LWT - Food Science and Technology 194 (2024) 115802

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Rheological properties, microstructure and stability of oil-in-water emulsions prepared with mango kernel starch (var. Sugar and Tommy)

David Ramírez-Brewer [a], Daniel A. Méndez [b], Luis A. Garcia-Zapateiro [a], Amparo López-Rubio [b], María José Fabra [b,*]

[a] Research Group on Complex Fluid Engineering and Food Rheology (IFCRA), University of Cartagena, Cartagena, 130015, Colombia
[b] Food Safety and Preservation Department, Institute of Agrochemistry and Food Technology (IATA-CSIC), Valencia, Spain

ARTICLE INFO

Keywords:
Starch
Emulsions
Rheology
Microstructure
Texture

ABSTRACT

In the present work, the emulsification capacity of the mango kernel starch var Sugar (Sg) and Tommy (To) was investigated. Oil-in-water emulsions were elaborated with Sg and To starch. The chemical composition of the Sg and To showed significant differences ($p < 0.05$) in the phenolic compounds, proteins and amylose content. The microstructure of the emulsions for each concentration of Sg and To (1.5, 3.5 and 6%w/v) showed a packing of the oil droplets and a reduction in their size with increasing oil content. A phase separation was observed for a Sg and To concentration of 1.5%w/v and an oil concentration of 40 and 60%v/v, indicating that there was not a good integration of the oil within the starch gel matrix. The emulsions showed pseudoplastic behaviour ($n < 1$). The consistency index, apparent viscosity, firmness, stickiness and spreadability were higher for the emulsions prepared with the highest oil content. The results obtained provide information on the composition of Sg and To and its capacity for the stabilisation of O/W emulsions, showing an advantage over other starches, which have to be modified to improve their emulsification capacity, thus indicating the great potential of these starches for the development and formulation of new food products

1. Introduction

Mango is a tropical and climacteric fruit, which according to the Food and Agriculture Organization (FAO) had an average world production of 57.01 million tons (FAO, 2023). It is used for the elaboration of processed foods and as a source for the development of new functional foods (Nawab et al., 2017). The mango fruit is considered an important source of phytochemicals such as phenolic compounds, vitamins, micronutrients, carbohydrates, proteins, fats, dietary fibre, which are of great importance for the health of human beings (Jahurul et al., 2015). During the industrial processing of Mango, a large amount of waste is produced annually, with 12–15% of the total waste belonging to the peel and 15–20% to the kernel. According to the variety, the mango kernel may contain approximately 58 wt% starch on a dry basis, this waste being a good source for obtaining and producing native fruit starches (Nawab et al., 2016). The potential for the recovery of mango by-products, such as the seed, has fostered great scientific interest in the development of alternative solutions that respect the environment, promoting the transition towards a circular economy through the development of biorefineries, which are based on the use of mango by-products. They can be processed to recover compounds of interest such as starches and bioactive compounds for the development of new value-added products using green and integrated technologies (Nayak & Bhushan, 2019). Furthermore, they must be economically viable, thus providing benefits to society and the industry (Panwar et al., 2021).

Starch is a biopolymer that can be used as stabilizer, gelling and thickener agent in various pharmaceutical and food applications (Abou El-Naga et al., 2022). Amylopectin and amylose are the two main starch polysaccharides. Amylose is a linear macromolecule made up of D-glucose units linked by α-1,4 bonds, while amylopectin is a branched macromolecule made up of D-glucose units joined by α-1,4 and α-1,6 bonds (Rodrigues, & SantosCostaFélixNascimentoLima, 2020), which has an important role in the gelling and stickiness properties of starch, for example, high amylose starch gels are much stronger and rigid than low amylose starch gels. Depending on the botanical source, the amylose content can vary between 0 and 75% w/w, with typical values between 20 and 25% w/w (Zhang et al., 2020).

An emulsion consists of dispersed droplets of a liquid phase that is

* Corresponding author.
E-mail address: mjfabra@iata.csic.es (M.J. Fabra).

https://doi.org/10.1016/j.lwt.2024.115802
Received 3 November 2023; Received in revised form 2 January 2024; Accepted 24 January 2024
Available online 2 February 2024

immiscible in another liquid phase. Emulsions are often stabilized with emulsifiers of animal origin (eg, egg and milk proteins) or synthetic surfactants (eg, Tweens). The emulsifying agents adsorb on the interface between the two immiscible liquid phases, imparting steric or electrostatic barriers between the neighbouring droplets and the colliding ones, thus avoiding the phenomenon of coalescence (Kasprzak et al., 2018). Adverse effects, such as biological interactions, air entrapment, irritation or foaming have been reported for emulsions, which may be related with the use of surfactants in emulsion stabilisation (Sjöö et al., 2015; Zhu, 2019). Currently, the consumption of natural foods and beverages with the addition of ingredients from vegan sources has increased their demand (McClements & Gumus, 2016; Zhu, 2019), which has prompted researchers to explore the use of stabilizing agents and/or emulsifiers from vegan sources, such as starch (McClements et al., 2017). Starch has characteristics such as low cost and market availability, it is non-allergenic and biodegradable which makes its use beneficial (Zhu, 2019), but its application as an emulsifier is not optimal due to its properties in its native form (Apostolidis et al., 2023; Basiak et al., 2017; Chen et al., 2020). The obtention of less refined starch extracts containing certain amounts of other compounds such as proteins or polyphenols could improve its emulsifying properties. For this reason, it is necessary to apply different extraction or modification methods (physical, chemical or enzymatic) in order to improve its emulsifying capacity (Apostolidis et al., 2023; Marefati et al., 2017; Zhu, 2019).

Previous studies have reported the use of modified starches as stabilizing agents in the formation of oil-in-water emulsions, including kudzu starch modified with octenyl succinic anhydride (Zhao et al., 2017), lauric acid esterified starch (Wang et al., 2023), and fatty acid-esterified waxy maize starch (Mirzaaghaei et al., 2023). Therefore, the objectives of this investigation were to: (i) analysed the emulsifying activity of native starches from the mango kernel compared to commercial corn starch, (ii) characterise the rheology, microstructure, and texture of the emulsions, and (iii) understand the mechanism for stabilisation of emulsions of mango kernel starches.

2. Materials and methods

2.1. Raw material

Mango (*Mangifera Indica* var. Sugar (Sg) and var. Tommy (To)) in a state of organoleptic maturity were purchased on the local market in Cartagena de Indias (Colombia). Sunflower oil (SO) was purchased in the supermarket. Folin-Ciocalteu reagent, gallic acid, sodium carbonate, potassium persulfate, 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), phosphate buffered saline (PBS), 6-hydroxy-2.5.7.8-tetramethylchromane-2-carboxylic acid (Trolox), trifluoroacetic acid (TFA), fucose, rhamnose, galactose, glucose, arabinose, xylose, mannose, galacturonic acid and glucuronic acid, hexane and commercial corn starch (Co) were acquired from Sigma-Aldrich (Madrid, Spain).

2.2. Sample preparation

Mangos were washed using a sodium hypochlorite solution with a concentration of 100 ppm, and then, pulp, peel and seed were separated. The seeds were immersed in water to remove any traces of adherent pulp, dried at 45 °C for 5 h, and then, the kernel was removed from the seed and dried by lyophilization using FreeZone 2.5 L Benchtop Freeze Dryer (Labconco). It was subsequently ground to reduce its particle size ($<200\ \mu m$).

2.3. Starch extraction

The starch of the Mango of the Sugar and Tommy variety was extracted following the methodology development by (Ramírez-Brewer et al., 2023). The powdered mango kernel was dispersed at a 1:10 ratio in a 1%w/v sodium bisulfite solution with constant stirring for 4 h at room temperature. Subsequently, the dispersion was stirred in an ultra-turrax (IKA T20, Staufen, Germany) for 5 min, filtered (100 mesh), distilled water was added to the residue in sufficient quantity and the filtrate was stored for 3 h to decant the starch. The supernatant was centrifuged at 3500 rpm for 30 min to precipitate the remaining starch. The mango starch obtained was dried at 45 °C for 36 h.

2.4. Protein and lipid content

The total nitrogen content was determined using an Elemental Analyzer Rapid N Exceed (Flash Smart Elemental analyser). About 250 mg of each of the powdered samples were pressed to form a pellet which was then analysed using the Dumas method. The nitrogen conversion factor used was 6.25. The lipid content was determined by the AOAC Official Method 991.36 (AOAC, 2022).

2.5. Carbohydrate composition and amylose content

The composition of monosaccharides was determined by acid hydrolysis of mango starches following the method by (Pérez-Bassart, 2023). Briefly, 1 mg of starch was added to 1 mL of trifluoroacetic acid (TFA) at 2 M, then heated to 120 °C, holding this temperature for 3 h. The monosaccharide composition of mango starches was analysed using a high-performance anion exchange chromatography with pulsed amperometric detection (HPAEC-PAD, Dionex, Sunnyvale, CA, USA) with CarboPac™ PA1 column. The amylose content was determined using the methodology reported by Morrison & Bernard, 1983.

2.6. Total phenolic content (TPC) and antioxidant activity

The TPC of the starches were calculated using the Folin-Ciocalteau reagent following the methodology proposed by (Bojorges et al., 2022; Singleton et al., 1999) with modifications. A 1:10 dilution of the Folin-Ciocalteu reagent was prepared in distilled water and 1000 μL were added and mixed with 200 μL of each sample (~1 mg/mL). Then, 800 μL of Na_2CO_3 (75 g/L) were added and the samples were kept at 40 °C for 30 min. Subsequently, the absorbance was determined at 760 nm. The TPC was expressed as mg GAE (gallic acid equivalents)/g starch.

The antioxidant capacity of starches was measured according to the methodology reported by (Bojorges et al., 2022; Re et al., 1999). Mango starch samples were added to distilled water at a concentration of 0.43 mg/mL, stirred with vortex for 5 min, then 20 μL was taken and added to 230 μL of the $ABTS^{*+}$ solution and left in the dark for 6 min Subsequently, the absorbances were determined at 734 nm. The antioxidant activity was expressed in mg TE (trolox equivalents)/g of Starch.

2.7. Development of starch solutions and emulsions

Starch solutions were prepared by adding samples of mango starch from the Sg and To varieties, and commercial corn starch (Co) in distilled water at a concentration of 1.5, 3.5 and 6%w/v with constant stirring, then heated to 90 °C to fully gelatinize the starch for 15 min and finally cooled to room temperature. Oil-in-water emulsions were elaborated by adding sunflower oil to the starch solution according to Table 1 and homogenising it in an Ultraturrax for 3 min at 9400 rpm. Sample's code was "xyz' where 'x' indicates the concentration of starch, 'y' refers to the type of starch used (Sg, To, or Co), and "z" indicates the oil concentration in the emulsion.

2.8. Storage stability

The stability of the emulsions were analysed after 8 days of storage by means of phase sepation. To this end, 10 mL of the freshly prepared emulsions were put into cylindrical glass tubes with a tightly closed plastic cap to prevent evaporation. Samples were stored under

Table 1
Sample code formulation of starch emulsions.

Starch (%)	Sunflower Oil (%)	Sample Code		
		Sg	To	Co
1.5	40	1.5Sg40	1.5To40	1.5Co40
	60	1.5Sg60	1.5To60	1.5Co60
	70	1.5Sg70	1.5To70	1.5Co70
3.5	40	3.5Sg40	3.5To40	3.5Co40
	60	3.5Sg60	3.5To60	3.5Co60
	70	3.5Sg70	3.5To70	3.5Co70
6	40	6Sg40	6To40	6Co40
	60	6Sg60	6To60	6Co60
	70	6Sg70	6To70	6Co70

refrigerated conditions (4 ± 0.5 °C) for 8 days.

2.9. Microstructural characterization of the emulsions

The stabilized emulsions were microstructurally analysed by confocal microscopy according to the methodology described by Mendez et al., 2021. Fluorescence images of the emulsions were characterized using a FV 1000-IX81 confocal laser scanning microscope (CLSM, Olympus, Japan) with a combination of 559 nm and 635 nm excitation wavelengths and with emission wavelength of 572 nm and 647 nm for Nile red and Fast green, respectively, for the fluorescence field. Nile Red (0.01%w/v) was added and homogenized with the oil before emulsion formation, while Fast Green (0.01%w/v) was added to the already prepared emulsion to stain the proteins. Images were analysed and processed by using FV10-ASW Version 4.02.03.06 (Olympus Corporation, Tokio, Japon).

2.10. Rheological characterization

The rheological characterization of the emulsions was evaluated in a rheometer HR20, (TA Instruments, Montreal, QC, Canada) using a plate/plate measurement system with a gap of 0.5 mm. The tests were carried out at a temperature of 25 ± 2 °C. The flow behaviour of the emulsions was evaluated in a strain rate range between 0.01 and 200 s^{-1}. The apparent viscosity (η_{app}) was evaluated at 100 s^{-1}. The results of the rheological characterization were adjusted to the power law model (Ostwald de Waele) (Eq. (1)):

$$\eta = K\gamma^{n-1} \quad (1)$$

where K is the consistency index ($Pa\ s^n$) and n is flow behaviour index.

2.11. Texture properties

Textural properties (spreadability, firmness, and stickiness) were measured using a TA. XT-Plus Texture Analyses (Stable Micro Systems Ltd., Godalming, UK), following to the method developed by (Mendez et al., 2021). Samples were filled into a female cone (90° angle) with special attention to avoid bubbles formation. Any excess of sample was scraped off with a ruler. Then, the filled cone sample holder was put in the base holder and a 45-degree cone probe was used to penetrate the samples. Pre-test speed of 1 mm/s was set with trigger force of 1 g. Then, a test speed of 3 mm/s was applied until the sample reached 80% strain. Force, expressed in Newtons, was measured for the duration of the test. Firmness, spreadability and stickiness were determined. All measurements were made, at least, in triplicate.

2.12. Statistical analysis

All the data were measured in triplicate and expressed as mean ± standard deviation. The analysis of variance (ANOVA) and the LSD test were used to determine significant differences and comparison of means respectively with $p < 0.05$. Statsgraphics Centurion 19 software was used for statistical analysis.

3. Results and discussions

3.1. Starch characterization

The results of the compositional and functional characterization of the two starches under study (Sg and To) and corn starch (Co) are shown in Table 2. The compositional analysis of the starches of the mango kernel of the Sugar (Sg) and Tommy (To) varieties shows that the total starch content was 70.29 g/100 g and 69.48 g/100 g, respectively. Higher yields (74%, 84.56 and 92.56%) were obtained from unripe mango kernel, Ihambu and Vetch starches, respectively (Patiño-Rodríguez, Agama-AcevedoRamos-LopezLuis & Bello-Pérez, 2020). The lipid content was 11.44% and 10.74% for Sg and To, respectively, while the protein content was 6.54% and 4.59% for Sg and To, respectively. These values are higher than those reported for sorghum starch (2.3%w/w of protein and 0.8%w/w of lipids) and for wheat starch (0.2–0.3% w/w of protein and 0.08–0.12% w/w of lipids) (Alcázar-Alay, & Meireles, 2015). The amount of phenolic compounds in the mango kernel starches was 49.6 and 85.5 mgGAE/g starch for Sg and To, respectively. Similar results have been reported for the mango starch var. Corazon (84.89 mg GAE/g Starch) (Mieles-Gómez, et al., 2023). The results of the ABTS test showed that Sg and To samples exerted antioxidant activity, which could mean better oxidative stability of the emulsion (Zhao et al., 2021). The amylose contents were 18.61%, 22.71% and 25% for the starches of the Sg, To and Co, respectively. Similar amylose contents are reported for cassava starch (17%), potato starch (21%), wheat starch (22.6%) and yam starch (19.80%) (Hernández-Medina et al., 2008; Przetaczek-RożnowskaIzabela, 2017; Rosicka - Kaczmarek et al., 2016), and lower than for mango starch var. Corazon (28.46%) (Mieles-Gómez et al., 2023). The monosaccharide profile showed that, as expected, glucose was present in the highest amount (702.9 μg/mg, 694.88 μg/mg and 953.96 μg/mg for the Sg, To and Co respectively), consistent with starch as the predominant polysaccharide. The results showed that there were not significant differences ($p > 0.05$) in the glucose contents of Sg and To, which indicates no significant differences in starch content. Traces of arabinose and galactose were present in Sg, while To had arabinose and galacturonic acid, all of which may arise from a minor contribution of pectin. As

Table 2
Characterization of starch obtained from mango kernel var Sugar (Sg), mango kernel var Tommy (To), and Commercial Corn (Co).

	Sg	To	Co
Lipid content (%)	11.44 ± 0.18^{a}	$10.74 \pm 0,20^{a}$	–
Protein content (%)	6.53 ± 0.31^{a}	4.59 ± 0.31^{b}	–
Amylose content (%)	18.61 ± 0.46^{1a}	22.71 ± 0.41^{1b}	25^{2c}
Monosaccharide composition [μg/mg]			
• Fucose	0 ± 0	0 ± 0	0.38 ± 0.10
• Rhamanose	0 ± 0	0 ± 0	0.26 ± 0.12
• Arabinose	4.29 ± 0.31	5.68 ± 5.68	1.10 ± 0.10
• Galactose	2.04 ± 3.54	0 ± 0	0.02 ± 0.03
• Glucose	702.9 ± 74.22^{a}	694.88 ± 26.79^{a}	953.96 ± 48.89^{b}
• Mannose	0 ± 0	0 ± 0	0 ± 0
• Xylose	0 ± 0	0 ± 0	0.96 ± 0.86
• GalA	0 ± 0	2.55 ± 4.42	1.11 ± 1.64
• GlcA	0 ± 0	0 ± 0	0.50 ± 0.17
TPC (mgGAE/g Starch)	49.58 ± 0.1^{a}	85.39 ± 0.80^{b}	–
ABTS (mgTE/g Starch)	56.40 ± 0.29^{a}	132.32 ± 0.61^{b}	–

GalA: Galaturonic acid; Glc A Glucorinic acid.
Different letters in the same row express statistically significant differences ($p < 0.05$).
Amylose content adapted from (Ramírez-Brewer et al., 2023).
Amylose content adapted from (Yu and sun, 2022).

expected, the glucose content for the commercial corn starch (Co) was higher than for the Sg and To starches. Similar starch purity results were reported by (Patiño-Rodríguez, Agama-AcevedoRamos-LopezLuis & Bello-Pérez, 2020), for mango kernel starch (74 g starch/100 g).

3.2. Formation of emulsions

The emulsification capacity of starches (Sg, To and Co) was evaluated by preparing oil-in-water emulsions at different starch concentrations (1.5, 3.5 and 6%w/v) and three concentrations of oil (40, 60 and 70%v/v). The results observed in Figs. 1 and 2 showed that mango seed starches had better emulsifying activity compared to the reference corn starch, where a phase separation was observed for all the formulations used. According to the chemical and functional composition of the kernel starches obtained, some of the factors that could modify the emulsifying properties are i) protein content related to the reduction of interfacial tension during gelatinization (Brewer et al., 2016; Zhao et al., 2017), ii) the formation of amylose-lipid complexes at the water-oil interface (Gómez-Luría et al., 2019) and iii) protein-polyphenol complexes, which increase the stabilisation of emulsions (Li et al., 2021).

3.3. Microstructural characterization and stability emulsions

Fig. 1 shows the macroscopy images of the fresh emulsions prepared with Sg, To and Co. The stability of the emulsions was evaluated during storage for 8 days at 4 °C (Fig. 2). As shown in Fig. 1, fresh emulsions prepared with 1.5%w/v of Sg with an oil concentration of 40 and 60%v/v showed phase separation, as did the emulsion prepared with 1.5%w/v of To with an oil concentration of 40%v/v. This suggests that, at this concentration, the gel structure formed by the starch matrix was weak, since the oil acted as an inactive filler (Geremias-Andrade et al., 2017; Zhao et al., 2022). The emulsions prepared with Sg and To at 6%w/v and with an oil concentration of 70%v/v showed phase separation, which could be related to the fact that the amounts of Sg and To starch were insufficient to form a firm mechanical barrier between the adjacent oil droplets to avoid coalescence during emulsion formation (Zhao et al., 2022). The emulsions prepared with fresh Co showed slight phase separations, the emulsification mechanism maybe due to the high viscosity of the gelatinised Co, as it will be detailed below. After 8 days of refrigerated storage, emulsions prepared with 1.5%w/v of To with an oil content of 60%v/v and emulsions prepared with 3.5%w/v of Sg and with an oil content of 70%v/v showed an apparent coalescence of oil droplets, showing a phase separation, which could be due to the fact that the oil droplets did not integrate well into the starch gel matrix and hindered gel network formation (Zhang et al., 2021; Zhao et al., 2022). Additionally, the emulsions prepared with Co showed phase separation, which was expected, since starch in its native form does not have optimal emulsifying properties (Apostolidis et al., 2023; Basiak et al., 2017; Chen et al., 2020). The stabilized emulsions showed a creamy appearance, which is consistent with their textural and rheological properties, as will be detailed below. Figs. 3 and 4 show the microstructure of the stabilized emulsions by confocal microscopy, where sunflower oil was stained with nile red. As observed, at low Sg and To concentrations, the particle size distribution was more heterogeneous. On the contrary, when the concentrations of Sg and To increased, a decrease in droplet size and a more homogeneous distribution of oil particle size were observed, indicating a better affinity of the oil with the gelatinised starch matrix. This is because oil spread over the surface of the gel network, acting as a filler and as the main structural component of the emulsion network, which is considered an active filler (Torres et al., 2017; Zhao et al., 2022). With increasing starch and oil content, the oil droplets showed a dense packing. Interestingly, the emulsions prepared with 3.5%w/v of Sg and with an oil content of 70%v/v produced an apparent coalescence of the droplets in contrast to the emulsions prepared with 3.5%w/v of To, where this phenomenon was not observed. Furthermore, a similar phenomenon was produced in emulsions prepared with 6%w/v of Sg and To for an oil content of 70%v/v. In order to study the influence of protein content on the microstructure of the emulsion, the samples were stained with fast green dye, which is widely used for protein staining (Mendez et al., 2021), as shown in Figs. 3 and 4. The protein content for Sg starch (6.53%) was higher than that for To (4.59%), while phenolics content for Sg (49.50 mg GAE/g starch) was lower than that of To (85.39 mg GAE/g starch). The ratio of phenolics/protein, much higher for To starch than for Sg, may influence the starch emulsification capacity. This can be contrasted with the stability of the To-formulated emulsions, where it was observed that for 3.5%w/v of To and oil content of 70%v/v, the emulsion did not present a phase separation, while its counterpart prepared with Sg did. This can

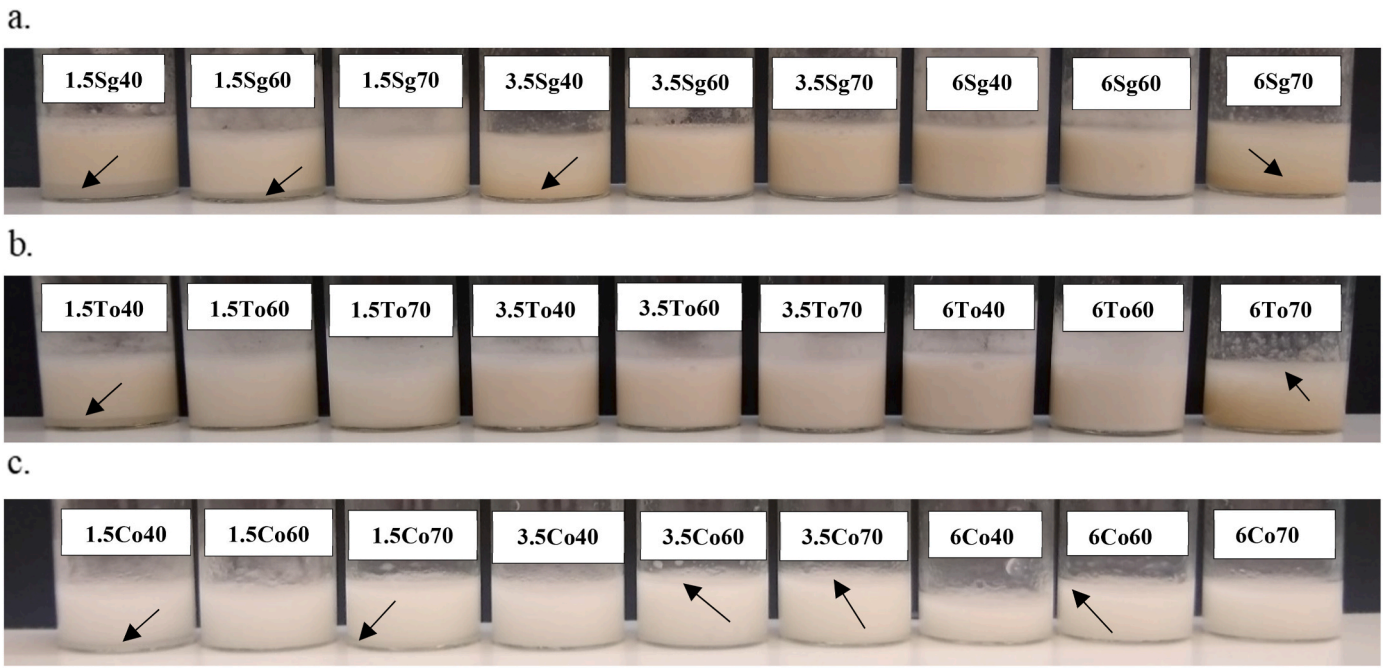

Fig. 1. Macroscopic images of the different emulsions in day 0 (freshly prepared). (a) Sg, (b) To and (c) Co. Black arrows indicate phase separation.

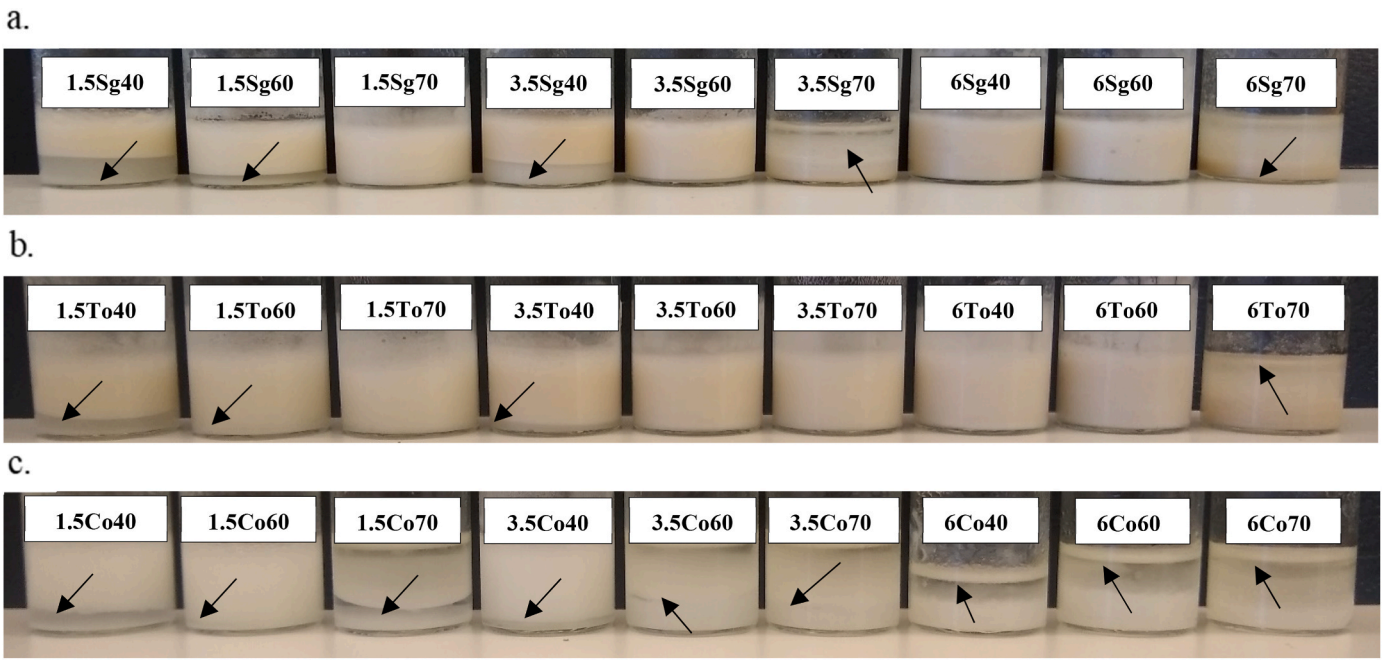

Fig. 2. Macroscopic images of the different emulsions after 8 days of storage (day 8) at 4 °C. (a) Sg, (b) To and (c) Co. Black arrows indicate phase separation.

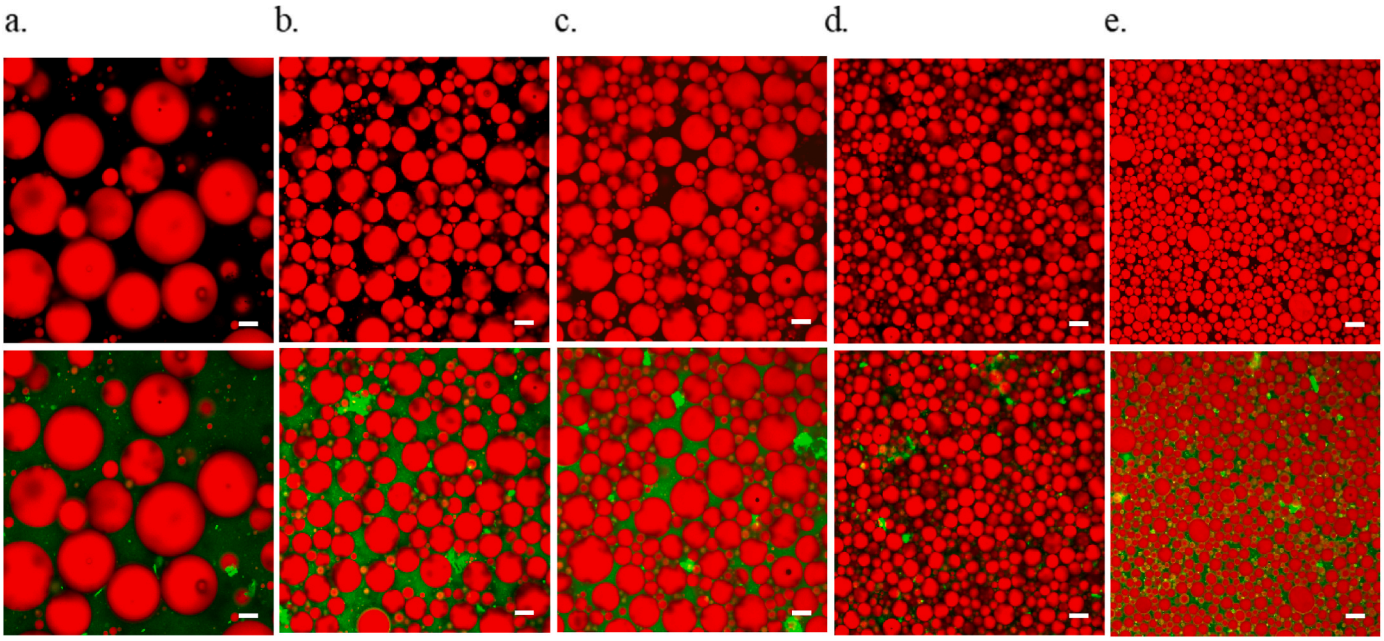

Fig. 3. Confocal microscopy images of stabilized mango kernel starch var Tommy-based emulsions. Oil droplets and proteins present in the emulsion are stained with nile red and fast green respectively. The scale bar corresponds to 20 μm. (The first row corresponds to the emulsions only the oil stained. The second row corresponds to the same emulsions with the oil and proteins stained.) (a) 1.5To70, (b) 3.5To60, (c) 3.5To70, (d) 6To40 and (e) 6To60.

be explained because not only the presence of protein contributes to the stabilisation of emulsions, but also the presence of phenolic compounds and the formation of protein-polyphenol complexes (Bandyopadhyay et al., 2012). These complexes improve the stability of emulsions, due to an increase in the hydrophobicity of their surface and improvement of their surface activity, which leads to the formation of a thicker interfacial layer that prevents the coalescence of the droplets (Chen et al., 2023). The increased flexibility, solubility, and surface hydrophobicity of proteins further improves their adsorption capacity on water and oil surfaces (Li et al., 2021). Furthermore, the formation of amylose-lipid complexes attached to the interface may contribute to the stability of emulsions (Gómez-Luría et al., 2019).

3.4. Rheological characterization

Fig. 5a and b displays the flow curves of the Sg and To emulsions, and Fig. 5c shows the flow curves corresponding to the gelatinised solutions of Sg, To, and Co (without oil). The rheological data of the starch solutions and emulsions were adjusted to the Power-law model (Ostwald de Waele), which showed a good fit ($R^2 > 0.9$). Tables 3 and 4 show the parameters of Power-law model (Ostwald de Waele) and the apparent viscosity (η_{app}) values for the emulsions and starch solutions

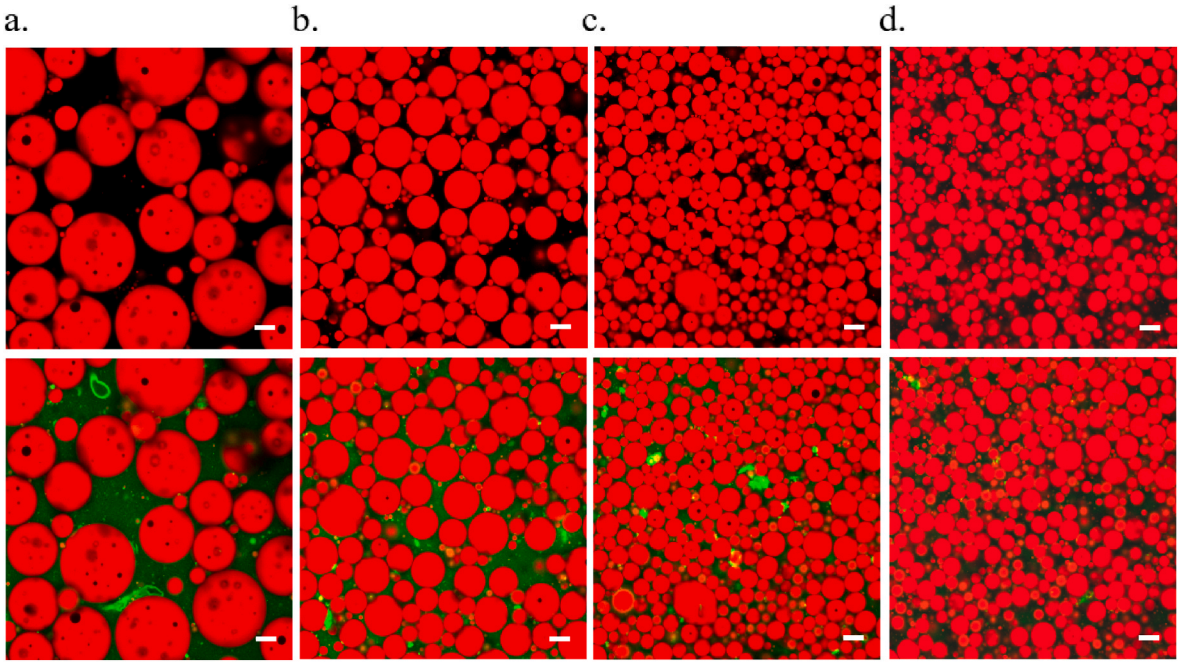

Fig. 4. Confocal microscopy images of stabilized mango kernel starch var Sugar-based emulsions. Oil droplets and proteins present in the emulsion are stained with nile red and fast green respectively. The scale bar corresponds to 20 μm. (The first row corresponds to the emulsions only the oil stained. The second row corresponds to the same emulsions with the oil and proteins stained.) (a) 1.5Sg70, (b) 3.5Sg60, (c) 6Sg40 and (d) 6Sg60.

respectively. The emulsions stabilized with Sg and To, and the starch solutions, exhibited both a shear-thinning (pseudoplastic) behaviour at shear rates of 0.1–200 s^{-1}, as previously reported for other types of starches (Li et al., 2020; Song et al., 2015; Ye et al., 2017).

This behaviour can be attributed to the breakdown of the starch structure during shearing, where the rate of destruction of the starch structure was higher than the rate of deformation rate (Ye et al., 2017). Additionally, shear-thinning may be due to rupture of the oil drop network due to hydrodynamic forces causing their rearrangement in a certain direction and resulting in less resistance to flow (Luo et al., 2019; Mendez et al., 2021; Meng et al., 2018). As observed in Fig. 5 and Tables 3 and 4, the addition of oil produced significant changes in the rheological behaviour, making the emulsions more pseudoplastic and more viscous than their counterpart starch solutions. A higher viscosity of the continuous phase of the O/W emulsions contributed to the stability of the emulsion, since it slows down the movement of the oil droplets, which limits flocculation and coalescence (Mendez et al., 2021; Ngouémazong, 2015). According to Table 3, an increase in the oil content in O/W emulsions was observed to significantly increase the consistency index (K) and apparent viscosity (η_{app}) at 100 s^{-1}, which was attributed to the increased packing of the oil droplets in the continuous phase, as can be seen in the microstructural analysis (Figs. 3 and 4) (Alfano et al., 2017; Hong et al., 2018; Zhang et al., 2020). In addition, it was observed that an increase in the oil content caused a decrease ($p < 0.05$) in the flow rate, which implies a more pronounced deviation from Newtonian behaviour, showing a gel-like texture, similar to an emulsion-gel (Hong et al., 2018). The consistency index (K) and apparent viscosity (η_{app}) at 100 s^{-1} significantly increased their value with increasing starch content in the solution (Table 4), being higher for Co, followed by To and Sg. This can be explained by the gelling properties of starches, which is related to their amylose content, since a higher amylose content increases the gelling capacity of starch (Zhang et al., 2020).

3.5. Texture analysis

Fig. 6a and b shows the firmness, spreadability and stickiness results of the emulsions prepared with Sg and To. According to the results shown in Fig. 6, the firmness, spreadability and stickiness values of the emulsions prepared with Sg and To were significantly affected ($p < 0.05$) by the amount starch and oil, which is correlated with the increase in the consistency index K and apparent viscosity η_{app} reported in the previous section. It should be mentioned that the textural properties of the emulsions prepared with Sg at a concentration of 1.5%w/v showed higher values of spreadability, firmness and stickiness than the emulsions with 3.5 and 6%w/v of Sg and with an oil concentration of 60 and 40%v/v, respectively. The emulsions prepared with 3.5 and 6%w/v of To at oil concentrations of 70 and 60%v/v, respectively, and the emulsions prepared with 1.5 and 6%w/v of Sg with oil concentrations of 70 and 60%v/v, respectively, showed the highest firmness, spreadability and stickiness values. Furthermore, the firmness, spreadability and stickiness values of the emulsions with 6%w/v starch (Sg and To) and 60%v/v oil showed significant differences ($p < 0.05$) with the emulsions prepared with 1.5%w/v, 3.5%w/v and 6%w/v. of starch (Sg and To) and 70%v/v, 60%v/v and 40%v/v of oil respectively. It seems that when the oil content increases, a packing of the oil particles is produced (Zhao et al., 2022), in agreement with the microstructure and rheological results (see Figs. 3 and 4).

3.6. Proposed mechanisms for stabilisation of mango kernel emulsion

Based on the results obtained, an emulsion stabilisation mechanism is proposed for mango kernel starches and is presented schematically in Fig. 7. During the emulsion preparation process, the gelatinised Sg and To starch was homogenized with the oil, allowing the system to be present in the form of a gel. According to the starch concentration used, the oil presented an active or inactive filling behaviour. In the case of the emulsions elaborated with 1.5%w/v of Sg and To, and oil concentration of 40 and 60%v/v, the oil behaved as an inactive filler in the matrix, showing that the oil droplets did not integrate well into the gel matrix and weakened the gel structure, facilitating the separation of the phases (Zhao et al., 2022) (Fig. 2a and b). For emulsions with a higher oil and starch content, there was a denser packing of oil droplets, in addition to a good integration of the oil in the gel matrix, which contributed to a

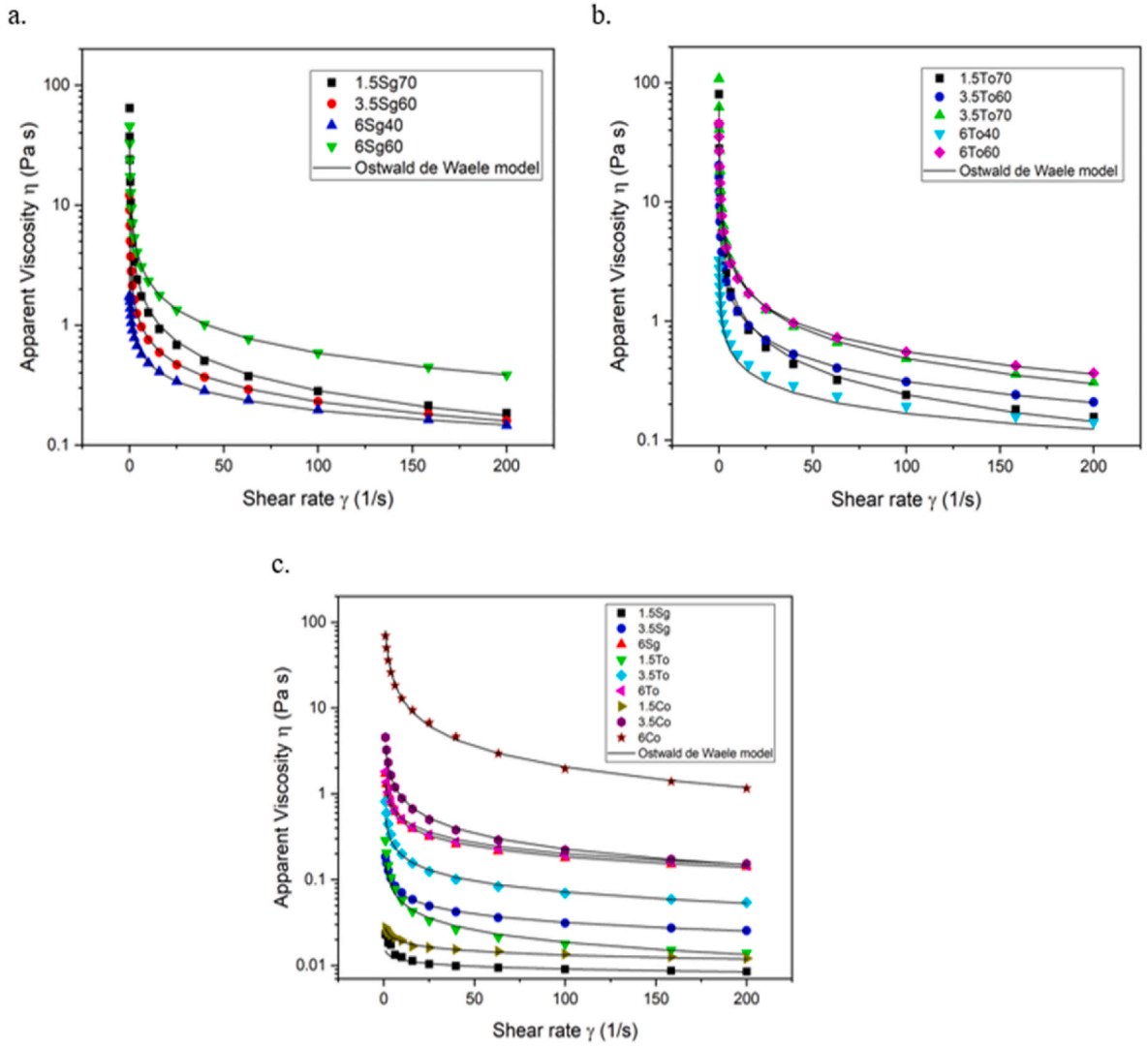

Fig. 5. Flow curves for (a) emulsions prepared with Sg at 1.5, 3.5 and 6%w/v starch concentration, (b) emulsions prepared with To at 1.5, 3.5 and 6%w/v starch concentration and (c) solutions prepared with Sg, To and Co at 1.5, 3.5 and 6%w/v starch concentration.

Table 3
The rheological properties (consistency index (K), flow behaviour index (n) and apparent viscosity (η_{app})) of oil-in-water emulsions stabilized with mango starch.

Samples	K ($Pa\,s^n$)	n	R^2	η_{app} ($Pa\,s$)
1.5Sg70	6.62 ± 0.75^{a}	0.32 ± 0.01^{a}	0.96	0.28
3.5Sg60	2.59 ± 0.47^{b}	0.48 ± 0.02^{b}	0.99	0.23
6Sg40	1.22 ± 0.00^{c}	0.6 ± 0.00^{c}	0.96	0.20
6Sg60	9.43 ± 0.43^{d}	0.40 ± 0.01^{d}	0.99	0.59
1.5To70	7.58 ± 0.34^{a}	0.25 ± 0.00^{e}	0.97	0.24
3.5To60	4.78 ± 0.31^{e}	0.41 ± 0.01^{d}	0.99	0.31
3.5To70	12.55 ± 1.45^{f}	0.30 ± 0.00^{f}	0.97	0.48
6To40	1.43 ± 0.05^{bc}	0.56 ± 0.01^{g}	0.99	0.19
6To60	9.76 ± 0.09^{d}	0.38 ± 0.00^{h}	0.99	0.55

Different letters in the same column express statistically significant differences ($p < 0.05$).

Table 4
The rheological properties (consistency index (K), flow behaviour index (n) and apparent viscosity (η_{app})) of starch solutions.

Samples	K ($Pa\,s^n$)	n	R^2	η_{app} ($Pa\,s$)
1.5Sg	0.02 ± 0.00^{a}	0.89 ± 0.00^{a}	0.92	0.01
3.5Sg	0.14 ± 0.01^{a}	0.67 ± 0.01^{c}	0.99	0.03
6Sg	1.21 ± 0.02^{b}	0.59 ± 0.01^{bc}	0.98	0.18
1.5To	0.16 ± 0.01^{a}	0.53 ± 0.00^{b}	0.97	0.02
3.5To	0.51 ± 0.00^{b}	0.57 ± 0.01^{c}	0.98	0.07
6To	1.34 ± 0.03^{b}	0.59 ± 0.00^{c}	0.98	0.19
1.5Co	0.03 ± 0.00^{a}	0.84 ± 0.04^{a}	0.99	0.14
3.5Co	3.60 ± 0.22^{b}	0.40 ± 0.01^{d}	0.99	0.22
6Co	79.45 ± 4.83^{c}	0.21 ± 0.01^{e}	0.99	1.96

Different letters in the same column express statistically significant differences ($p < 0.05$).

greater gel strength, as shown in their confocal images (Figs. 3 and 4), and rheological properties. The stability of the emulsions can be attributed to the presence of proteins and the formation of protein-polyphenol complexes, as they adsorb on the surfaces of newly formed oil droplets created by homogenization, where they facilitate further disruption of the oil droplets by reducing interfacial tension and delay coalescence by forming protective layer around the droplets (Brewer et al., 2016; Zhao et al., 2022).

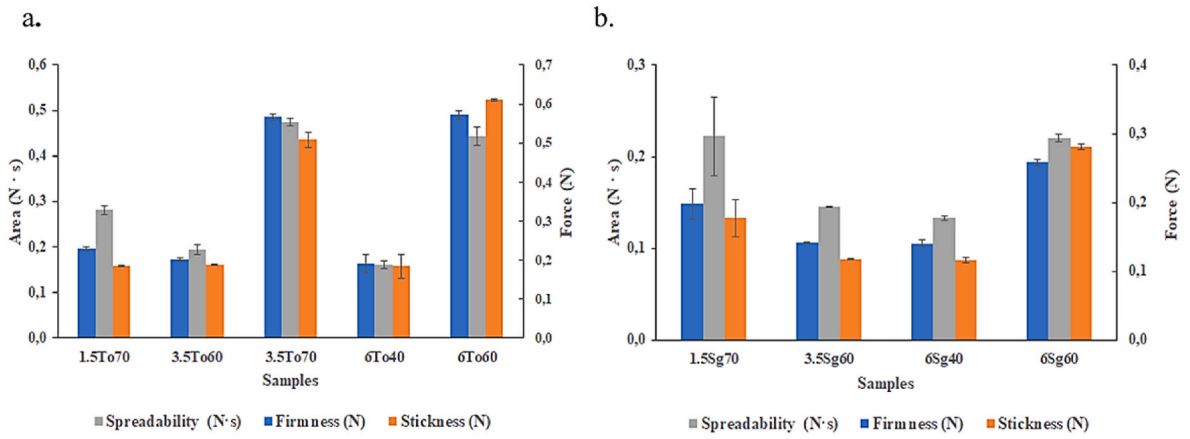

Fig. 6. Spreadability, firmness and stickiness values of (a) the starch emulsions at three different concentrations of mango kernel starch var Tommy (1.5, 3.5 and 6% w/v) and with oil at 40, 60 and 70%v/v) and (b) the starch emulsions at three different concentrations of mango kernel starch var Sugar (1.5, 3.5 and 6%w/v) and with oil at 40, 60 and 70%v/v.

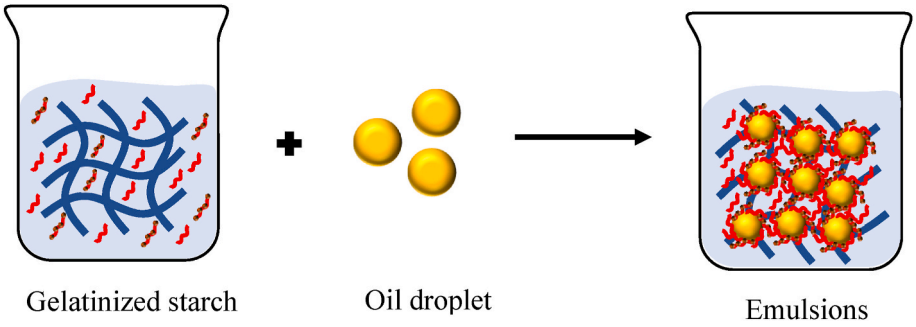

Fig. 7. Schematic representation of the proposed stabilisation of the emulsion for the starch mango kernel. Protein () and protein-polyphenol complexes ().

4. Conclusions

In this study, emulsions prepared with Sg and To starches were evaluated to understand their stabilisation mechanism, comparing it with commercial corn starch. The microstructural, rheological and textural results of the emulsions prepared with Sg and To showed a strong dependence on the oil content. In emulsions prepared with 1.5% w/v of Sg and To with oil content of 40 and 60%v/v, the oil acted as an inactive filler, which resulted in a decrease in gel strength, causing phase separation. An increase in the starch concentration (Sg and To) caused a decrease in droplet size and better droplet distribution of the emulsions. The rheological and textural results were consistent with the microstructural results. The emulsions stabilized with Sg and To showed non-Newtonian fluid behaviour (pseudoplastic type). The consistency index, apparent viscosity, firmness, spreadability and stickiness were higher for the emulsions prepared with the highest oil content at the starch concentration of Sg and To use in the study, which was related to a higher gel strength and to the packing of the oil particles. The protein and polyphenol content of Sg and To starches played an important role in the emulsification, since proteins contribute to the reduction of oil-water interfacial tension, as well as the complexes formed by proteins-polyphenols. The emulsification mechanism of starches was influenced by the amylose content (gelling capacity) and its interaction with lipids, in addition to the interaction of proteins and polyphenols. Therefore, the starches obtained from the mango kernel present an advantage over the native commercial starches in terms of emulsification properties, as they are capable of forming emulsions with high oil content. Furthermore, these starches have not been modified, which represents another advantage in terms of their use in the food and pharmaceutical industry for the elaboration of new products based on emulsions.

CRediT authorship contribution statement

David Ramírez-Brewer: Formal analysis, Methodology, Writing – original draft. **Daniel A. Méndez:** Investigation, Methodology. **Luis A. Garcia-Zapateiro:** Writing – review & editing. **Amparo López-Rubio:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **María José Fabra:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgements

David Ramirez Brewer and Luis Garcia Zapateiro are thankful to be supported by the Ministry of Science, Technology and Innovation, MinCiencias (Contract 368–2019, Research Project No. 110780864755; and a high-level human capital training programme (Minciencias - Doctoral Excellence Scholarships) with resources from the Colombian government. The Accreditation as Center of Excellence Severo Ochoa CEX 2021-001189-S funded by MCIN/AEI/10.13039/501100011033 is also fully acknowledged. David Ramirez Brewer acknowledged the Institute of Agrochemistry and Food Technology of Valencia-IATA-CSIC for a Doctoral Internship.

References

Abou El-Naga, H. M. H., El-Hashash, S. A., Yasen, E. M., Leporatti, S., & Hanafy, N. A. N. (2022). Starch-based hydrogel nanoparticles loaded with polyphenolic compounds of moringa oleifera leaf extract have hepatoprotective activity in bisphenol A-induced animal models. *Polymers, 14*(14). https://doi.org/10.3390/polym14142846

Alcázar-Alay, S. C., & Meireles, M. A. A. (2015). Physicochemical properties, modifications and applications of starches from different botanical sources. *Food Science and Technology (Brazil), 35*(2), 215–236. https://doi.org/10.1590/1678-457X.6749

Alfano, E. H., Crosta, T., Martinez, M. J., Pérez, O. E., & Farías, M. E. (2017). Submicron O/W emulsions embedded into modified waxy maize starch based matrix: Rheological and microstructural characterization. *Food Hydrocolloids, 67*, 120–129. https://doi.org/10.1016/j.foodhyd.2016.12.038

AOAC. (2022). *AOAC international – in food & agriculture, we set the standard*. AOAC International. https://www.aoac.org/.

Apostolidis, E., Stoforos, G. N., & Mandala, I. (2023). Starch physical treatment, emulsion formation, stability, and their applications. *Carbohydrate Polymers, 305*.

Bandyopadhyay, P., Ghosh, A. K., & Ghosh, C. (2012). Recent developments on polyphenol-protein interactions: Effects on tea and coffee taste, antioxidant properties and the digestive system. *Food & Function, 3*(6), 592–605.

Basiak, E., Lenart, A., & Debeaufort, F. (2017). Effect of starch type on the physico-chemical properties of edible films. *International Journal of Biological Macromolecules, 98*, 348–356. https://doi.org/10.1016/j.ijbiomac.2017.01.122

Bojorges, H., Fabra, M. J., López-Rubio, A., & Martínez-Abad, A. (2022). Alginate industrial waste streams as a promising source of value-added compounds valorization. *Science of the Total Environment, 838*. https://doi.org/10.1016/j.scitotenv.2022.156394

Brewer, D. R., Maria Franco, J., & Garcia-Zapateiro, L. A. (2016). Rheological properties of oil-in-water emulsions prepared with oil and protein isolates from sesame (sesamum indicum). *Food Science and Technology (Brazil), 36*(1), 64–69. https://doi.org/10.1590/1678-457X.6761

Chen, L., Ao, F., Ge, X., & Shen, W. (2020). Food-grade pickering emulsions: Preparation, stabilization and applications. *Molecules, 25*(14).

Chen, Y., Yao, M., Su, P., Fang, Y., Wan, L., Shang, W., Dong, X., & Zhang, W. (2023). Development of protein-polyphenol particles to stabilize high internal phase pickering emulsions by polyphenols' structure. *Food Chemistry, 428*. https://doi.org/10.1016/j.foodchem.2023.136773

FAO. (2023). Food and agriculture organization of the united nations (FAO). Retrieved https://www.fao.org/faostat/. (Accessed 9 October 2023).

Geremias-Andrade, I. M., Nayla, P. D., Souki Izabel, B. G., Moraes, C. F., & Pinho, S. C. (2017). Rheological and mechanical characterization of curcumin-loaded emulsion-filled gels produced with whey protein isolate and xanthan gum. *LWT, 86*, 166–173. https://doi.org/10.1016/j.lwt.2017.07.063

Gómez-Luría, D., Vernon-Carter, E. J., Alvarez-Ramirez, J., & Cruz-Sosa, F. (2019). Insights of the ability of gelatinized fractions from non-chemical modified corn, rice, wheat, and waxy corn starches to stabilize O/W emulsions. *Food Hydrocolloids, 89*, 726–734. https://doi.org/10.1016/j.foodhyd.2018.11.045

Hernández-Medina, M., Torruco-Uco, J. G., Chel-Guerrero, L., & Betancur-Ancona, D. (2008). Caracterización fisicoquímica de Almidones de Tubérculos cultivados en yucatán, méxico. *Ciênc. Tecnol. Aliment., Campinas, 28*(3), 718.

Hong, L. F., Cheng, L. H., Gan, C. Y., Lee, C. Y., & Peh, K. K. (2018). Evaluation of starch propionate as emulsion stabiliser in comparison with octenylsuccinate starch. *LWT, 91*, 526–531. https://doi.org/10.1016/j.lwt.2018.01.076

Jahurul, M. H. A., Zaidul, I. S. M., Ghafoor, K., Al-Juhaimi, F. Y., Lin Nyam, K., Norulaini, N. A. N., Sahena, F., & Mohd Omar, A. K. (2015). Mango (mangifera Indica L.) by-products and their valuable components: A review. *Food Chemistry, 183*, 173–180.

Kasprzak, M. M., Macnaughtan, W., Harding, S., Wilde, P., & Wolf, B. (2018). Stabilisation of oil-in-water emulsions with non-chemical modified gelatinised starch. *Food Hydrocolloids, 81*, 409–418. https://doi.org/10.1016/j.foodhyd.2018.03.002

Li, M., Ritzoulis, C., Du, Q., Liu, Y., Ding, Y., Liu, W., & Liu, J. (2021). Recent progress on protein-polyphenol complexes: Effect on stability and nutrients delivery of oil-in-water emulsion system. *Frontiers in Nutrition, 8*.

Li, S., Zhang, B., Li, C., Fu, X., & Huang, Q. (2020). Pickering emulsion gel stabilized by octenylsuccinate quinoa starch granule as lutein carrier: Role of the gel network. *Food Chemistry, 305*. https://doi.org/10.1016/j.foodchem.2019.125476

Luo, S. Z., Hu, X. F., Jia, Y. J., Pan, L. H., Zheng, Z., Zhao, Y. Y., Mu, D. D., Zhong, X. Y., & Jiang, S. T. (2019). Camellia oil-based oleogels structuring with tea polyphenol-palmitate particles and citrus pectin by emulsion-templated method: Preparation, characterization and potential application. *Food Hydrocolloids, 95*, 76–87. https://doi.org/10.1016/j.foodhyd.2019.04.016

Marefati, A., Wiege, B., Haase, N. U., Matos, M., & Rayner, M. (2017). Pickering emulsifiers based on hydrophobically modified small granular starches – Part I: Manufacturing and physico-chemical characterization. *Carbohydrate Polymers, 175*, 473–483. https://doi.org/10.1016/j.carbpol.2017.07.044

McClements, D. J., Bai, L., & Chung, C. (2017). Recent advances in the utilization of natural emulsifiers to form and stabilize emulsions. *Annual Review of Food Science and Technology, 8*, 205–236.

McClements, D. J., & Gumus, C. E. (2016). Natural emulsifiers — biosurfactants, phospholipids, biopolymers, and colloidal particles: Molecular and physicochemical basis of functional performance. *Advances in Colloid and Interface Science, 234*, 3–26.

Mendez, D. A., Fabra, M. J., Martínez-Abad, A., Martínez-Sanz, Gorria, M., & López-Rubio, A. (2021). Understanding the different emulsification mechanisms of pectin: Comparison between watermelon rind and two commercial pectin sources. *Food Hydrocolloids, 120*. https://doi.org/10.1016/j.foodhyd.2021.106957

Meng, Z., Qi, K., Guo, Y., Wang, Y., & Liu, Y. (2018). Macro-micro structure characterization and molecular properties of emulsion-templated polysaccharide oleogels. *Food Hydrocolloids, 77*, 17–29. https://doi.org/10.1016/j.foodhyd.2017.09.006

Mieles-Gómez, L., Quintana, S. E., & García-Zapateiro, L. A. (2023). Ultrasound-assisted extraction of mango (mangifera Indica) kernel starch: Chemical, techno-functional, and pasting properties. *Gels, 9*(2). https://doi.org/10.3390/gels9020136

Mirzaaghaei, M., Ali, N., Keramat, J., Goli, S. A. H., Dinari, M., & Desobry, S. (2023). Influence of fatty acid-esterified waxy maize starch type and concentration on stability and properties of oil-in-water emulsions. *International Journal of Biological Macromolecules, 233*. https://doi.org/10.1016/j.ijbiomac.2023.123526

Morrison, W. R., & Bernard, L. (1983). An improved colorimetric procedure for determining apparent and total amylose in cereal and other starches. *Journal of Cereal Science, 1*(1), 9–20. https://doi.org/10.1016/S0733-5210(83)80004-6

Nawab, A., Alam, F., Haq, M. A., & Hasnain, A. (2016). Effect of guar and xanthan gums on functional properties of mango (mangifera Indica) kernel starch. *International Journal of Biological Macromolecules, 93*, 630–635. https://doi.org/10.1016/j.ijbiomac.2016.09.011

Nawab, A., Alam, F., Haq, M. A., Lutfi, Z., & Hasnain, A. (2017). Mango kernel starch-gum composite films: Physical, mechanical and barrier properties. *International Journal of Biological Macromolecules, 98*, 869–876. https://doi.org/10.1016/j.ijbiomac.2017.02.054

Nayak, A., & Bhushan, B. (2019). An overview of the recent trends on the waste valorization techniques for food wastes. *Journal of Environmental Management, 233*, 352–370.

Ngouémazong, E. D. (2015). Stefanie christiaens, avi shpigelman, ann van Loey, and marc hendrickx. *The Emulsifying and Emulsion-Stabilizing Properties of Pectin: A Review, 14*(6), 705–718. https://doi.org/10.1111/1541-4337.12160. Comprehensive Reviews in Food Science and Food Safety.

Panwar, D., Saini, A., Panesar, P. S., & Chopra, H. K. (2021). Unraveling the scientific perspectives of citrus by-products utilization: Progress towards circular economy. *Trends in Food Science and Technology, 111*, 549–562.

Patiño-Rodríguez, O., Agama-Acevedo, E., Ramos-Lopez, G., Luis, A., & Bello-Pérez. (2020). Unripe mango kernel starch: Partial characterization. *Food Hydrocolloids, 101*. https://doi.org/10.1016/j.foodhyd.2019.105512

Pérez-Bassart, Z., Fabra, M. J., Martínez-Abad, A., & López-Rubio, A. (2023). Compositional differences of β-glucan-rich extracts from three relevant mushrooms obtained through a sequential extraction protocol. *Food Chemistry, 402*. https://doi.org/10.1016/j.foodchem.2022.134207

Przetaczek-Rożnowska, & Izabela. (2017). Physicochemical properties of starches isolated from pumpkin compared with potato and corn starches. *International Journal of Biological Macromolecules, 101*, 536–542. https://doi.org/10.1016/j.ijbiomac.2017.03.092

Ramírez-Brewer, D., Quintana, S. E., & García-Zapateiro, L. A. (2023). Effect of microwave treatment on technological, physicochemical, rheological and microstructural properties of mango (mangifera Indica) kernel starch variety Tommy and sugar. *LWT, 187*, Article 115311. https://doi.org/10.1016/j.lwt.2023.115311

Re, R., Pellegrini, N., Anna, P., Pannala, A., Yang, M., & Rice-Evans, C. (1999). *Antioxidant activity applying an improved ABTS radical cation decolorization assay*.

Rodrigues, A. A. M., Santos, L. F.dos, Costa, R. R.da, Félix, D. T., Nascimento, J. H. B., & Lima, M. A. C.de (2020). Characterization of starch from different non-traditional sources and its application as coating in 'palmer' mango fruit. *Ciencia E Agrotecnologia, 44*, 1–12. https://doi.org/10.1590/1413-7054202044011220

Rosicka - Kaczmarek, J., Makowski, B., Nebesny, E., Tkaczyk, M., Komisarczyk, A., & Nita, Z. (2016). Composition and thermodynamic properties of starches from facultative wheat varieties. *Food Hydrocolloids, 54*, 66–76. https://doi.org/10.1016/j.foodhyd.2015.09.014

Singleton, V. L., Orthofer, R., & Lamuela-Raventós, R. M. (1999). *Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent*.

Sjöö, M., Emek, S. C., Hall, T., Rayner, M., & Wahlgren, M. (2015). Barrier properties of heat treated starch pickering emulsions. *Journal of Colloid and Interface Science, 450*, 182–188. https://doi.org/10.1016/j.jcis.2015.03.004

Song, X., Pei, Y., Qiao, M., Ma, F., Ren, H., & Zhao, Q. (2015). Preparation and characterizations of pickering emulsions stabilized by hydrophobic starch particles. *Food Hydrocolloids, 45*, 256–263. https://doi.org/10.1016/j.foodhyd.2014.12.007

Torres, O., Mercado Tena, N., Murray, B., & Sarkar, A. (2017). Novel starch based emulsion gels and emulsion microgel particles: Design, structure and rheology. *Carbohydrate Polymers, 178*, 86–94. https://doi.org/10.1016/j.carbpol.2017.09.027

Wang, Q., Li, J., Shi, Y., Cong, T., Liu, H., & Gao, Y. (2023). Preparation of lauric acid esterified starch by ethanol solvothermal process and its pickering emulsion. *International Journal of Biological Macromolecules, 248*. https://doi.org/10.1016/j.ijbiomac.2023.125941

Ye, F., Miao, M., Jiang, B., Hamaker, B. R., Jin, Z., & Zhang, T. (2017). Characterizations of oil-in-water emulsion stabilized by different hydrophobic maize starches. *Carbohydrate Polymers, 166*, 195–201. https://doi.org/10.1016/j.carbpol.2017.02.079

Yu, J. K., & Moon, Y. S. (2022). Corn starch: Quality and quantity improvement for industrial uses. *Plants, 11*(1).

Zhang, Y., Li, M., You, X., Fang, F., & Li, B. (2020). Impacts of guar and xanthan gums on pasting and gel properties of high-amylose corn starches. *International Journal of Biological Macromolecules, 146*, 1060–1068. https://doi.org/10.1016/j.ijbiomac.2019.09.231

Zhang, Y., Yang, H., Zheng, H., Yuan, D., & Mao, L. (2021). Physical properties and salt release of potato starch-based emulsion gels with OSA starch-stabilized oil droplets. *LWT, 141*. https://doi.org/10.1016/j.lwt.2021.110929

Zhao, X., Dong, L., Wang, L.jun, & Wang, Y. (2022). Rheological properties and microstructure of a novel starch-based emulsion gel produced by one-step emulsion gelation: Effect of oil content. *Carbohydrate Polymers, 281*. https://doi.org/10.1016/j.carbpol.2021.119061

Zhao, T., Huang, L., Luo, D., Xie, Y., Zhang, Y., Zhang, Y., Jiao, W., Su, G., & Zhao, M. (2021). Fabrication and characterization of anchovy protein hydrolysates-polyphenol conjugates with stabilizing effects on fish oil emulsion. *Food Chemistry, 351*. https://doi.org/10.1016/j.foodchem.2021.129324

Zhao, Y., Khalid, N., Shu, G., Neves, M. A., Kobayashi, I., & Nakajima, M. (2017). Formulation and characterization of oil-in-water emulsions stabilized by gelatinized kudzu starch. *International Journal of Food Properties, 20*, 1329–1341. https://doi.org/10.1080/10942912.2017.1347675

Zhu, F. (2019). Starch based pickering emulsions: Fabrication, properties, and applications. *Trends in Food Science and Technology, 85*, 129–137.