Rheological and tribological characterization of herbal sweet sauce with different stabilizing systems

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ABSTRACT

Rheological and tribological analyses were compared between two polysaccharide-based stabilizing systems (xanthan gum and corn syrup) of a traditional herbal sweet sauce. Imitative testing showed that XG sauces have a greater surface stickiness but lower stringiness than CS sauces. Oscillatory (O) shear tests showed that XG sauce exhibited greater gel strength and elasticity. Between the frequency range 100.0–0.1 rad/s, both sauces showed weak gel characteristics and long-term stability to sedimentation. In rotational (R) shear tests, both sauces displayed the shear-thinning flow behavior. The XG sauce had a higher consistency index (K) and a slightly lower flow behavior index (n). In time-dependent O/R/O measurements, XG sauce showed a lower viscosity under high shear but higher regeneration after 40 s; structural elasticity was comparable under low shear. Type of stabilizing system affected boundary and hydrodynamic lubrication regimes; CS sauce showed greater potential to lower the friction between interacting surfaces.

Caracterización reológica y tribológica de la salsa dulce de hierbas con diferentes sistemas estabilizadores

RESUMEN

En este estudio se compararon los análisis reológicos y tribológicos de una tradicional salsa dulce de hierbas a la que se aplicaron dos sistemas estabilizadores a base de polisacáridos (goma xantana (XG) y jarabe de maíz (CS)). Las pruebas imitativas dieron cuenta de que las salsas XG tienen mayor pegajosidad superficial y menos fibrosidad que las salsas CS. Las pruebas de corte oscilatorio (O) mostraron que la salsa XG presenta mayor fuerza de gel y elasticidad. Por otra parte, se constató que en el rango de frecuencias de 100.0-0.1 rad/s, ambas salsas exhiben características de gel débil y estabilidad de largo plazo a la sedimentación. En las pruebas de corte rotacional (R), ambas salsas mostraron el comportamiento de flujo de adelgazamiento por cizallamiento. La salsa XG registró un índice de consistencia (K) más alto y un índice de comportamiento de flujo (n) ligeramente más bajo. En las mediciones O/R/O dependientes del tiempo, la salsa XG exhibió menor viscosidad en la modalidad de alto cizallamiento, pero mayor regeneración después de 40 s mientras que la elasticidad estructural era comparable a la registrada en la modalidad de bajo cizallamiento. El tipo de sistema estabilizador afectó los regímenes de lubricación límite e hidrodinámica; la salsa CS mostró mayor potencial para reducir la fricción entre las superfi cies que interactúan.

1. Introduction

Herbal sweet sauces can be classified as plant-tissue-based food suspensions that consist of particle fractions and continuous serum phases. Like other types of sauce, the task for the product developer is to enrich the watery base, giving it a desirable and more substantial consistency. This can be achieved by obstructing the free movement of obstacles via the addition of starches or other vegetable or animal particles, oils, or even bubbles of air (Belitz et al., 2009). During production, the suspension may experience structure-enabling unit operations (including blending, mixing, sieving, and high-pressure homogenization) and preservation unit operations (such as heating and high-pressure treatments) (Moelants et al., 2014). The stability of suspensions with highly soluble solids, such as sweet sauces, can be achieved by adding thickening agents to literally bind the water molecules to each other, effectively reducing the fluidity and increasing the viscosity of the sauce. Corn syrup is often added to commercial sweet sauces to reduce recrystallisation, while xanthan gum is a hydrocolloid added to give stability independent of temperature to the product; both rheological additives employ different water-immobilizing strategies (Chen et al., 2015; Diantom et al., 2017; O’Connel & Hartel, 2022; Ramírez-Sucre & Baigts-Allende, 2016). Gamonpilas et al. (2011) report that the manufacturing process for sweet sauces involves mixing and cooking materials under high shear conditions (around 3000 RPM at 90–95°C), and the resulting sauce is subsequently pumped into a reservoir to allow it to cool down before being poured into containers.

From manufacturers’ perspectives, a good understanding of the rheological characteristics of liquid foods is pertinent
to optimizing the flow process, product quality control, and storage stability (Sikora et al., 2003). Tribological characteristics reflecting the properties of interacting surfaces and relating to the oral processing of these thickened liquids can give further insight into consumers’ sensory perceptions and preferences. The desirable in-mouth characteristics of stabilizers in structured liquids relate to their bulk-thickening and lubricating capabilities on oral surfaces in the presence of saliva (Murray et al., 2021). The knowledge obtained from instrumental texture analyses, such as stickiness, viscosity, and friction, provides information about a sample’s easiness to eat. Therefore, rheological and tribological characterizations can help accurately define and better customize products for specific populations and applications.

The traditional role of stabilizers in sauces is to suspend solid particles and control flavor release. However, emerging applications include modifying oral processing behaviors, bolus formation, and sensory perceptions of solid carrier foods; tailoring condiment-carrier combinations can be an effective strategy to encourage healthy eating and improve food appreciation (van Eck et al., 2020); supporting claim of plant-based ingredient and fat replacer without compromising product quality and shelf life (Pourfarzad & Derakhshan, 2021).

Texture of sauce, which can be subdivided into surface texture, thickened characteristics, coating ability, and flow characteristics, consist of a multidimensional matrix of interactions (Sheldrake, 2003). To understand the interactions in sauce system by looking at micro- and macroscopic effect on product texture required a holistic point of view. The current study aims to demonstrate the ability of fundamental and imitative texture measurements to differentiate water-based sweet sauces with identical viscosities, using rheological measurements, both rotational and oscillatory shear measurements, a mixture of these two, and tribological measurements. Polysaccharide-based starch (corn syrup) and nonstarch (xanthan gum) stabilizers were compared in order to characterize the viscoelastic and lubrication properties of sweet sauces and identify a set of instrumental measures sensitive to detecting texture difference. The identification and determination of these properties of sauces, as influenced by different stabilizing systems, are of great interest within the food industry.

2. Materials and methods

2.1. Materials

Xanthan gum (XG), corn syrup (CS), and the seasoning (herbs, spices, sugar) were obtained from a local distributor. Herbs and spices used included shallot, garlic, and galangal. Sugar used were both coconut sugar and granulated sugar in equal proportions. All of them were certified by Thai Food and Drug Administration.

2.2. Preparation of the dipping sauce

Two formulations of an herbal dipping sweet sauce were developed in our laboratory according to the method developed by Saengprakai et al. (2015). The quantities of ingredients and the concentration of the stabilizers (0.20% XG and 20.00% CS) used in the formulations followed traditional recipes, and a commercial product (Wiset Chef, Rayong Fish Sauce Industry Co., Ltd., Muang, Rayong, Thailand) was used as a benchmark. The concentrations of hydrocolloid chosen was based on the most acceptable formulation for this specific product from our previous study; outside these suggested ranges, poor pourability of the formulated sauce was observed. In preparing the dipping sauces, herbs and spices were roughly cut into small pieces, roasted in a pan until fragrant, and then ground into a homogeneous paste. Sugar was dissolved in hot water before adding all the seasonings and the paste. The mixture was boiled and mixed thoroughly, then poured into glass bottles while hot, capped, and cooled down to room temperature with tap water. This preparation protocol was strictly followed to ensure reproducibility.

2.3. Physicochemical analysis

After one day of storage at room temperature, the pH of the sauce samples was determined using a pH meter (IQ Scientific Instruments, Carlsbad, California, USA), and their total solids content (TSC) was measured by drying 2.0 g of sauce in an oven at 100 ± 5°C for 24 hrs. Five replicates were performed for each dipping sauce. The compositions and physicochemical properties of these sauces are summarized in Table 1.

2.4. Instrumental texture analysis

The texture and mouthfeel of the two sauces were characterized at both the macro- and microscopic levels under different shear rates, strain scales, and time contexts, as detailed in the following sub-sections.

2.4.1. Adhesive test

The surface stickiness and stringiness of the samples were analyzed using a 35-mm flat-ended aluminum cylinder mounted to a Texture Analyzer (Model TA-XTplus®; Texture Technologies Corp., Scarsdale, N.Y., U.S.A.) equipped with a 50-kg load cell (Stable Micro System’s application study, REF: SYR1/P35). The sample was contained in a petri dish and placed centrally on the base under the probe, which was set to travel at a crosshead speed of 1.00 mm/s with trigger force of 5 g before applying 6 g of force to the sample for 2 s. After this time, the probe was withdrawn from the sample at 8.00 mm/s and stopped at a distance of 140 mm above the sample surface. The applied force value chosen are considered suitable to achieve full contact

| Ingredient/stabilizer | 20% Com Syrup | 0.2% Xanthan |
|-----------------------|---------------|--------------|
| Liquid                | 46            | 82           |
| Sugar                 | 10            | 10           |
| Herbs and spices      | 24            | 8            |
| Thickeners/stabilizer | 20            | 0.2          |
| Properties            |               |              |
| pH                    | 3.4 ± 0.0     | 3.5 ± 0.0    |
| TSC (%)               | 37.2 ± 0.7b   | 12.3 ± 0.6a  |

Table 1. Composition (%) and physicochemical properties (mean ± SD) of herbal sweet sauces thickened with corn syrup or xanthan gum.

a,bMeans with different superscripts within the same response are significantly different (n = 3; p < .05).

"Las medias con superíndices diferentes dentro de la misma respuesta son significativamente diferentes (n = 3; p < .05)."
between the sample and the probe surface, and texture values obtained are only relative at the specified contact force, time for which they were tested as well as the speed of probe-sample separation (Stable Micro System’s application study, SYR1/P35). Adhesive test of similar setting for sauce product have been reported, for example, by Savouré et al. (2021), Pourfarzad and Derakhshan (2021), and Burke and Hartel (2021). Data were recorded and analyzed using Texture Exponent software (version 3.0.5.0; Stable Micro System Ltd., Godalming, Surrey, U.K.). The maximum force required to separate the sample was recorded as the stickiness. The stringiness value was recorded as the distance the probe moved away from the sample surface before the force dropped to 2.5 g (Figure 1).

The steady and dynamic rheological shear properties of the samples were determined using a modular compact stress/strain-controlled rheometer (Model MCR 302, Anton Paar GmbH, Graz, Austria) equipped with parallel-plate geometry, with a 50-mm upper-plates diameter and a gap width of 1 mm. The average surface roughness (Ra) of the measuring plate is 0.8 µm and the plates are made of steel. The rheological measurements were controlled at +25°C using a peltier thermostated temperature device (Model P-PTD 200, Anton Paar GmbH, Graz, Austria). Before performing the measurement, the samples were allowed to rest for 1 minute between the parallel plates to ensure that the sample were free from artefacts of residual stress. For all test except ORO, the time interval between measurements was automatically determined by the instrument software according to the time required for the samples to reach steady state conditions at each set variable.

2.4.2. Oscillatory shear measurement
The dynamic oscillatory shear rheological properties of the samples were analyzed using an MCR 302 rheometer with parallel-plate geometry. The viscoelastic rheological characterization of the samples was determined using oscillatory shear measurements. The linear viscoelastic range was determined using amplitude sweep tests before starting frequency sweep tests. To understand the structural character of the samples, amplitude sweeps were carried out by implementing a logarithmic increase of the strain (γ) from 0.01% to 100% with six measuring points per decade and a constant angular frequency (ω) of 10.0 rad/s. The temperature was set to remain constant at 25°C. Storage moduli (G’) and loss moduli (G”) were recorded and analyzed using RheoCompass™ software (Version 1.30, Anton Paar GmbH, Graz, Austria). The linear viscoelastic (LVE) range within which the G’ and G” ran parallel to the x-axis was identified. The structural strength of the sauce was expressed as the G’ value within the LVE range. Further, the limiting value of the LVE range (γL) was the strain value at which G”-curve begins to deviate from the LVE plateau with the range of the tolerated deviation at 5%. The crossover point where G’ = G” was also identified. Frequency sweep tests were conducted at strain = 0.05% between 0.1 and 10.0 rad/s with three measuring points per decade. The gel characteristics of the samples were analyzed according to G’ and G”.
A dynamic oscillatory test was used to test stability and was performed at 25°C with ω = 100.0–0.1 rad/s in a pre-determined linear viscoelastic range at γ = 0.05% to investigate the time-dependent deformation behaviors of the samples.

Time-dependent mixed oscillatory, rotation, and oscillation (ORO) tests were conducted to characterize the structural deformation and regeneration after shearing or thixotropic behaviors of the samples. This test was performed based on Mezger (2014) procedure with a combination of alternating intervals representing the test modes of rotation and oscillation directly connected in series. The pre-programmed setting and measurements are shown in Figure 6(a). The advantage of this method is to have the option to apply a considerably higher shear load in the second interval. In our case, the application of high shear could simulate of the technical processes of, for example, dip coating (1–100 s−1), spreading (10–1000 s−1), and dripping or flow under gravity (0.01–1 s−1). The ORO test was carried out in three intervals, each one at a constant strain amplitude, while G’, G”, “shear viscosity (η), and structural regeneration were observed. The test was programmed as follows:
Interval 1: Low shear, oscillation at γ = 0.05%, ω = 10.0 s−1
Interval 2: High shear, rotation at γ = 1000.0, 100.0, 10.0, or 1.0 s−1
Interval 3: Low shear, oscillation at γ = 0.05%, ω = 10.0 s−1

Structural regeneration (%) was calculated as the difference of G’ at 40 s (t40s) from the value at the end of the first low shear-condition interval (the reference value of G’-at-rest; t0s).

![Figure 1](image-url)

Figure 1. Instrumental set up of the adhesive test, consisting of a 35-mm flat-ended cylinder mounted to a TA-XTplus® Texture Analyzer (left). Schematic representation of a typical force–deformation curve for surface stickiness (g) and stringiness (mm) (right).

Figura 1. Montaje instrumental del ensayo de adhesión, consistente en un cilindro de extremo plano de 35 mm montado en un analizador de textura TA-XTplus® (izquierda). Representación esquemática de una curva típica de fuerza-deformación para la pegajosidad de la superficie (g) y la fibrosidad (mm) (derecha).
2.4.3. Rotational shear measurement

The steady rotational shear measurements of the viscosity and flow behaviors of the samples followed those previous reported by Aussananasuwannakul et al. (2020). The shear rate was applied within the range of 0.1–1000 s⁻¹ with 100 measuring points using ascending logarithmic steps. The total measuring time was $t = 200$ seconds; this corresponds to 2 seconds for each measuring point. While it was observed that the two stabilizing system exhibited shear thinning behavior at different magnitude, the viscosity at shear rate of 50 s⁻¹ was also used as a predictor for thickness perception of non-Newtonian foods according to Stokes (2012). The recorded shear rate vs. the shear stress data were fitted to the Herschel – Bulkley model according to the following equation Equation (1):

$$\tau = \tau_0 + K\gamma^n$$

where $\tau$ is shear stress (Pa), $\tau_0$ is yield stress (Pa), $K$ is the consistency index (Pa·sⁿ), $\gamma$ is the shear rate (s⁻¹), and $n$ is the flow behavior index (dimensionless).

2.4.4. Tribological measurement

The frictional properties of the samples were analyzed using a tribological measuring cell (Model T-PTD 200, Anton Paar GmbH, Graz, Austria) mounted to an MCR 302 Rheometer with a ball-on-three-pins measurement geometry. The geometry consists of a sample holder for three cylindrical 6-mm polydimethylsiloxane (PDMS) pins placed on a Peltier temperature control system; the measuring system shaft holding a 0.5° soda-lime glass ball is connected to a motor. The average surface roughness (Ra) of the ball is 0.8 (±0.03) µm and that of the pins is 0.15 (±0.01) µm.

The normal force was controlled by the rheometer at 1 N, whereas the system temperature was set to remain constant at 35°C (typical human-body temperature). The normal force was chosen based on both in-house results as well as the data available in the literature. This normal force results in a contact pressure of around 350 kPa, which while is larger than the real-life contact pressure at the tongue-bolus-palate interface, still provides decent data with high degree of reproducibility.

For each analysis, the measuring method was programmed to run in two consecutive intervals. First, the system was allowed to relax with the freshly applied load. Then, the speed was increased from $10^{-6}$ revolutions per minute (RPM) to 2000 RPM. The friction force that corresponded to the sliding/rotational speed of the tribological system (Streibeck curves) was recorded and analyzed using RheoCompass™ software.

2.5. Statistical analysis

This experiment was conducted as a completely randomized design with the stabilizing system (xanthan gum and corn syrup) as a single main effect. All data were analyzed using the statistical software XLSTAT (version 2020.2.3, Addinsoft; New York, NY, USA). Student’s t test was performed on each data set in which the measurements were replicated at least three times. A significant main effect was defined as $p < .05$.

3. Results

3.1. Physicochemical properties

The composition and physicochemical properties of herbal sweet sauces are shown in Table 1. The pH values of the herbal sweet sauces ranged from 3.39 (CS) to 3.47 (XG) while the TSC were in the range of 12.3 (XG) to 37.2 (CS). Significant difference between the two thickeners was observed only in TSC.

3.2. Instrumental texture

Based on the adhesive test, the XG sauce has relatively higher surface stickiness but lower stringiness than the CS sauce (Figure 2).

From amplitude sweep test (Figure 3), both stabilizing systems shared the same LVE range, with a shearing strain of 0.05%; at this point, the gel strength (G': G") of the CS sauce (4.8) was lower than that of the XG sauce (7.8). The limit of the LVE range ($\gamma_L$) for CS sauce was equal to XG sauce (0.3). Crossover point (G'= G") occurred in CS sauce at higher strain value (14.5) than XG sauce (5.9).

The frequency sweep test (Figure 4) showed within the observed frequency range that G' were always higher than those of G" and the G'/G" ratios were higher than 1.0 for both sauces. The moduli values of the XG sauce were stable as a horizontal line and positioned in a higher range than those of the CS sauce. The parallel straight lines of G' and G" were observed, with G': G" = 3.39 for CS sauce and 5.34 for XG sauce at $\omega = 0.1$ rad/s. For both sauces, a continuing G' curve with a constant slope (0.1 Pa/rad/s) was observed towards the left side of the diagram. At $\omega = 0.1$ rad/s, the G' of XG sauce is 4220 Pa whereas the G' of CS sauce is 239 Pa.

Figure 5 shows the viscosity and flow curves of the two sauces plotted as a function of the shear rate. The viscosity curve showed a downward trend suggesting a shear-thinning behavior for both sauces. With increasing the shear rate, an upward shift of the flow curves was observed. The stress values of the CS sauce were higher
Figure 3. Amplitude sweeps of the two sauces using the two different stabilizing systems (20% corn syrup vs. 0.2% xanthan gum), showing the representative storage moduli ($G'$) and loss moduli ($G''$) profiles with respect to strain (%).

Figure 3. Barridos de amplitud de las dos salsas utilizando dos sistemas estabilizadores diferentes (jarabe de maíz al 20% y goma xantanaal 0.2%), mostrando los perfiles representativos de los módulos de almacenamiento ($G'$) y de pérdida ($G''$) con respecto a la deformación (%).

Figure 4. Frequency sweep of the two sauces using the two different stabilizing systems (20% corn syrup vs. 0.2% xanthan gum), showing the representative storage moduli ($G'$) and loss moduli ($G''$) values with respect to angular frequency (rad/s).

Figure 4. Barrido de frecuencia de las dos salsas utilizando dos sistemas estabilizadores diferentes (jarabe de maíz al 20% y goma xantanaal 0.2%), mostrando los valores representativos de los módulos de almacenamiento ($G'$) y los módulos de pérdida ($G''$) con respecto a la frecuencia angular (rad/s).

Figure 5. Flow behavior of the two sauces with shear stress and viscosity values by shear rate (1/s), comparing the corn-syrup-based stabilizing system to the xanthan-gum-based stabilizing system at 20% and 0.2% by weight, respectively.

Figure 5. Comportamiento de flujo de las dos salsas con los valores de tensión cortante y viscosidad por velocidad de cizallamiento (1/s), comparando el sistema estabilizador a base de jarabe de maíz con el sistema estabilizador a base de goma xantana al 20% y al 0.2% en peso, respectivamente.
than and the curve was steeper than those of the XG sauce.

Both sauces exhibited structural recovery in ORO test. Figure 6(b) shows the representative ORO test results when the shear rate was set at 1000.0 s⁻¹. Their G' values were higher than their G" values throughout the whole period. For this specific test, the shear rate in the 2nd phase was varied from 1000.0 to 1.0 s⁻¹ while the viscosity in 2nd interval and the percentage of regeneration after 40 s in the 3rd interval were observed (Table 3). It was observed in the second interval that the viscosity of both sauces decreased; CS sauce showed greater value than the XG sauce at every preset shear-rate value. In the third interval (shear rates = 100.0 and 1000.0 s⁻¹), the XG sauce showed a higher recovery percentage.

The type of stabilizing system affected tribological profiles of the sauce (Figure 7). Two transitions were observed. The first occurred between 0.01 and 0.10 mm/s with a friction reading of 0.11 for the XG and 0.14 for the CS. The second appeared as a valley at the end of the higher speeds between 100.00 and 1000.00 mm/s with friction readings of 0.05 for the XG sauce and 0.10 for the CS sauce.

4. Discussion

4.1. Physicochemical properties

The herbal sweet sauces produced in this study fulfilled the minimum requirements of Thailand’s food legislation in terms of both pH and TSC. The type of stabilizer used influenced the pH, viscosity, and color of the sweet sauce samples. The pH in the range of 3.39 to 3.47 complied with the required standard value of <4.50 (Thai Agricultural Standard, 2008); they were comparable to commercial chili sauces, which ranged from 3.43 to 3.93 (Gamonpilas et al., 2011). As in the chili sauces, acidic properties in the sweet sauces were contributed by the vinegar, garlic, and chili added into the sauce (Mahmood et al., 2017). The TSC were in the range of 12.3 to 37.2 fulfilled the minimum required TSC value set by Thailand’s Ministry of Public Health Notification (2000) of ≥20.00%. The higher the percentage of spices added, the higher the TSC value and viscosity of the sauce (Mahmood et al., 2017). The presence of total sugars (4.00%) and carbohydrates (29.00%) in the fresh garlic contributed to the higher TSC of the chili sauce (Puranik et al., 2012). High TSC and consistency can be

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**Table 3:**

| Interval | Relaxation | Low shear | High shear | Relaxation | Low shear |
|----------|------------|-----------|------------|------------|-----------|
| Duration: |            |           |            |            |           |
| Total (s) | 1          | 100       | 1          | 0.5        | 400       |
| Data (points) |            |           |            |            |           |
|            |            | 5         | 10         | -          | 20        |
| Time/point (s) |            |           |            |            |           |
|            | -          | 20        | 0.1        | -          | 20        |

**Figure 6:** (a) pre-programmed setting showing time constraint, preset parameters, and data recorded for each interval; (b) time-dependent functions of G', G", and viscosity (η) of the sauce systems (20% corn syrup, CS vs. 0.2% xanthan gum, XG) in three intervals, each at a constant strain amplitude (γ = 0.05%); (1) at low-shear conditions (20–100 s, ω = 10.0 rad/s), showing the “reference value of G'-at-rest” (2) at high-shear structural decomposition (100–101 s; γ = 1000.0 s⁻¹); and (3) at low-shear structural regeneration (122–280 s; 10.0 rad/s), measuring temperature = 25°C.

**Figure 6:** (a) ajuste preprogramado que muestra la restricción de tiempo, los parámetros preestablecidos y los datos registrados para cada intervalo; (b) funciones dependientes del tiempo de G', G" y la viscosidad (η) de los sistemas de salsa (al 20% de jarabe de maíz (CS) y al 0.2% de goma xantana (XG)) en tres intervalos, cada uno de ellos con una amplitud de deformación constante (γ = 0.05 %): (1) en condiciones de baja velocidad de cizallamiento (20–100 s; ω = 10.0 rad/s), mostrando el “valor de referencia de G' en reposo”; (2) en descomposición estructural de alta velocidad de cizallamiento (100–101 s; γ = 1000.0 s⁻¹); y (3) en regeneración estructural de baja velocidad de cizallamiento (122–280 s; 10.0 rad/s), temperatura de medición = 25°C.

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associated with increased viscosity in chili sauces (Gamponpilas et al., 2011).

Increasing solid content can improve product appeal without compromising stability and texture. For example, in fruit-based sauces with high pectin levels in the dispersion phase, pulp can be added at concentrations as high as 54.00% with 18.00% water. In strawberry-enriched ketchup sauces with 54.00% pulp, 18.00% water, and 16.00% sugar as main ingredients, the increase in the strawberry pulp concentration led to less firmness, consistency, and cohesiveness and a lower viscosity index, and the replacement of up to 50.00% of the tomato pulp with strawberry pulp did not change the acidity, flavor, or overall acceptability of the samples (Ahouagi et al., 2021). The addition of fibers to sauces also has an impact on the texture, viscosity, and viscoelastic and sensory properties due to their different polysaccharide derivatives and solubility. Szafranska and Solowiej (2020) have evaluated the effect of various types of dietary fiber (bamboo, acacia, potato, and citrus fiber) that contain different amounts of soluble and insoluble compounds on the textural, rheological, and sensory properties of processed cheese sauces. The processed cheese sauces with the most desirable instrumental and sensory textures were created with the addition of fiber (citrus and potato fibers), with the total insoluble fraction (that is lignin, cellulose, and non-cellulosic polysaccharides) contributing around 55.00% of the total weight, while the rest comprised the soluble fraction (Szafranska & Solowiej, 2020). Similar relationships were observed by Figueroa and Genovese (2018), who found that products with a higher water-soluble pectin content had thicker and stronger gel networks, while the insoluble fraction of the fiber used acted as a filler, reinforcing the structure.

4.2. Adhesive test

In sweet sauce, cohesive and adhesive properties greatly influence their performance before consumption, and the perception of texture in the mouth (Stable Micro Systems,
For sweet sauce, stickiness, the texture term for adhesive properties, is caused by sugars, fats, gums, starches, or mixes of these ingredients. Stickiness was determined by the adhesive test where a flat-surface cylindrical probe applies a force over the sample for 2 s to achieve a good bond between the two surfaces before it is withdrawn until the sample completely separates (failure).

Our previous study evaluated sensory properties of a model sauce using either 20% corn syrup or 0.2% xanthan gum stabilizing system and using a panel of 30 persons. They were asked to rate intensity of brightness, stickiness, thickness, and flavor of the samples as well as liking score on 5-point scale (Figure 8; Saengprakai et al., 2015). We found that the sensory panel could not differentiate the sensory stickiness and thickness of the two sauces (P > 0.05). However, in the current study, an adhesive test using a texture analyzer was able to identify the effects of different stabilizing systems on texture. Based on the instrumental data, the XG sauce has relatively higher surface stickiness but lower stringiness than the CS sauce (Figure 2). At a macroscopic level, adhesive tests were used to assess the strength of bonding between prove and sample surfaces, imitating real-world applications in the context of force, distance, and time.

We also found through visual analysis of the probe surface that the deformation of both sauces tended toward cohesive failure. Cohesive failure occurs within the material and leaves residues in both surfaces, and there is also legging or little necking deformation of the sticking materials. For solid and semi-solid materials where the interfacial bonding balances against the internal mechanical strength of the material, either adhesive or cohesive failure mechanisms could be possible, but for many viscous (or viscoelastic) fluid foods, cohesive failure is most likely the dominant mechanism (Stable Micro Systems, 2016).

According to Wang and Hartel (2020), the average molecular weight of saccharides and sugar positively correlated with stickiness and generally exhibited elevated glass transition temperature and viscoelasticity. The surface stickiness of sugar-based syrup represents a sticky amorphous sugar matrix at the interface; a reduction in the surface area of amorphous sugar in contact with the probe causes a direct reduction in stickiness (Burke & Hartel, 2021).

An increase in xanthan concentration from 0.5 to 1 g/100 g increase the adhesiveness of the hazelnut sauce compared to the controls (Pourfarzad & Derakhshian, 2021). XG can raise the sensory attribute rate of breakdown of thickened food and liquid although the gum is not hydrolyzed by alpha-amylase in the saliva due to its pseudoplasticity that could aid in reducing oral friction (Steele et al., 2015). Rate of breakdown of the texture-modified product was negatively correlated to instrumental parameter of cohesiveness, whereas instrumental adhesiveness was positively correlated to sensory attributes adhesive to mouth and throat, and difficulty to swallow (Peh et al., 2022).

Based on our sensory data from the previous study and the current imitative test results, it can be concluded that predicting the sensory perception of sauce product requires a combination of instrumental measurement. Savouré et al. (2021) showed that stringiness and consistency index is sufficient to characterize the texture of okra sauces and to predict the sensory perception of their consistency and elongational properties.

4.3. Rheological analysis

4.3.1. Oscillatory shear

For manufacturers, the challenge in formulating dipping sauces is modifying their viscoelastic behaviors so that the particles do not separate out, while still ensuring that the product remains viscous enough to pour and elastic enough to regain its original structure and appear as an even layer on the food surface. Small amplitude oscillatory shear measurements, such as amplitude sweeps and frequency sweeps, are well suited to measuring these properties. The structural characteristics of both samples were determined under oscillatory shear at a low amplitude value (0.05%) in the LVE range. The LVE, or critical strain amplitude, indicates the maximum strain in the linear viscoelastic region and provides the maximum deformation amplitude that can be applied without affecting the dynamic moduli and thus the structure (Mezger, 2014). At 0.05% strain, while the gel strength of the CS sauce was lower than that of the XG sauce, the limit of the LVE range (γc) for CS sauce was equal to XG sauce. These characteristics indicate that the structure of the sample shows no significant change at these low deformations. At strain higher than γc, the limit of the LVE range is exceeded and the structure of the sample has been changed reversibly. Crossover point (G” = G”) which is the point at which the internal structure breaks to such an extent that it causes the material to flow occurred in CS sauce at higher strain value (14.5) than XG sauce (5.9). Crossover point could suggest an order of magnitude of the yield stress, a more meaningful parameter independent of frequency used, which will be explained in later section under steady shear flow.

Both sauces also demonstrated gel-like consistency in the low-shear range (shear rate < 1.0 s⁻¹), with the XG sauce exhibiting greater rigidity (a higher elastic modulus value) than the CS sauce and thus more stability at ambient
storage. The behaviors of these sauces in the low-shear range give an indication of the degree of surface leveling and sagging after application. These behaviors are further discussed in ORO test.

Frequency sweeps (Figure 4) was conducted to determine the dispersion stability of the two sauces. Within the observed frequency range, the G’ values higher than those of G” indicate that both sauces have the dominant elastic properties characteristic of a solid structure. The G’/G” ratios higher than 1.0 indicate a soft and flexible gel structure. Thus, both sauces can be classified as weak gels (Rao, 2014). Similar behavior has been reported for other plant-tissue-based food suspension products, such as peach puree (21 °Brix; Massa et al., 2010), siriguela pulp (15.8% TSC; Augusto et al., 2012), tomato ketchup with 0.3% xanthan gum (Mirzaei et al., 2018), and Plantago major seed gum in aqueous dispersions (1–2% wt/vol; Niknam et al., 2019). The moduli profile of the XG sauce that was stable along the horizontal line and positioned higher than those of the CS sauce suggests that the former is likely to be more stable for long storage and less likely to experience phase separation or sedimentation. Both sauces exhibited viscous, gel-like characteristics and long-term stability to sedimentation, as observed by the parallel straight lines of G’ and G”. At ω = 0.1 rad/s, the higher G’/G” ratio and higher G’ value suggests that the XG sauce had a relatively higher network stiffness and higher structural strength at rest.

4.3.2. Rotational shear
A viscosity curve showing a downward trend, representing shear-thinning, was characteristic of both sauces (Figure 5). Both sauces displayed shear-thinning flow behavior, which is typical for dispersions with strongly pronounced shear thinning in the lower shear-rate range. Shear-thinning materials show a viscosity that decreases with increasing shear rates in a steady flow. Logically, these differences can also be derived from the Herschel – Bulkley parameters. All fitted parameters are summarized in Table 2. Yield point is the lowest shear-stress value above which a material will behave like a fluid, and below which the material will act like a – sometimes very soft – solid matter (ISO 3219, 2021). A higher yield stress and greater consistency were observed in the XG sauce. According to Heyman et al. (2010), the exact yield stress value is largely determined by the type of hydrocolloid, with concentration having little influence. They found that white sauces containing xanthan gum exhibited the highest yield stress among other non-starch hydrocolloids, probably due to XG’s interlinked polymer chains. The general guidelines offered by Mezger (2014) indicate that polymer/structure liquids with yield values below 1 Pa will flow, even at rest. This means that they can flow into even the smallest gaps on the surface to be coated. Moreover, dispersions with yield points of above 10 Pa have sufficient structural strength at rest to show a certain physical stability against the sedimentation of particles (Mezger, 2014). Thickened liquids, such as fruit- and vegetable-based products, also possess yield stresses and so behave like solids with small, applied stresses and like liquids with larger applied stresses (Moelants et al., 2014).

Increasing the shear rate systematically caused an upward shift of the flow curves (Figure 5). The most distinct changes were observed in the CS sauce. The stress values of the CS sauce were higher and the curve was steeper than those of the XG sauce, which, on the other hand, seemed less responsive to the increasing shear rate. The difference between the two sauces was most noticeable at higher shear rates. Both sauces showed shear-thinning behaviors with yield stress values. In other words, the apparent viscosity of both sauces decreased with increasing shear rates. The Herschel Bulkley model best describes the flow behavior of samples with R² values higher than 0.9998. The sauce stabilized by XG showed a five-fold higher consistency index (K) value than that stabilized by CS (η < 0.05; Table 2). The flow behavior indices (η) of both sauces were lower than one, with the values of the XG sauce slightly lower than those of the CS sauce, indicating shear-thinning behavior in both samples. With respect to oral rheology, the type of stabilizing system generally did not significantly affect the apparent viscosity (η50) values, a predictor of thickness sensation. The η50 of plant-tissue-based suspensions is more sensitive to processing parameters. In apricot sauces, for example, the η50 decreased with increasing blanching temperatures, blanching times, and storage periods, and increased with increasing sieve diameters (Levent & Alpaslan, 2018). The viscosity of plant-tissue-based sauces has also been reported to decrease throughout the storage period (Nongmuc, 2013; Usiak et al., 1995). However, we shall see later that the relevance of shear-thinning behavior of these sauces is more for the tribological tests, wherein, the formation of a load-bearing fluid film, and the viscous drag in the hydrodynamic friction regime largely relies on the rheological behavior at higher shear rates.

4.3.3. ORO test
An ORO test was used to characterize the time-dependent structural reorganization and thixotropic behaviors of the sauce systems after shearing. Presumably, stabilizers may affect the elastic behaviors of samples by modifying the

| Sample         | Oscillatory shear | Steady shear*          |
|---------------|-------------------|------------------------|
|               | Gel Strength (G’/G”) in LVE range | Limit of LVE range (%) | Crossover Point (G’= G”) | Apparent viscosity [Pa·s] at 50 s⁻¹ | Yield Stress (τ0) Pa | Consistency (K) Pa·s | Flow index (n) |
| 20% Corn Syrup| 4.8 ± 0.1⁸       | 0.3 ± 0.0              | 5.9 ± 0.1⁸               | 0.1 ± 0.0                     | 0.1 ± 0.0⁸               | 0.1 ± 0.0⁸               | 0.8 ± 0.0⁸ |
| 0.2% Xanthan  | 7.8 ± 0.2 b       | 0.3 ± 0.0              | 14.5 ± 0.3b              | 0.1 ± 0.0                     | 1.2 ± 0.0⁸               | 0.6 ± 0.0⁸               | 0.5 ± 0.0⁸ |

*Data fitted to the Herschel-Bulkley model. 
**Means with different superscripts within the same response are significantly different (n = 3; p < 0.05).

Tabla 2. Parámetros de cizallamiento oscilatorio y rotacional de las salsas dulces (media + DE) utilizando jarabe de maíz o goma xantana como sistema estabilizador.
mobility of water in the systems and thus their viscosity. The tendency to sagging after application was tested using a three-interval step test at room temperature.

The evaluation shows that both sauces exhibited structural recovery, and their G’ values were higher than their G” values throughout the whole period, indicating a gel-like structure and suggesting their ability to maintain solidity without sagging or forming a watery surface. The regeneration (%), which is a general indicator of the recovered structure after high shear exposure, showed significant differences between XG and CS sauce at each level of shear rate in the second interval (Table 3). Moreover, the shear rate negatively correlated with viscosity and regeneration in both samples. With increasing preset shear-rate value, viscosity of both sauces in the second interval decreased, while the CS sauce showed greater viscosity than the XG sauce. However, in the third interval, with higher shear rates of 100.0 and 1000.0 s⁻¹, the XG sauce showed a higher recovery percentage, indicating superior structural regeneration than its counterpart. The lower viscosity at high shear (100.0–1000.0 s⁻¹) and better recovery at low oscillatory shear (10.0 rad/s) suggests that the XG sauce is relatively easier to pour and better at coating surfaces. This is in line with the greater consistency and lower flow index of the XG sauce.

In general, both sauces showed G’ > G” after t = 40 s in the third interval. This means they both remained viscoelastic solid after the shear load and did not sag. Their comparable recovery after the preset shear rate at the lower range (1.0–10.0 s⁻¹) suggests their similar dripping or flow behaviors under gravity. They are both less likely to exhibit sagging, as G’ > G”, and the early plateau observed in the third interval suggests structural solidity; in other words, the shear force could distribute evenly in the sauces, causing irreversible permanent deformation to their structure (surface coating). Despite their similar viscosity at rest, the XG sauce has a lower viscosity under shearing than the CS sauce. At 1000.0 s⁻¹ which is a typical range for pouring liquid out of the bottle, pipe flow according, and surface coating (Mezger, 2014), we also compared structural regeneration of the sauces at certain time from 20 to 180 s. After the shear load, the XG sauce clearly demonstrated complete structural regeneration (at 20 s) quicker than the CS sauce, despite the XG sauce’s lower viscosity in the second phase. The CS sauce demonstrated a considerably slower structural recovery, which was complete only at 150 s. The regeneration speed is an indication of layer thickness. The structural regeneration of the CS sauce took longer than that of the XG sauce. This means that the CS sauce will potentially take longer time to flow on a food surface, which results in a thinner surface coating than the XG sauce.

Thixotropy implies a reversible time-dependent decrease or increase, respectively, of the viscosity that is induced by flow at a fixed shear rate (Barnes, 1997; Mewis & Wagner, 2009). The higher regeneration percentage of the XG sauce at high shear rates suggests its greater structural rigidity and the extended nature of its molecular component. The ability of XG to endure shear loads and provide structural resilience to sauces is due to its linear, cellulose backbone, which is stiffened and shielded by anionic trisaccharide side chains (Damodaran et al., 2008). Comparing other commercial hydrocolloids, XG is relatively large polymeric structure (2 to 6 × 10⁵ Da) with polyionic side chain. In dispersion, hydrophilic groups entangled into regular network structure by hydrogen bonding and van der Waals forces, which enabled wrapping of more free water (Patel et al., 2020). Consequently, its viscosity is larger and pseudoplasticity came into existence; this ability to endure external stress was shown as its higher structural regeneration at higher shear rate. Our result is in line with Alghooneh et al. (2018) who used the in-shear structural recovery test with 300 s⁻¹ pre-shearing and found that XG at 1% w/w exhibited the structuring effect and aggregation/agglomeration resulted from its recovered elastic component with 81.27% recovery.

4.4. Tribological analysis

The study of friction and lubrication between interacting surfaces has emerged as a key tool for deconvoluting complex oral processing and providing insights into the physics of the in-mouth processes relating to sensory perception (Sarkar et al., 2021). Classical theories of lubrication define four regimes of lubrication in the form of a Striebeck curve that presents data as a function of a speed-dependent parameter related to the film thickness between substrates (Bongaerts et al., 2007). As shown in Figure 7, the lubrication provided by the two sauces was characterized as friction according to the sliding speed. The resulting friction profiles revealed that boundary and hydrodynamic regimes are mostly affected by the type of stabilizing system used (Figure 7).

Two transitions represented key phenomena between interacting surfaces with regard to the sweet sauce samples. First, the initial peak represented the transition from static to sliding friction and indicates the magnitude of the breakaway friction of the system. This transition occurred between 0.01 and 0.10 mm/s with a friction reading of 0.11 for the XG and 0.14 for the CS. These values offer insight into the limiting friction of the system, that is, the resistance to the initiation of motion. When a critical torque is reached, the
counter surface starts moving over the ground surface (Blau, 2005). After passing the yield point, sliding friction starts (Rosenkranz, 2014). We can also attribute them to the stickiness of the system. The tallest peak indicates the amount of resistance offered by the system even after the initiation of motion.

Secondly, there is a valley at the end of the higher speeds between 100.00 and 1000.00 mm/s with friction readings of 0.05 for the XG sauce and 0.10 for the CS sauce. This signifies the transition into a hydrodynamic friction regime where the surfaces are continuously removed from each other, and a first stable thin film is generated. The magnitude of friction here depends upon a few factors, the most important being the viscosity of the sample (Bongaerts et al., 2007). Hence, the results would indicate that, with higher break-away friction, the CS sauce shows greater potential to lower the friction between interacting surfaces than xanthan gum. The CS higher breakaway friction could possibly be explained by its relatively higher viscosity. During the initial approach of the glass ball towards the PDMS pins, not all sample is squeezed out of the contact and as we start rotating, the existence of a relatively thicker film would help in reducing the friction as the contact between the ball and the pins takes relatively longer to happen. This is also the reason that once the set speed is attained, one does not see much of a difference in the friction coefficient until the systems reach their transition from mixed to hydrodynamic regime.

As the CS sauce has a higher break-away friction, there is more room to decrease the same. It is very probable that viscosity is a contributing factor for the differences observed in the break-away friction of the two sauces. In many cases, it has been observed that a higher viscosity leads to a lower break-away friction by forming a film between the interacting surfaces which is not squeezed out of the contact due to the low loads that are being applied (Funami & Nakamura, 2021; Gamonpilas et al., 2022; Sharma et al., 2022). In the hydrodynamic lubrication regime though, a higher viscosity would imply a greater viscous drag, ergo a higher friction coefficient, which we observe in this case study as well. As it turns out, the measurements from an imitation-type adhesive test substantiate this observation. Based on the ORO test, the CS sauce may also develop a lubricating mouth coating that is more desirable.

The goal of tribological analysis is to define the surface behaviors that suit the application, not necessarily to determine high or low friction or wear. Thus, translating tribological test results into product preferences requires further sensory study. Murray et al. (2021) suggest that an ideal stabilizing system is associated with a smooth mouthfeel as a consequence of its relatively high viscosity and its role as a saliva-interacting lubricant in thin films between oral surfaces. Tribological characterizations of thickened sauces suggest that oral lubrication and bulk flow may also possibly influence flavor perceptions. Nakatomi et al. (2021) have found that favorable flavors reduced the perception of oral viscosity when using a xanthan gum-based thickener added to water and apple juice. Demonstrated by tribological analysis, they found that the reduction in the perception of the oral viscosity of the liquid sample was due to the mixing of the thickener with stimulated saliva, which suppressed its unpalatability. This may explain why we observed that the flavor of the XG sauce with higher viscosity in the low shear-rate range was less distinguishable than that of the CS sauce (Figure 8).

Research has focused on the stabilization and mechanical characterization of emulsions and suspensions and on structuring the continuous external phase to avoid or delay phase-separation phenomena. Sweet sauces are complex multiphase suspensions of deformable herbs and spice particles and, sometimes, liquid deformable particles, such as oil droplets. The continuous phase is essentially water or a solution of macromolecules in water, which includes hydrocolloids, salt, organic acid, or other components, to achieve an acidic characteristic and to preserve the product. The addition of hydrocolloids is thought to be necessary in the manufacture of sweet sauces to provide sufficient viscosity and to stabilize the suspensions to prolong shelf life. It is a focus of the current study to characterize and compare the instrumental texture of two polysaccharide-based stabilizing systems with unique sensory characteristics. It was found that although their sensory qualities are comparable, as shown by the instrumental texture characterization, the XG-based sauce is superior to the CS sauce in terms of its stability and technical applications. Corn syrup, which is a common starch hydrolysis mixture of oligosaccharides used as thickener in traditional sweet sauces, was found to be less effective in providing suspension stability than xanthan gum, a non-starch polysaccharide, in terms of its water-to-thickerener ratio (410.0 vs. 2.3 w/w). However, corn syrup provides molecular products such as caramelization, a characteristic flavor, and color. Both polysaccharides modify and control the mobility of water in food systems, and water plays an important role in influencing the physical and functional properties of polysaccharides (Damodaran et al., 2008). Polysaccharides and water together control the texture and mouthfeel of sweet sauces.

Knowledge of the rheological characteristics of these thickened fluids is important in the design of flow processes, in quality control, and in storage and processing stability. The current study has characterized the viscoelastic and flow behaviors of sweet sauces and found them to be dependent on both time and shear load. Comparing rheological and tribological properties of sweet sauces with different stabilizer at very different concentration (20% CS vs. 0.2% XG), the aim is to demonstrate their water mobilizing capability. By this experimental design, the liquid phase of the XG sauce is much larger than the liquid phase of the CS sauce. At their comparable stability, the concentration of herbs and spices added were not equal in the two sauces (24% vs. 8%). Alvarez et al. (2004) have observed that commercial sweet sauces that use only syrup/sugar and water as ingredients at ratios ranging from 1–5 (wt/wt) presented Newtonian behavior, while their consistency indices decreased linearly when the temperature increased. The intended design of herbal sweet sauce of the current study, however, was a more complex (non-Newtonian) system to enable load of herbs and spices that give the sauces a unique flavor and texture. The content and type of these herbs and spices vary from recipe to recipe. In general, a suspension’s rheology is largely determined by the particle properties of the dispersed phase. With plant-tissue particles, flow behavior can change. Omoregie and Bushi (2008) observed three commercial fruit sauces (solid content =
28.00% and specific gravity = 1.15) to be non-Newtonian and shear-thinning in temperatures ranging from 10°C-60°C, behaving like weak gels with linear viscoelasticity of about 1.00% and unaffected by frequency ranges of 30.0–160.0 rad/s. Moelants et al. (2014) have indicated that particle concentration, size, morphology, and deformity are key structural properties affecting the rheological parameters of plant-tissue-based food suspensions with a low starch content (<1.0 wt.%) and containing low serum pectin concentrations (<0.5 wt.%). The current study observed that the particle concentration at 24% in CS sauce could give sensory acceptance, ease of application and storage stability. This higher concentration was in line with their higher sensory flavor intensity and overall liking scores as compared to XG sauce with only 8% herbs and spices. Our findings are in accordance with Moelants et al. (2014) who found that the increase in total solid content, size, degree of surface irregularity, and particle deformity have been associated with increased apparent viscosity, yield stress, and storage moduli (G’) at low angular frequency. The higher levels of solid particles in the CS sauce (24.00%) might have contributed to its relatively low stability compared to the XG sauce (8.00%). The current study used transient tests and tribology to give further insight into product applications and mouthfeel. Using nondestructive methods, we also compared the elasticity and structural relaxation of the two stabilizing systems. Alternative to frequency sweep tests (fixed % strain), thixotropic testing is another option for the time-dependent characterization of materials to observe their real-world applications at non-static and different ranges of stress to the system. While flow behaviors can vary depending on the type of stabilizing system used and the particle properties, the ultimate goal might be sensory acceptance, ease of application (for example, pouring, surface coating), and storage stability (that is no phase separation, sedimentation). Texture-taste interactions may be underlying factors affecting the indiscrimination of sensory textures between the two stabilizing systems using general subjects. In beverages with a viscosity ranging from 1.000–2.000 mPa.s, Kappe et al. (2006) found that consumers’ ability to detect mouthfeel differences between diet and regular carbonated beverages, despite the small instrumental viscosity difference (0.527 mPa.s), was due to the different mouthfeel detection thresholds of the sweeteners used in the products. In the sauces examined in the current study, the differences in instrumental (rather than sensory) texture may have been related to the panelists’ ability to detect small differences in mouthfeel within a specific viscosity range (that is 9.000 Pa.s), meaning the two sauces are not significantly different. Therefore, future studies should try to differentiate between sensory cues from starch and non-starch-based stabilizing systems by controlling for the effect of flavoring ingredients and using trained panelists. As the friction profiles in this study suggests differences in the time-dependent surface properties between the two stabilizing systems, their interactions with saliva will allow us to directly relate the instrumental data to oral sensations.

5. Conclusions
Multiple rheological and tribological tests can be used to characterize the inner structure and water-mobilizing characteristics of two stabilizing systems. Corn syrup gives a unique flavor and color to products due to caramelization. However, xanthan gum stabilizing systems are superior in terms of product stability. Both systems can be differentiated by lubrication. Instrumental texture data reveal the possible behaviors of sweet sauces and the contributions of the two stabilizing systems to storage and to applications relating to perceptions and preferences. This information is important for product development and for the customization of plant-tissue-based food suspensions.

This study married tribology with other well-established tools such as rheology and texture analysis for a set of sauces which has not been done before. The mouthfeel experience is a sum of multiple effects including, but not limited to, the techniques mentioned above, and we are working towards establishing a correlation between certain mouthfeel attributes and individual or a combination of parameters that can be obtained through instrumental techniques. The takeaway point is that the methodology being used in this study can differentiate between the samples, and this is vital especially for tribological tests, as the choice of parameters – normal force, test specimen, test profile, temperature, running-in, etc. – can (and in most cases does) influence the outcome of the tests.

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