Tanzania Journal of Science 51(1): 141-155, 2025
ISSN 0856-1761, e-ISSN 2507-7961

Rheological and Physicochemical Properties of Soy-Moringa Beverages: The Role of Xanthan Gum Stabilisation

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Received 15 Dec 2024; Revised March 25; Accepted 25 March; Published 15 April 2025
https://dx.doi.org/10.4314/tjs.v51i1.16

Abstract

The increasing demand for functional foods underscores the need to develop stable plant-based products. In this study, soy-moringa beverages with varying concentrations of xanthan gum were produced and stored at 4 °C for two weeks. During storage, rheological properties were analysed using a Brookfield rheometer, and assessments of physicochemical properties and beverage stability. The rheograms revealed that shear stress increased with the shear rate, while viscosity decreased by 92.31% in S_3 and 97.37% in S_4 as the shear rate increased. The Ostwald-de Waele model effectively described the flow behaviour of the soy-moringa beverage. Beverages enriched with xanthan gum exhibited shear-thinning behaviour ($n < 1$), whereas the control sample exhibited shear-thickening behaviour ($n > 1$) throughout storage. Significant increases ($p < 0.05$) were observed in moisture content (2.38%), ash content (32.95%), and total solids (28.80%) with increasing xanthan gum concentration. The results indicate that adding 0.3% to 0.5% xanthan gum enhanced the stability of the soy-moringa beverages during storage. Incorporating xanthan gum enhances the stability, texture, and shelf life of soy-moringa beverages, providing valuable insights for developing stable plant-based functional beverages.

Keywords: Soy-Moringa Beverage; Xanthan Gum; Rheology; Non-Newtonian Fluids; Physicochemical Properties; Storage

Introduction

Public awareness of health-promoting foods has expanded beyond basic nutritional needs, leading to increased consumer demands for healthy-oriented products. This shift has driven the food industry to develop food products with nutraceutical properties (Đorđević et al. 2015), as consuming such foods may ultimately improve human health. However, many locally available beverages are high in sugar and low in protein, fibre, vitamin, and mineral contents, highlighting the need for improved nutritional quality. Since different foods offer distinct nutritional profiles and physicochemical properties, formulating products with diverse ingredients can enhance nutritional, antioxidant, and functional benefits. For instance, combining plant-based materials such as soybeans and moringa can provide valuable nutrients and bioactive compounds (Alphonce et al. 2019, Rweyemamu et al. 2015).

Soybeans (*Glycine max*) are protein-rich legumes, containing approximately 43 % protein, 18 % polyunsaturated and monounsaturated fatty acids, and 31 % carbohydrates. It is also an excellent source of minerals and vitamins (Van Ee 2009). About 50 % of the total fat in soybeans is linoleic acid, which supports human health. Furthermore, Nielsen (1996) noted that soybeans provide most essential amino acids, making them superior to many other plant-based proteins. Due to these remarkable nutritional qualities, soybean have become increasingly popular for producing various supplementary and nutraceutical food products (Alphonce et al. 2019, Ayo et al. 2014, Farzana and Mohajan 2015).

Moringa leaves (*Moringa oleifera*) are excellent sources of micronutrients and antioxidants, including vitamins, minerals, phytochemicals, tocopherols, polyphenols, flavonoids, and carotenoids (Aja et al. 2014, Chhikara et al. 2021, Fahey 2005, Foidl et al. 2001, Ogunsina et al. 2010, Sreelatha and Padma 2009). Fahey (2005) found that moringa leaves contain high-quality protein, surpassing milk and egg, along with higher vitamin C content than oranges and more vitamin A than carrots. Additionally, they provide more calcium than banana and more iron than milk. These nutritional properties contribute to positive health effects and may help prevent various chronic diseases (Santos et al. 2019). Consequently, moringa leaves are increasingly used as key ingredients in nutritional food products (Alphonce et al. 2019, Boniface et al. 2020).

Soy-moringa beverages can be prepared from soybean and moringa leaves through processes such as blanching, blending, filtration, and pasteurisation (Matabura and Rweyemamu 2022). These beverages contain significant amounts of macro- and micronutrients, which can help combat malnutrition, especially among infants and mothers of childbearing ages. However, the physicochemical properties of soybean and moringa leaves may interact in ways that impact the rheological and stability properties of the final product. Rheological properties are essential for describing a beverage's flow behaviour and consistency (Matabura and Rweyemamu 2021). From a food processing perspective, understanding rheological properties is critical for product development, predicting stability, and assessing quality and shelf life (Beristain et al. 2006, Falguera and Ibarz 2010, Liang et al. 2006).

Rheological properties also play a key role in consumer acceptance, influencing texture and mouthfeel (Ibrahim et al. 2011, Matabura and Rweyemamu 2021). While soymilk tends to form a stable suspension, the addition of moringa leaves introduces fine particulates that can lead to sedimentation. As a result, a soy-moringa beverage behaves as an emulsion, containing water-soluble proteins, carbohydrates, and oil droplets (Rweyemamu et al. 2015). To create a consistent and stable soy-moringa beverage without sedimentation, the inclusion of hydrocolloid agents such as xanthan gum is essential. Xanthan gum is widely used in food suspensions and emulsions for stabilise insoluble solids, enhance water-holding capacity, and improve rheological properties (De Cássia da Fonseca et al. 2009, Dickinson 2003, Genovese and Lozano 2001, Liang et al. 2006, Matabura and Rweyemamu 2021, Mirhosseini et al. 2008). This hydrocolloid stabiliser not only enhances texture but also extends shelf life (Chi et al. 2024, Huang et al. 2022).

Despite the benefits of xanthan gum, there are limited studies on its effects on the rheological and physicochemical properties of soy-moringa beverages. Additionally, the growing consumer demand for nutraceuticals—food products that offer health benefits beyond basic nutrition—has led to driven increased study into plant-based functional beverages (Park 2021, SV and Praveen 2022). These beverages play a crucial role in addressing nutrient deficiencies, boosting immune function, and preventing diet-related chronic diseases. Soy-moringa beverages, in particular, are promising due to their rich protein, antioxidant, and micronutrient profiles (Matabura and Rweyemamu 2022). However, their physicochemical instability during storage limits their commercialisation and consumer acceptance. In this context, understanding how hydrocolloids such as xanthan gum can enhance stability and rheology is essential for developing viable plant-based functional beverages.

Therefore, this study aims to investigate the impact of xanthan gum on these properties. To achieve stabilisation, xanthan gum will be added to the soy-moringa beverages at varying concentrations, and the samples will be stored at 4 °C for 14 days. The inclusion of xanthan gum is expected to stabilise insoluble particles and provide valuable insights into product quality.

Materials and Methods

Materials and chemicals

Fresh moringa (*Moringa oleifera*) leaves were harvested from a botanical orchard at the University of Dar es Salaam (-6.8101° S, 39.2797° E), while soybean (*Glycine max* L.) was supplied by Stayfit Nutrisupplies Company Ltd., Dar es Salaam, Tanzania. A total of 6 kg of soybean and 2 kg of moringa leaves were brought to the Food Science Laboratory in the Department of Food Science and Technology of the University of Dar es Salaam for experimentation. Sodium bicarbonate was obtained from Sigma-Aldrich (Steinheim, Germany), and xanthan gum (with an 82% degree of esterification and molecular weight of 85,000) was purchased from Lab Equip Co. Ltd., of Dar es Salaam, Tanzania. All these chemical reagents were of food-grade quality.

Preparation of soy-moringa beverage

The soy-moringa beverage was prepared following the method outlined by Matabura and Rweyemamu (2022). Soybean samples were sorted, washed with tap water, and then mixed with distilled water at a mixing ratio of 1:3 (w/w) to soak for 8 hours. After soaking, the hulls were gently removed by hand, and then the soaking water was discarded. The de-hulled soybeans were blanched for 5 minutes in boiling water containing 1% of sodium bicarbonate, after which the blanching water was discarded. The blanched soybeans were then mixed with hot water of 85 °C in a 1:8 (w/w) ratio. This mixture was blended in a Vitamix S50 blender (UK) at 1600 rpm for 4 minutes, using two-thirds of the hot water during blending and the remaining one-third to rinse any suspended soymilk from the blender. The mash was filtered through a food-grade 200-mesh nylon cloth to separate the raw soymilk from the okara (soy pulp).

For the moringa preparation, mature leaves were stripped from sorted branches, then washed with tap water. The washed leaves were mixed with distilled water at a 1:1 (w/w) ratio and blanched at 90 °C for 3 minutes, then immediately cooled to 25 °C using ice water. The cooled moringa leaves were blended with raw soymilk in a 3:7 (w/w) ratio. This mixture was processed in a Vitamix S50 blender (UK) at 1600 rpm for 1 minute and then filtered through a 200-mesh food-grade nylon cloth to yield the soy-moringa beverage.

Xanthan gum addition and storage

Five soy-moringa beverage samples, designated S_1 to S_5, were prepared to assess the effects of xanthan gum addition on stabilisation. Xanthan gum was added to each 100 mL sample at varying ratios: 0.1% (S_1), 0.2% (S_2), 0.3% (S_3), 0.4% (S_4), and 0.5% (S_5). The xanthan gum ratios were selected based on Gawai et al. (2017) and preliminary tests. Xanthan gum is widely used as hydrocolloid agent in plant-based beverages for stabilisation (Chi et al. 2024**,** Dickinson 2003, Huang et al. 2022, Matabura and Rweyemamu 2021). Each formulation was homogenised, pasteurised at 80 °C for 20 minutes, and then transferred into sterilised 200 mL plastic bottles, which were sealed with lids. The stabilised samples were stored at 4 °C for 14 days. A control sample (S_0) without xanthan gum was also prepared and stored under the same conditions.

Measurement of rheological properties

The rheological properties of soy-moringa beverages were measured using a Brookfield R/S Plus rheometer (UK) at ambient temperature. Before measurement, samples were equilibrated to room temperature overnight and the method was calibrated using control sample (S_0). The rheometer setup consisted of a measuring chamber (with 36 mm diameter, 70 mm height) and a cylinder spindle (with 25 mm diameter, 45 mm height) for rheological analysis. For each sample, 12 mL of the beverage was poured into the chamber. The spindle was immersed in the sample by securing the chamber to the rheometer, ensuring a consistent distance between the spindle’s end and the chamber bottom throughout the experiment. Preliminary tests indicated that the viscometer should operate within a shear rate range of 2 to 3900 s^{-1}, and shear stress (Pa) and viscosity (mPa s) data were recorded within 40 seconds.

Data fitting

Non-Newtonian fluid models, such as the Power-law, Herschel-Bulkley, and Bingham models, are commonly used to characterise the rheological properties of liquid and suspension foods (Falguera and Ibarz 2010, Diamante and Umemoto 2015, Matabura and Rweyemamu 2021). In this study, the Power-law, also known as the Ostwald-de Waele model, was applied to describe the flow behaviour of the soy-moringa beverages produced. The Ostwald-de Waele model is expressed as $\tau = K\gamma^n$, whereas τ represents shear stress (Pa), γ is the shear rate (s^{-1}), K is the consistency coefficient or viscosity index (Pa s^n), and n is the flow behaviour index. The parameters K and n are critical for describing flow behaviour. Model parameters were estimated by fitting the Ostwald-de Waele model to the experimental data of shear stress (τ) and shear rate (γ).

When $n < 1$, the food product exhibits shear-thinning behaviour, meaning that apparent viscosity decreases as the shear rate increases (Diamante and Umemoto 2015, Matabura and Rweyemamu 2021). Conversely, when $n > 1$, the food product shows shear-thickening properties, indicating that apparent viscosity increases with increasing shear rate. For Newtonian behaviour ($n = 1$), viscosity remains constant regardless of changes in shear rate. These variations in rheological behaviour occur due to differences in the components of liquid foods and their structural interactions (Matabura and Rweyemamu 2021).

Physicochemical properties analysis

Moisture content and density determinations

The moisture content of the soy-moringa beverage samples was determined by heating them in an oven following standard methods (AOAC, 2000). For each sample, 2 g was poured into a clean and pre-dried porcelain crucible. The crucibles containing the samples were placed in a forced-air oven set at 102 ± 2°C and dried to a constant weight. An analytical balance (Sartorius GMBH, G*öttingen*, Germany) with a precision of 0.001 g was used for weighing. After drying, the samples were stored overnight in a desiccator before moisture analysis. Moisture content was calculated on a wet basis. For density determination, the mass (g) and the volume (mL) of each soy-moringa sample were measured.

Ash content

The ash content of the soy-moringa beverage was determined by weighing 2 g of the sample into a clean, pre-dried porcelain crucible. The sample was placed in an oven set at 105°C and dried for 3 hours to evaporate all moisture. The dried samples were then transferred to a furnace set at 550 °C for ashing over 3 hours. After ashing, the furnace was switched off, and the samples were allowed to cool. The ash content (%) of the soy-moringa beverage was calculated on a wet basis.

Total solids

The total solids of the soy-moringa beverage were determined using the gravimetric method. Flat-bottomed porcelain dishes were cleaned with distilled water, dried in an air oven for 30 minutes, and cooled in an airtight desiccator for 30 minutes. Approximately 2 g of the beverage sample was poured into each dried porcelain dish and then placed in a hot air oven set at 105 °C for drying over 5 hours. The dried samples were removed, cooled to ambient temperature in a desiccator, and weighted. The samples were returned to the oven for additional drying in 30-minutes interval, cooled, and reweighted. These steps were repeated until the difference between two successive weights was 0.5 mg or less. The total solids percentage was estimated by dividing the mass of the dried residue by the initial mass of the beverage sample.

Beverage stability

For the beverage stability test, 15 mL of soy-moringa beverage was poured into a 20 mL test tube and stored at 4 °C for two weeks. Stability measurements were taken on days: 1, 3, 7, 10, and 14 by monitoring the sedimentation level. The stability of soy-moringa beverage (BS) was expressed as a percentage, calculated using the initial height of the beverage (HB) and the height of the sediment level formed (HS) as follows: BS = (HB – HS) × 100 / HB.

Statistical analysis

The experimental datasets were imported into Matlab (R2019a, Mathworks Inc., Natick, MA, USA) for analysis. Analysis of variance (ANOVA) was performed at 95% confidence level to assess the significant effects of xanthan gum on each soy-moringa beverage sample. Following a significant ANOVA result, Tukey's Honest Significant Difference (HSD) was applied to identify specific differences among group means, which were expressed as mean ± standard deviation ($\bar{x} \pm$ S.D.). Four replicates were used for each measurement.

Results and Discussion

Rheological properties

Shear stress and shear rate

The results of shear stress (Pa) and shear rate (s^{-1}) for soy-moringa beverages blended with xanthan gum and varying concentrations (S_1 to S_5) and the control (S_0) are depicted in Figure 1. The addition of xanthan gum influenced shear stress and shear rate pattern, with the rate of change diminishing as xanthan gum concentration increased over storage period. Notably, in S_5 sample, shear stress values after 14 days overlapped with those measured on day zero (Figure 1), indicating no significant change in shear stresses for the beverage with 0.5% xanthan gum during two weeks of storage. The high stability of S_5 can be attributed to xanthan gum's ability to maintain an entangled polysaccharides network, effectively preventing phase separation and sedimentation products (Kim et al. 2025). In contrast, the control sample (S_0), which lacked xanthan gum, exhibited a significant difference in shear stress between day zero and 14 days of storage, likely due to particle aggregation and phase separation, leading to a weaker network structure over time (Rao 2010). This observation aligns with previous studies, which reported hydrocolloids like xanthan gum enhance viscosity and stability in beverage system by forming a three-dimensional network that resists deformation (Dickinson 2003, Genovese and Lozano 2001, Liang et al. 2006, Matabura and Rweyemamu 2021).

Figure 1 also show a decreasing trend in shear rate with increasing xanthan gum concentration. The S_0 sample exhibited the broadest range of shear rates, from 1200 to 3900 s^{-1}, followed closely by the S_1 sample (500 to 3200 s^{-1}). In contrast, the other soy-moringa samples demonstrated narrower shear rate ranges, with S_2 spanning from 2 to 200 s^{-1}, and S_3, S_4, and S_5 ranging from 2 to over 90 s^{-1}. The inverse relationship between xanthan gum concentration and shear rate supports previous findings that higher concentrations of xanthan gum induce stronger shear-thinning behaviour (as discussed in Section 3.1.3), reducing the extend of flow under applied shear stress (Cho and Yoo 2015, Saha and Bhattacharya 2010).

The rheograms further reveal distinct flow behaviours among the soy-moringa beverage samples, each with varying yield stresses (Figure 1). Yield stress decreases notably in S_1 and S_2 samples over the storage period, with an even more pronounced decline in the S_0 sample. The observed reduction in yield stress for lower xanthan gum concentrations suggests a weakening of intermolecular interactions due to limited polymer entanglement and subsequent phase separation (Dickinson 2003). In contrast, yield stresses in S_3, S_4, and S_5 remained relatively stable, highlighting the stabilising effect of xanthan gum in the soy-moringa beverage. These findings agree with previous studies, which reported xanthan gum's efficacy as a thickening agent to stabilises insoluble particles and enhances the rheological properties of food products (Genovese and Lozano 2001, Liang et al. 2006, Mirhosseini et al. 2008, Nsengiyumva and Alexandridis 2022, Somogyi 1996).

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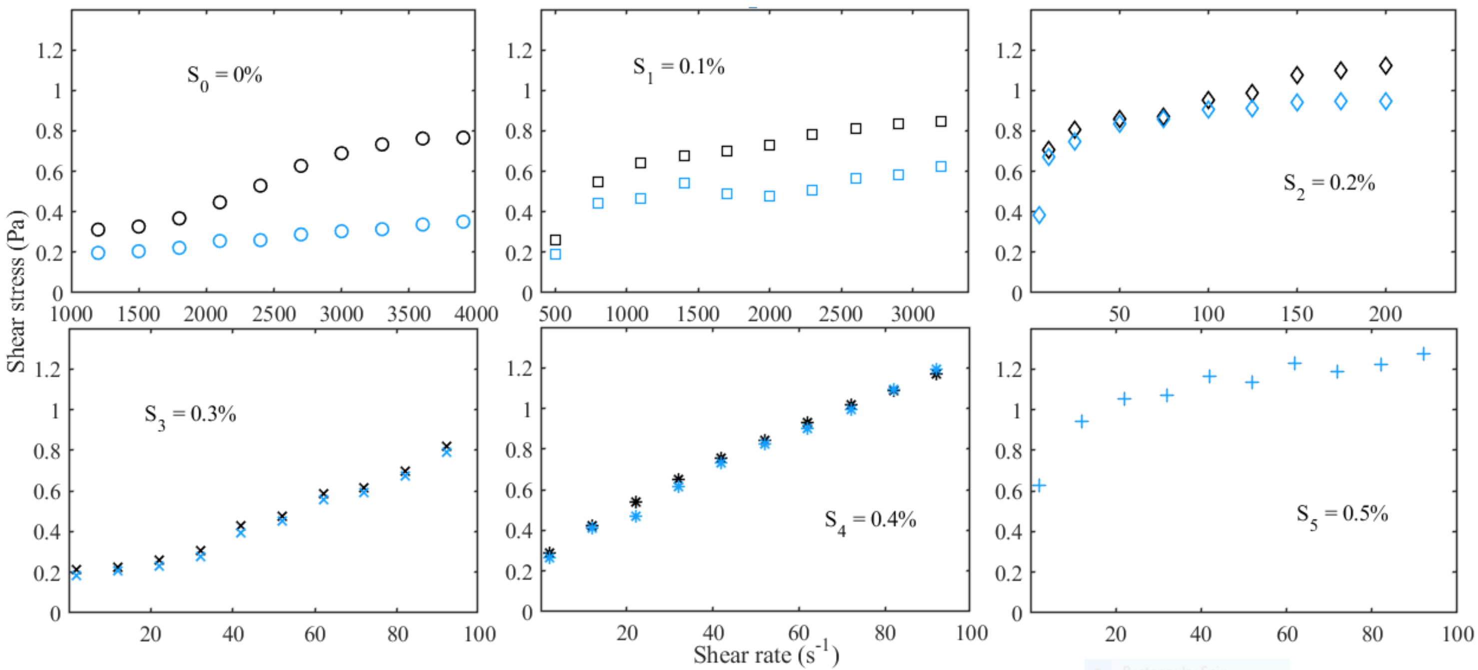

Figure 1: Rheograms showing relationship between shear stress, τ (Pa) vs. shear rate, γ (s^{-1}) for soy-moringa beverages with varying xanthan gum concentrations (samples S_1 to S_5) and the control sample (S_0). Black and blue data points represent experimental measurements taken on day 0 and 14 days of storage at 4°C, respectively.

Viscosity and flow behaviour

Figure 2 illustrates the changes in viscosity for soy-moringa beverages added with xanthan gum during two weeks of storage, along with the control sample (S_0). The results demonstrate a clear decreasing trend in viscosity for samples S_1 to S_5 as xanthan gum content increases, indicating that these sample exhibit non-Newtonian fluid behaviour. Viscosity decreases exponentially with increasing shear rate, with more pronounced changes at low shear rates and gradual decreases at high shear rates. This behaviour is a characteristic of shear-thinning (pseudo-plastic) fluids, where viscosity decreases under applied stress due to polymer chain alignment (Rao 2010). Notably, this pattern was consistent for samples $S_1 – S_5$ on both day zero and 14 days of storage at 4 °C (Figure 2). Conversely, the control sample (S_0) exemplifies a slight linear increase in viscosity at both time points, suggesting that the soy-moringa beverage without xanthan gum demonstrate distinct non-Newtonian behaviours compared to the xanthan-supplemented samples. The increase in viscosity observed in S_o may be attributed to phase separation and structural rearrangements due to lack of hydrocolloid stabilisation (Dickinson 2003, Rao 2010).

The effect of xanthan gum is evident in the viscosity stability of each soy-moringa beverage. As xanthan gum concentration increases, the viscosity at day zero and 14 days of storage shows no significant difference ($p > 0.05$), as shown in Figure 2. This finding is particularly apparent for the soy-moringa beverages containing 0.3%, 0.4%, and 0.5% xanthan gum (samples S_3, S_4, and S_5 samples, respectively). These results alight with previous studies on xanthan gum's application in food products (Beristain et al. 2006, Genovese and Lozano 2001, Liang et al. 2006). Genovese and Lozano (2001) reported the ability of xanthan gum to maintain viscosity and yield stress in apple juice under storage conditions, emphasising its role in improving the functional and rheological properties of food products. Matabura and Rweyemamu (2021) observed a decrease in viscosity in *Aloe vera*–moringa leaf juice blended with xanthan gum as the shear rate increased. This consistency suggests that xanthan gum plays a crucial role in stabilising plant-based beverages by preventing sedimentation and phase separation, a phenomenon commonly observed in liquid food systems lacking hydrocolloid stabilisers (Saha and Bhattacharya 2010).

Non-Newtonian behaviour and model fitting

According to rheological properties analysis, a non-Newtonian fluid model effectively describes the flow behaviour of soy-moringa beverages. To better understand this behaviour, experimental data on shear stress and shear rate were fitted to the Ostwald-de Waele (power law) model, which is widely used to characterise the flow behaviour of food dispersions and hydrocolloid-containing systems (Diamante and Umemoto 2015, Matabura and Rweyemamu 2021). Table 1 presents the parameter estimates from this model, including the consistency coefficient (K), the flow behaviour index (n), and the coefficient of determination (R^2). The model outputs indicate that all soy-moringa beverages exhibit non-Newtonian behaviour across samples.

Soy-moringa beverages enriched with xanthan gum exhibit a shear-thinning property, as indicated by flow behaviour indices $n < 1$. For samples S_1 to S_5, the flow behaviour indices ranged from 0.156 to 0.802 at both time points (day zero and 14 days of storage) (Table 1). This suggests a reduction in viscosity as shear rate increases, supporting the previous trend in viscosity decrease with shear rate (Rao 2010). Shear-thinning behaviour is essential property in beverage formulations, as it enhances texture and provides a desirable mouthfeel (Nsengiyumva and Alexandridis 2022, Saha and Bhattachrya 2010). Conversely, the control sample (S_0) showed shear-thickening behaviour ($n > 1$), meaning its viscosity increased with shear rate. This behaviour may be attributed to the flocculation and aggregation of dispersed particles in the absence of a stabilising agent, leading to increased resistance to flow at higher rates (Pushpadass et al. 2019).

The consistency coefficient (K), which reflects the initial viscosity of the fluid at low shear rates, varied significantly with xanthan gum concentration, ranging between 0.0028 and 0.583 Pa s^n for the soy-moringa beverages containing xanthan gum (Table 1). These results are consistent with studies by Diamante and Umemoto (2015) and Krokida et al. (2001), who reported that an increase in soluble solids, particularly hydrocolloids significantly impacts the viscosity indices and enhances the overall viscosity stability of non-Newtonian food products. The variations in K suggest that xanthan gum concentration plays a crucial role in determining the initial viscosity and structural stability of the beverage, which is essential for preventing phase separation during storage (De Cássia da Fonseca et al. 2009, Dickinson 2003).

The coefficient of determination (R^2) values, analysed for each sample to assess model fitting, range between 0.88 and 0.99 (Table 1). These high R^2 values indicate that the power law model accurately describes the flow behaviour of the soy-moringa beverages, reinforcing the observation that xanthan gum contributes to shear-thinning properties and long-term viscosity stability (Rao 2010).

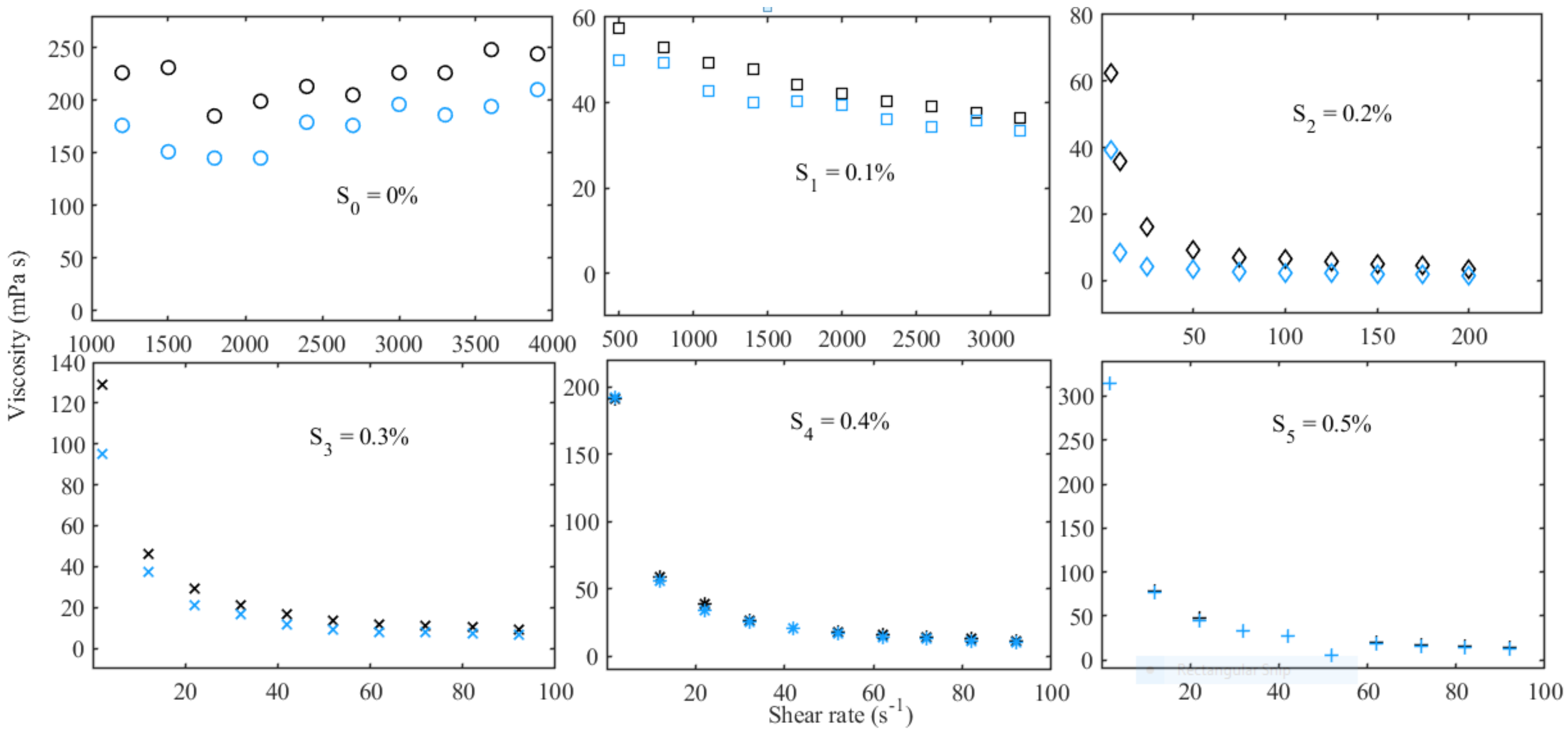

Figure 2: Graphics of apparent viscosity (mPa s) for soy-moringa beverages with added xanthan gum at various ratios (S_1 to S_5) and for the control sample (S_0). Black and blue points represent experimental data collected on days 0 and 14 of storage at 4°C, respectively.

Table 1: Model parameter estimates for each soy-moringa beverage with added xanthan gum at varying ratios and for the control sample.

Soy-moringa beverage	Storage time (day)	*K* (Pa s^n)	*n*	R^2
S_0	0	0.000028	1.234	0.96
	14	0.000013	1.325	0.97
S_1	0	0.0028	0.751	0.99
	14	0.0018	0.802	0.99
S_2	0	0.176	0.272	0.94
	14	0.143	0.156	0.94
S_3	0	0.233	0.296	0.96
	14	0.185	0.268	0.88
S_4	0	0.337	0.239	0.98
	14	0.349	0.235	0.97
S_5	0	0.583	0.175	0.97
	14	0.583	0.175	0.97

Physicochemical compositions

Moisture content

Table 2 presents the physicochemical properties of soy-moringa beverages formulated with varying concentrations of xanthan gum, along with a control sample. The moisture content of the soy-moringa beverages significantly increased ($p < 0.05$) as xanthan gum concentration increased, ranging from 94.17 ± 0.26% in sample S_1 to 95.41 ± 0.05% in sample S_5. The control sample (S_0), which contained no xanthan gum, exhibited a significantly lower moisture content of 93.14 ± 0.21%, highlighting the hydrophilic nature of xanthan gum. This increase in moisture content can be attributed to high water-binding capacity of xanthan gum, which enhances the water retention of food matrices by forming a stable, three-dimensional network that traps water molecules (Saha and Bhattachrya 2010).

Ash content and total solids

Both ash content and total solids showed significant increases ($p < 0.05$) with the addition of xanthan gum (Table 2). Ash content, which reflects the total mineral content in food, increased from 0.65 ± 0.02% in S_1 to 0.88 ± 0.05% in S_5, suggesting that xanthan gum may contribute to improved dispersion of minerals within beverage matrix. Similarly, total solids increased from 4.46 ± 0.06% in S_1 to 5.73 ± 0.06% in S_5, indicating enhanced retention of solid components due to xanthan gum's thickening and stabilising properties. These values were significantly different ($p < 0.05$) from those observed in the control sample (S_0), which had no xanthan gum. The observed increase in total solids in consistent with previous studies on hydrocolloids, where the incorporation of stabilisers such as xanthan gum, leads to improved suspension stability and homogeneity in liquid food systems (Genovese and Lozano 2001, Liang et al. 2006).

Density

A notable trend was observed in density, which decreased with increasing xanthan gum concentrations (Table 2). Density declined from 0.97 ± 0.02 in S_1 to 0.91 ± 0.01 g/mL in S_5, with xanthan gum-enriched S_3 to S_5 samples exhibiting significantly lower density compared to the control sample (S_o). This reduction in density may be linked to the structural modifications induced by xanthan gum, which increases the viscosity and apparent volume of the beverage while reducing overall bulk density. Hydrocolloids such as xanthan gum alter fluid structure by increasing intermolecular interactions and entrapping air, leading to lower density values in thickened beverages products (De Cássia da Fonseca et al. 2009).

The observed changes in physicochemical properties can be attributed to the stabilising effects of xanthan gum, which involve complex interactions with fat, protein, and carbohydrates in food matrices. Xanthan gum enhances beverage stability by increasing viscosity, preventing phase separation, and improving the distribution of insoluble particles. It forms a pseudo-plastic (shear-thinning) gel network that resists gravitational settling, which is crucial for maintaining uniform texture and preventing sedimentation in plant-based beverages (Kim et al. 2025; Saha and Bhattachrya 2010). These findings align with previous studies demonstrating xanthan gum's role in improving water-holding capacity, viscosity stability, and texture in hydrocolloid-based food systems (De Cássia da Fonseca et al. 2009, Dickinson 2003, Genovese and Lozano 2001, Liang et al. 2006).

Table 2: Physicochemical properties of soy-moringa beverage samples blended with varying xanthan gum concentrations and the control samples. Mean values are presented with their standard deviations ($\bar{x}$ ± S.D.) For each parameter, values with different superscripts indicate significant differences between means (p < 0.05).

Soy-moringa beverage sample	Moisture content (%)	Ash content (%)	Total solids (%)	Density (g/mL)
S_0	93.14 ± 0.21^{a}	0.59 ± 0.01^{a}	4.08 ± 0.20^{a}	0.98 ± 0.01^{a}
S_1	94.17 ± 0.26^{b}	0.65 ± 0.02^{b}	4.46 ± 0.06^{b}	0.97 ± 0.02^{ab}
S_2	94.44 ± 0.10^{b}	0.73 ± 0.01^{c}	4.66 ± 0.11^{c}	0.96 ± 0.03^{abc}
S_3	94.89 ± 0.30^{c}	0.72 ± 0.04^{c}	4.96 ± 0.30^{c}	0.94 ± 0.01^{bc}
S_4	95.21 ± 0.11^{c}	0.75 ± 0.06^{c}	5.41 ± 0.10^{d}	0.92 ± 0.02^{cd}
S_5	95.41 ± 0.05^{d}	0.88 ± 0.05^{d}	5.73 ± 0.06^{e}	0.91 ± 0.01^{d}

Beverage stability

Table 3 presents the stability of soy-moringa beverages after two weeks of storage, highlighting the effects of xanthan gum concentration on sedimentation and overall dispersion stability. Results show that the stability of S_1 and S_2 samples decreased significantly during storage, with noticeable sedimentation occurring after 3 and 7 days, respectively. This trend was also observed in the control sample (S_0), which contained no xanthan gum and exhibited the highest sedimentation levels. In contrast, samples S_3, S_4, and S_5 formulated with higher xanthan gum concentrations, remained well- stabilised throughout the storage period, demonstrating minimal phase separation.

The improved stability observed in samples with higher xanthan gum concentrations can be attributed to the thickening and stabilising properties of hydrocolloids, which increase viscosity and create a pseudo-plastic network that prevents the aggregation and sedimentation of suspended particles (Mirhosseini et al. 2008; Nussinovitch 1997). Xanthan gum's ability to interact with proteins and carbohydrates enhances the homogeneity of liquid food systems, reducing syneresis and phase separation over time (Kim et al., 2025).

Interestingly, the current findings contrast with those reported by Liang et al. (2006), who found that reconstituted carrot juice with a low xanthan gum concentration of about 0.2% remained stable over 60 days of storage. The discrepancy between the stability of soy-moringa beverages and carrot juice could be attributed to differences in the composition and physicochemical properties of these beverages. Carrot juice contains naturally occurring pectin and dietary fibre, which contribute to enhanced structural stability even at lower xanthan gum concentrations. In contrast, soy-moringa beverages contain higher protein and lipid content (Matabura and Rweyemamu 2022), which may require higher xanthan gum concentrations to prevent phase separation, as protein-polysaccharide interactions significantly influence beverage stability (Mirhosseini et al. 2008, Kim et al. 2025).

In general, polysaccharide-based thickeners such as xanthan gum enhance the physical stability of food products by modifying the viscoelastic properties of the continuous phase (Ibrahim et al. 2011, Nussinovitch 1997, Sinchaipanit and Kerr, 2007). Sinchaipanit and Kerr (2007) reported that carrot juice supplemented with polysaccharide thickeners exhibited reduced sedimentation, supporting the role of hydrocolloids in improving beverage stability. Similarly, Beristain et al. (2006) observed that soluble dietary fibres to effectively stabilised various beverage formulations, including sports and energy drinks and protein-based beverages, by creating a charged polysaccharides-protein network that minimised particle settling. According to Dickinson (2003), the stabilisation of food dispersions and emulsions is largely influenced by protein-hydrocolloid interactions, where negatively charged polysaccharides interact with proteins, forming electrostatic repulsion forces that prevent particle aggregation. This mechanism explains why soy-moringa beverages with higher xanthan gum concentrations (S_3 - S_5) maintained better stability over time (Table 3). The binding of free carboxyl groups on xanthan gum to proteins creates a repulsive charge effect, reducing sedimentation and phase separation (Beristain et al. 2006; Kim et al. 2025). These findings reinforce the role of xanthan gum as an effective stabiliser in plant-based beverages, particularly in protein-rich formulations like soy-moringa beverages, where maintaining uniform dispersion is crucial to food science.

Table 3: Stability level (%) analysed in soy-moringa beverage during two weeks of storage in a fridge set at 4°C

Soy-moringa beverage sample	Stability level (%) during storage at 4°C				
	day 1	**day 3**	**day 7**	**day 10**	**day 14**
S_0	100	95	88	86	60
S_1	100	100	95	90	84
S_2	100	100	100	100	97
S_3	100	100	100	100	100
S_4	100	100	100	100	100
S_5	100	100	100	100	100

Practical relevance

This study provides valuable insights into how xanthan gum enhances the stability of soy-moringa beverages by minimising phase separation and sedimentation, thereby extend shelf life and maintaining product quality during storage and transportation (Chi et al. 2024, Huang et al. 2022). These stabilising effects are particularly beneficial for the functional beverage industry, where maintaining homogeneity and sensory appeal is crucial for consumer acceptance. By optimising viscosity and flow properties, xanthan gum not only enhances beverage texture and mouthfeel but also improves consistency, factors that significantly influence consumer preference and marketability (De Cássia da Fonseca et al. 2009, Dickinson 2003).

Furthermore, these findings support the development of plant-based functional beverages that are rich in essential nutrients, offering potential solution to micronutrient deficiencies in regions affected by high malnutrition rates. The food industry can leverage these insights to refine their formulations, ensuring consistent product quality while utilising xanthan gum as a natural stabiliser. This approach enhances production efficiency of plant-based beverage (Yin et al. 2024, Zang et al. 2024).

Additionally, the incorporation of soy and moringa in functional beverage production aligns with climate-resilient food systems and contributes to global food security. Both crops are highly nutritious (Matabura and Rweyemamu 2022) and sustainable, requiring fewer resources compared to conventional livestock-based protein sources. Promoting their utilisation in food processing supports sustainable agriculture, reduces environmental impact, and provides affordable nutrition options in food-insecure regions.

Conclusions

The study characterised the effects of xanthan gum on stability and rheological properties of soy-moringa beverages, demonstrating its significant role in improving flow behaviour and storability. The results indicate that shear stress increases with higher xanthan gum content, while viscosity decreased with increasing shear rate, indicating the non-Newtonian behaviour of the beverage. The Ostwald-de Waele model effectively described the shear stress-shear rate relationship, with coefficients of determination (R^2) ranging from 0.88 to 0.99 across all samples. Model outputs indicated that soy-moringa beverages containing xanthan gum exhibit shear-thinning behaviour ($n < 1$), whereas the control sample revealed shear-thickening behaviour ($n > 1$) during storage. These findings suggest the functionality of xanthan gum as a stabilising agent, enhancing the rheological properties and process stability of of soy-moringa beverages, making it viable stabiliser in nutraceutical formulation.

Furthermore, soy-moringa beverage containing 0.3% to 0.5% xanthan gum revealed significant stability through storage, with reduced phase separation and sedimentation. Increased xanthan gum concentration resulted in significant increases ($p < 0.05$) in moisture content, ash content, and total solids, while density decreases, which collectively contribute to improved texture and extended shelf life. These physicochemical modifications provide novel insights into quality changes in xanthan gum-enriched soy-moringa beverages with enhanced functional properties.

Future studies should explore the sensory evaluation and functional properties of soy-moringa beverages to assess their consumer acceptability and therapeutic potential. Understanding these aspects could drive further product innovation in the plant-based beverage industry, promoting the development of nutritionally enhanced food that support sustainable and climate-resilient food systems.

Declaration of competing interest

No conflicts of interest to disclose.

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