314	0.0130	4.6381
	0.20	0.5090	0.1372	20.2830
	0.30	0.2324	1.4278	78.7490
	0.50	0.0650	6.1597	188.2000

Distinct differences among stabilizers were observed due to variations in molecular structure and interaction mechanisms. Xanthan gum exhibited strong pseudoplasticity and high consistency index values, attributable to its rigid, double-helical backbone and high molecular weight, which promote entanglement and resistance to flow at low shear rates [28]. In contrast, guar gum exhibited a pseudoplastic flow behaviour, attributed to its high galactomannan content—a polysaccharide composed of a mannose backbone and galactose branches. Galactomannan is valued for its efficiency in producing viscous solutions even at low usage levels, which supports its widespread use as a thickener. Numerous studies have explored its rheological properties, emphasizing its significant effect on viscosity, flow behaviour, and overall consistency of solutions. A similar behaviour was also reported [30] in dispersions of young sugar palm fruit (*Arenga pinnata*), which is also rich in galactomannan.

Carrageenan and gellan gum demonstrated concentration-dependent transitions associated with network formation. Carrageenan interacts electrostatically with plant proteins and cations, forming weak gel-like structures that enhance suspension stability but may induce excessive thickening at higher concentrations [31]. Low-acyl gellan gum, even at low concentrations, can form ordered junction zones through double-helix aggregation, explaining the sharp increase in viscosity and consistency index observed beyond critical concentrations [32]. CMC, as a linear, anionic cellulose derivative, increased viscosity mainly through water binding and polymer overlap, producing smoother flow behaviour with lower yield tendencies compared to gellan or carrageenan systems [33,34]. These results highlight that stabilizer effectiveness is governed not only by concentration but also by molecular architecture and interaction potential. While all stabilizers exhibited shear-thinning behaviour desirable for plant-based milk applications, their distinct rheological profiles underscore the importance of selecting appropriate stabilizer types and concentrations to achieve targeted texture and stability without compromising pourability or sensory acceptance.

Predictive model of stabilizer concentration range based on rheological properties

Based on the rheological data in **Table 1**, soy milk E was used as the upper limit, while oat milk B was selected as the lower limit. Justification of rheological boundaries based on commercial benchmarks and their representative positioning within the commercial product spectrum. The selection of Soy Milk E (representing the upper limit of viscosity) and Oat Milk B (representing the lower, more fluid limit) was not arbitrary but was based on a combination of consumer acceptability and industrial stability criteria. Soy Milk E displayed a high consistency coefficient and a relatively low n value, placing it at the boundary for a thick, stable, and highly viscous mouthfeel that reduces sedimentation. Conversely, Oat Milk B represented the threshold for adequate emulsion stability while maintaining

the required fluidity for processing and consumer pourability. Using these products as boundaries ensured that predicted stabilizer concentration ranges remained practically relevant and aligned with market-accepted textures rather than theoretical extremes.

To translate these rheological trends into practical formulation guidance, predicted concentration ranges were derived by intersecting the regression models with rheological boundaries established from commercial plant-based milk benchmarks. Rather than targeting single-point values, the modelling approach defines acceptable concentration windows that simultaneously satisfy multiple rheological criteria (n , K , and apparent viscosity). This multi-parameter constraint reduces the likelihood of selecting concentrations that meet one rheological target while compromising others.

The mathematical forms for nonlinear regression models can include exponential, power, and logarithmic regressions [35]. The closer the coefficient of determination (R^2) value is to one, the stronger the ability of the independent variable to explain the dependent variable, indicating that the model explains the variability in the data very well [14]. Based on the R^2 value calculation, for the relationship between flow behaviour index (n) and stabilizer concentration, logarithmic regression was used as the best fit model due to its highest R^2 . The relationship between stabilizer concentration and flow behaviour index is shown in Figure 5.

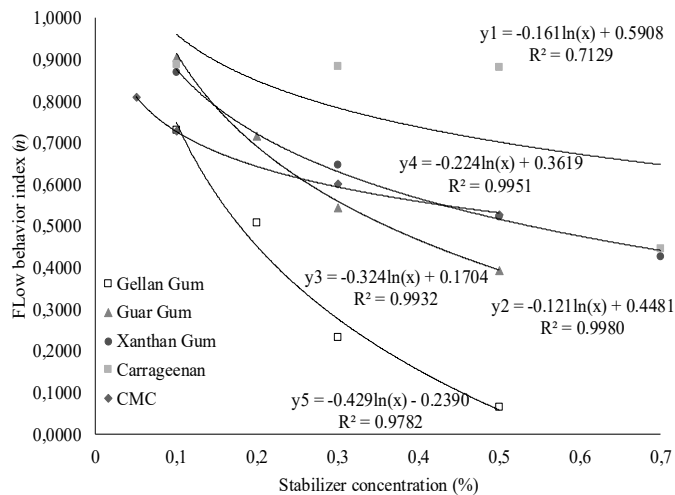


Fig. 5 Relationship between stabilizer concentration (%) and flow behaviour index (n) for different hydrocolloids, illustrating differences in flow behaviour as affected by stabilizer type and concentration, fitted using logarithmic regression.

Based on the defined upper and lower limits, the concentration range was estimated. The predicted concentration ranges based on the flow behaviour index (n) are presented in Table 4.

TABLE 4
PREDICTED STABILIZER CONCENTRATION RANGE BASED ON THE FLOW BEHAVIOUR INDEX (n)

Stabilizer type	Equations	Concentration range (%)
Carrageenan	$y = -0.161\ln(x) + 0.5908$	0.0868–0.5410
CMC	$y = -0.224\ln(x) + 0.3619$	0.0119–0.1358
Guar gum	$y = -0.324\ln(x) + 0.1704$	0.0811–0.2013
Xanthan gum	$y = -0.121\ln(x) + 0.4481$	0.0621–0.2314
Gellan gum	$y = -0.429\ln(x) - 0.2390$	0.0577–0.1148

Based on the R^2 values for the relationship between consistency index (K) and stabilizer concentration, the Power Law regression was selected. The relationship between stabilizer concentration and consistency index (K) is shown in Figure 6.

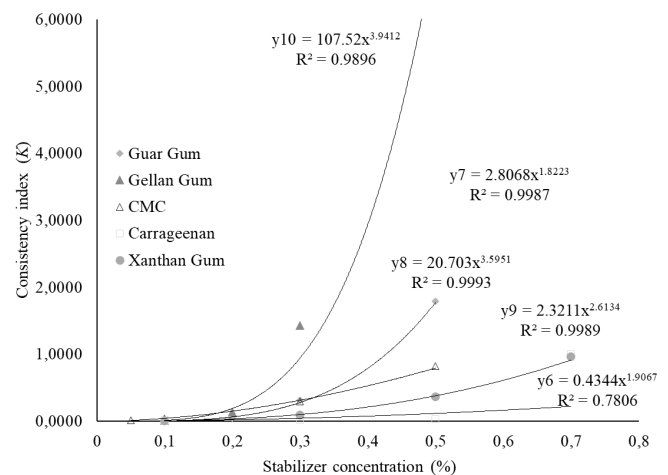


Fig. 6 Relationship between stabilizer concentration (%) and consistency index (K) for different hydrocolloids, illustrating differences in flow behaviour as affected by stabilizer type and concentration, fitted using Power Law regression.

The predicted stabilizer concentration ranges corresponding to the consistency index (K) are shown in Table 5.

TABLE 5
PREDICTED STABILIZER CONCENTRATION RANGE BASED ON THE CONSISTENCY INDEX (K)

Stabilizer type	Equations	Concentration range (%)
Carrageenan	$y = 0.4344x^{1.9067}$	0.0493–0.3091
CMC	$y = 2.8068x^{1.8223}$	0.0154–0.1051
Guar gum	$y = 20.703x^{3.5951}$	0.0692–0.1831
Xanthan gum	$y = 2.3211x^{2.6134}$	0.0586–0.2236
Gellan gum	$y = 107.52x^{3.9412}$	0.0576–0.1399

The Power Law regression was used as the best fit model for the relationship between apparent viscosity and stabilizer concentration because it had the R^2 value closest to one. The

relationship between stabilizer concentration and apparent viscosity is shown in **Figure 7**.

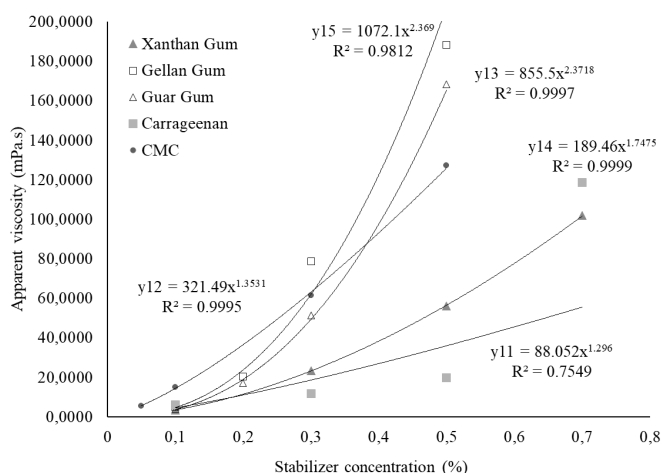


Fig. 7 Relationship between stabilizer concentration (%) and apparent viscosity for different hydrocolloids, illustrating differences in flow behaviour as affected by stabilizer type and concentration, fitted using Power Law regression.

The predicted stabilizer concentration ranges corresponding to the apparent viscosity at a shear rate of 50 s^{-1} are shown in **Table 6**.

TABLE 6
PREDICTED STABILIZER CONCENTRATION RANGE BASED ON APPARENT VISCOSITY

Stabilizer type	Equations	Concentration range (%)
Carrageenan	$y = 88.052x^{1.296}$	0.0388–0.2339
CMC	$y = 321.49x^{1.3531}$	0.0171–0.0955
Guar gum	$y = 855.50x^{2.3718}$	0.0650–0.1733
Xanthan gum	$y = 189.46x^{1.7475}$	0.0580–0.2196
Gellan gum	$y = 1072.1x^{2.369}$	0.0589–0.1573

The concentration range was estimated for each type of stabilizer based on the defined upper and lower limits. After predicting the concentration ranges for all three parameters the average range for each stabilizer was calculated. These average ranges are proposed for use in formulating plant-based milk products (soy milk). The results are presented in **Table 7**.

TABLE 7
AVERAGE RANGE OF STABILIZER CONCENTRATION

Stabilizer type	Concentration range (%)
Carrageenan	0.0583–0.3613
CMC	0.0148–0.1121
Guar gum	0.0718–0.1859
Xanthan gum	0.0596–0.2249
Gellan gum	0.0581–0.1373

The convergence of predicted concentration ranges across different rheological parameters strengthens the robustness of

the modelling framework. Stabilizers exhibiting narrow overlap regions, such as gellan gum, require precise dosage control, whereas stabilizers such as CMC and guar gum offer broader formulation flexibility. These differences have direct implications for industrial application, where robustness to processing variability is often as important as achieving target texture.

Application and Verification of Predicted Stabilizer Concentrations in Soy Milk

Although mathematical modeling serves as the basis for determining the stabilizer concentrations used, the actual results may also be influenced by other components in the plant-based milk formulation, such as proteins, fats, sugars, and salts. Therefore, this verification stage is essential to ensure that the resulting plant-based milk product meets the targeted rheological characteristics. In this stage, each stabilizer was tested at two concentrations selected based on the predicted range. One point was set at the lower limit of the range to assess the product's response to stabilizer addition, while the second point was chosen at the mid-low range or near the upper limit before the texture becomes overly thick or gel-like. Based on this consideration, the following concentrations were used: carrageenan at 0.05% and 0.10%; CMC at 0.05% and 0.10%; guar gum at 0.07% and 0.10%; xanthan gum at 0.10% and 0.20%; and gellan gum at 0.05% and 0.10%.

The soy milk formulations in this study consisted of 6.00% sugar, 0.10% salt, and 0.02% vanillin. The addition of the stabilizer was carried out according to the predetermined concentration. A control formulation without stabilizer was also prepared. After combining all components, soy extract was added to each formulation to reach a total of 100%. This procedure enabled the assessment of the impact of stabilizer type and concentration on the rheological characteristics of soy milk.

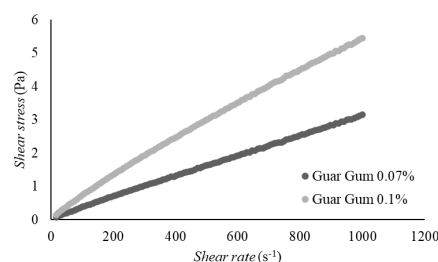


Fig. 8 Shear stress as a function of shear rate for soy milk using guar gum at different concentrations, illustrating non-Newtonian shear-thinning behaviour and the concentration-dependent increase in flow resistance.

All soy milk samples with stabilizer application exhibited non-Newtonian shear-thinning behaviour, characterized by an increase in shear rate greater than the increase in shear stress, and a decreasing viscosity trend as shear rate increased [20], [36]. These rheological patterns were consistent with

commercial plant-based milk products and support previous findings [19]. To avoid redundancy, only the flow behaviour and viscosity curve of soy milk with guar gum are shown in **Figure 8** and **Figure 9** as a representative, since other stabilizers (xanthan gum, CMC, carrageenan, and gellan gum) demonstrated similar profiles.

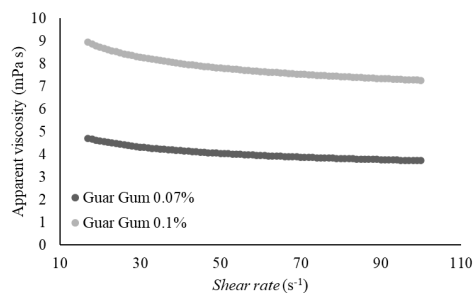


Fig. 9 Apparent viscosity as a function of shear rate for soy milk using guar gum at different concentrations, showing pronounced shear-thinning behaviour and a concentration-dependent increase in viscosity.

All soy milk formulations containing stabilizers had flow behaviour index (n) values below 1, confirming shear-thinning and pseudoplastic characteristics across treatments. The rheological properties of soy milk with each stabilizer are shown in **Table 7**.

TABLE 7
RHEOLOGICAL PROPERTIES OF SOY MILK WITH PREDICTED STABILIZER CONCENTRATIONS

Stabilizer type	Concentrations (%)	Rheological Properties			°Brix
		n	K (Pa·s ^{n})	Viscosity 50s ⁻¹ (mPa·s)	
Control		0.9049	0.0025	1.7434	10.85
Xanthan gum	0.10	0.8666	0.0083	4.8460	11.20
	0.20	0.7744	0.0283	11.2610	10.80
Guar gum	0.07	0.8951	0.0093	5.9261	11.70
	0.10	0.8775	0.0128	7.7875	11.75
CMC	0.05	0.9127	0.0059	4.1351	10.90
	0.10	0.8753	0.0128	7.6365	11.10
Carrageenan	0.02	0.7518	0.0135	5.1332	11.20
	0.05	0.6999	0.0413	12.5500	10.90
Gellan gum	0.10	0.5581	0.0912	55.9880	11.10
	0.05	0.8141	0.0073	4.6381	10.75
Gellan gum	0.10	0.7164	0.0178	20.2830	11.10

Most formulations fell within the target rheological ranges determined from commercial products ($n = 0.6897\text{--}0.9490$, $K = 0.0042\text{--}0.0463$ Pa·s ^{n} , and apparent viscosity = 3.6500–13.3990 mPa·s). However, carrageenan at 0.1% exceeded the viscosity threshold, likely due to its strong water-binding and gelling capabilities, particularly of the kappa-type used in this study [37,38]. As carrageenan tends to significantly increase viscosity and form strong gels, with gel strength increasing as its concentration rises [30],[40], an additional lower-dose formula

(0.02%) was tested. This adjustment was made because the 0.05% carrageenan sample already approached the upper rheological limits. Previous studies [5] suggest that 0.02–0.04% carrageenan is sufficient for stabilizing legume-based milk.

The addition of various types of stabilizers (hydrocolloids) to plant-based milk showed a significant effect on rheological parameters, including apparent viscosity at shear rate 50 s⁻¹, flow behaviour index (n), and consistency index (K). In general, increasing gum concentration from 0.05% to 0.2% increased viscosity and the consistency index, while decreasing n , indicating a shift toward more pronounced pseudoplastic fluid characteristics.

Nevertheless, all stabilizers evaluated produced rheological properties that remained within consumer-acceptable limits when formulated within the predicted concentration windows. From an industrial and product development perspective, the proposed predictive modelling framework offers a systematic alternative to empirical trial-and-error formulation by providing stabilizer concentration ranges that are aligned with rheological profiles of commercially accepted plant-based milk products. This approach enables faster formulation screening, reduces the number of experimental iterations, and minimizes excessive stabilizer usage, thereby supporting cost efficiency, formulation speed, and improved reproducibility during product development.

Nevertheless, several limitations should be considered when extending the proposed framework. Hydrocolloid functionality and rheological responses are sensitive to processing conditions such as shear intensity, homogenization, thermal treatment, and holding time, which may vary between laboratory, pilot, and industrial scales. In addition, differences in protein composition, lipid structure, and total solids among other plant-based milks may influence stabilizer behaviour. Therefore, the predicted concentration ranges should be interpreted as practical formulation guidance rather than fixed values, and further validation across different plant matrices and processing conditions is recommended to broaden the applicability of the approach.

IV. CONCLUSION

This study showed that all commercial plant-based milk samples exhibited pseudoplastic, shear-thinning behaviour ($n < 1$), with apparent viscosity and consistency index values forming a practical rheological benchmark for consumer-accepted products. Increasing stabilizer concentration consistently decreased the flow behaviour index (n) while increasing the consistency index (K) and apparent viscosity at 50 s⁻¹, strongly dependent on stabilizer type. Network-forming hydrocolloids (gellan gum and carrageenan) produced sharper viscosity increases at lower concentrations, whereas xanthan gum, guar gum, and CMC exhibited more gradual rheological responses. Based on non-linear regression modelling anchored to commercial benchmarks, suitable stabilizer concentration ranges were predicted as follows: carrageenan (0.0583–

0.3613%), xanthan gum (0.0596–0.2249%), guar gum (0.0718–0.1859%), gellan gum (0.0581–0.1373%), and CMC (0.0148–0.1121%). Experimental verification in soy milk confirmed close agreement between predicted and measured rheological parameters (n , K , and apparent viscosity at 50 s^{-1}). These findings demonstrate that predictive rheological modelling can effectively reduce empirical trial-and-error formulation while supporting efficient, reproducible development of plant-based milk products.

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