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Influence of thickeners (microfibrillated cellulose, starch, xanthan gum) on rheological, tribological and sensory properties of low-fat mayonnaises

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ABSTRACT

Microfibrillated cellulose (MFC) is obtained by high-shear treatment of cellulose. MFC is suitable for use as clean-label, low-calorie thickener in semi-solid foods such as mayonnaises due to its high water holding capacity. The aim of this study was to determine the effect of type and concentration of thickener on rheological, tribological and sensory properties of low-fat mayonnaises. Low-fat mayonnaises were prepared with four types of thickeners (MFC, chemically modified starch, native waxy corn starch, xanthan gum) at three concentrations. Higher biopolymer concentrations resulted in increased shear viscosities, G′ and G″, yield stress and enhanced lubrication (*i.e.* lower friction coefficients). Mayonnaises with modified starch and xanthan gum generally had higher shear viscosity and yield stress compared to mayonnaises with comparable concentrations of MFC and waxy corn starch. MFC-thickened mayonnaises had highest G', G" and boundary friction coefficients. Sensory properties of mayonnaises were determined using the Rate-All-That-Apply (RATA) method ($n = 80$). Addition of xanthan gum induced high sliminess and pulpiness, and low melting, creaminess and smoothness. Sensory properties of mayonnaises with MFC were generally similar to those with modified and waxy corn starch, despite differences in appearance (increased yellowness and slightly lower glossiness). Multiple Factor Analysis revealed that more shear-thinning mayonnaises were perceived as slimy. Boundary friction was negatively correlated with stickiness, while friction at the start of the hydrodynamic regime was positively correlated with melting sensations. We conclude that microfibrillated cellulose can be used as a thickener in low-fat mayonnaise as an alternative to commercially used chemically modified starch without considerably affecting its sensory texture properties.

1. Introduction

Microfibrillated cellulose (MFC), sometimes called nanofibrillated cellulose, is a type of nanocellulose produced by mechanical treatment of cellulose (Gómez et al., 2016; Klemm et al., 2011; Lavoine, Desloges, Dufresne, & Bras, 2012). Cellulosic materials can be derived from wood and agricultural crops, including fruit and vegetables peel (Gómez et al., 2016; Lavoine et al., 2012). MFC has been developed and patented in the 1980s by Turbak and colleagues (Turbak, Snyder, & Sandberg, 1983a), who used high-pressure homogenisation to obtain MFC from wood pulp fibres. The high mechanical shear applied to the cellulose dispersion causes cellulose fibres to deagglomerate and disintegrate into individual cellulose microfibrils and bundles thereof. These have diameters in the nanometer range, and the term 'microfibrillated' therefore refers to the disintegration process into microfibrils upon shear treatment rather than the size of material. As a consequence MFC has a high aspect ratio and an increased surface area, resulting in high water absorption capability that facilitates the formation of stable, viscous dispersions with pseudo-plastic properties at concentrations below 10 wt% (Klemm et al., 2011; Lavoine et al., 2012). MFC is produced without significant chemical treatment and thus contains both the crystalline and amorphous regions of cellulose. Its biodegradability, renewability and the possible use of agricultural by-products such as fruit and vegetable peels as starting material for MFC offer environmental and sustainability benefits

Abbreviations: MFC, Microfibrillated cellulose.

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(Lavoine et al., 2012). MFC is a dietary fibre that is not absorbed or digested in the human digestive tract. It can therefore be used as a thickener or fat substitute to produce low-calorie foods (Kleinschmidt, Roberts, Fuqua, & Melchion, 1988; Tuason, Ruszkay, & Heese, 2004; Turbak, Snyder, & Sandberg, 1983b). Despite its potential health benefits (Gill, Rossi, Bajka, & Whelan, 2020) the main application of MFC in food industry has been in food packaging (Gómez et al., 2016). Commercialisation of MFC has been challenging due to the energy-consuming production process and the associated high production costs (Klemm et al., 2011; Ström, Öhgren, & Ankerfors, 2013). Its application is furthermore hampered by the fact that MFC cannot be redispersed after dehydration due to irreversible aggregation of the cellulose fibrils (hornification) (Déléris & Wallecan, 2017).

In recent years more efficient and less energy-consuming production methods for MFC have been developed, making MFC more affordable and allowing for its commercialisation as a functional food ingredient (Ström et al., 2013). Several researchers established the potential of MFC to improve foam stability (Ström et al., 2013) and to stabilise oil-in-water emulsions (e.g. Aaen, Brodin, Simon, Heggset, & Syverud, 2019; Lu et al., 2019; Nomena et al., 2018; Ström et al., 2013; Turbak et al., 1983b; Turbak, Snyder, & Sandberg, 1984; Winuprasith & Suphantharika, 2015). Apart from its emulsifying properties, its gel-like characteristics make MFC suitable as clean-label thickener in foods (Blok et al., 2021). As a result MFC has been studied in various foods including soups, gravies, dips, puddings, toppings (Turbak, Snyder, & Sandberg, 1982) and fruit-fillings in cookies (Kleinschmidt et al., 1988). Several authors studied the effect of addition of MFC to mayonnaises. Choublab and Winuprasith (2018) found that it is possible to produce egg-free mayonnaise by using MFC as the sole emulsifier. The viscosifying effect of MFC in mayonnaises has been established by Heggset et al. (2020), who demonstrated that lower viscosity and moduli (G', G") evoked by fat reduction in mayonnaises can be regained by addition of 0.42 wt% MFC. Although these authors thoroughly characterised rheological properties of the mayonnaises, they did not explore the effect of MFC on sensory properties. Golchoobi, Alimi, Shokoohi, and Yousefi (2016) studied the effect of a range of mixtures of thickeners on rheological and hedonic properties of low-fat mayonnaises. Addition of 1 wt % MFC to low-fat mayonnaise resulted in hedonic evaluations similar to commercially available low-fat mayonnaise, which is typically thickened by addition of starch. This study focused on hedonic evaluations of mayonnaises by trained assessors and did not explore sensory properties of mayonnaises or the impact of MFC concentration on mayonnaise properties. In contrast to MFC, starch and xanthan gum have been extensively studied in model systems (e.g. Stokes, Macakova, Chojnicka-Paszun, de Kruif, & de Jongh, 2011; Torres et al., 2019) and various complex food matrices including custards, beverages, soups (de Wijk, van Gemert, Terpstra, & Wilkinson, 2003; Godoi, Bhandari, & Prakash, 2017; Kim, Hwang, Song, & Lee, 2017) to better understand the impact of these thickeners on food properties. Knowledge on sensory, rheological and tribological properties of semi-solid foods thickened with MFC is thus limited compared to that of commonly used thickeners such as starches or xanthan gum.

The aim of this study was to determine the effect of type and concentration of thickener on rheological, tribological and sensory properties of low-fat mayonnaises. Furthermore, we sought to determine relationships between sensory, rheological and tribological properties of the mayonnaises. Low-fat mayonnaises were prepared with four types of biopolymers (MFC, modified starch, waxy corn starch, xanthan gum) varying in concentration. By comparing rheological, tribological and sensory properties of low-fat mayonnaises thickened by different biopolymers, we examine whether MFC can be used as a clean-label, low-calorie alternative thickener. We chose in this study to compare low-fat mayonnaises differing in type and concentration of thickener, rather than comparing these mayonnaises to full-fat mayonnaises or low-fat mayonnaises without added thickeners. Whereas we acknowledge that including a full-fat or low-fat mayonnaise without thickener could have provided additional insights, we chose not to do this as this comparison lacks ecological validity (commercially available low-fat mayonnaises contain thickeners and this study examines whether MFC can be used as thickener instead of other thickeners) and potentially distorts the sensory space of the sample set. The sensory properties of full-fat or low-fat mayonnaises without thickener are expected to be substantially different compared to low-fat mayonnaises with thickeners. These potentially large differences in sensory properties in a sample set might overshadow expected smaller, subtle differences in sensory properties caused by the addition of different types of thickeners. As the effect of MFC on rheological and sensory properties in aqueous model foods has been established previously (Blok et al., 2021) this study focuses on oil-in-water emulsions, in particular low-fat mayonnaises.

2. Materials & methods

2.1. Mayonnaise preparation

Low-fat mayonnaises (20 wt% fat) were prepared with four thickening agents: microfibrillated cellulose (MFC), chemically modified corn starch (MS; E1442; Ingredion Incorporated, Westchester, IL, USA), native waxy corn starch (WCS; Novation® 2300, Ingredion Incorporated, Westchester, IL, USA) and xanthan gum (XG; Jungbunzlauer, Basel, Switzerland). Each thickening agent (MFC, MS, WCS, XG) was added to low-fat mayonnaises at three concentrations which were categorized as low, medium, and high, resulting in twelve low-fat mayonnaises in total. Table 1 summarises the composition of the low-fat mayonnaises. We aimed at obtaining comparable viscosities of the continuous phase of the four mayonnaises (before emulsification) at a certain thickener concentration (low, medium and high), *i.e.* viscosity of MFC-low was comparable to MS-low, WCS-low and XG-low. The choice of MS and WCS concentrations was based on knowledge and experience on using these ingredients in mayonnaises and reflects starch concentrations used in commercial low-fat mayonnaises. The concentrations of MFC and XG were based on previous work on these ingredients (Blok et al., 2021).

The first step in preparation of the low-fat mayonnaises was to prepare the aqueous hydrocolloid solutions and dispersions. Modified and waxy corn starch were first mixed with water and cooked for 5 min at 85 °C in a Thermomix® while continuously stirring (Thermomix® TM5, Vorwerk, Germany). The starch pastes were left to cool down to 50 °C and the amount of water lost due to evaporation was added back to the paste. Xanthan gum was dissolved in water by mixing at room temperature for at least 60 min using an overhead stirrer. Microfibrillated cellulose dispersions were prepared by first suspending citrus fibre powder (HERBACEL® AQ® Plus, Herbafood Ingredients, Werder, Germany) in deionised water. pH of the samples was adjusted to pH 4 using 1M HCl (Sigma-Aldrich, Saint Louis, MO, USA). The suspensions were thoroughly mixed using a L5M-A Silverson laboratory mixer with a 1 mm screen hole (Silverson Machines Ltd., Chesham, United Kingdom) at 3000 rpm for 10 min, followed by one passage through a high-pressure homogeniser (Microfluidizer M-110S, Microfluidics™, Newton, MA, USA) with a z-shape geometry (ø 87 μm) at a pressure of 1200 bar.

The hydrocolloid solutions and dispersions were subsequently mixed with the other ingredients of the aqueous phase and combined with egg yolk (Table 1). Sucrose (coarse medium, 0.315–1.25 mm), salt (salt evaporated non-iodized), sorbic acid (Nutrinova®) and calcium disodium ethylenediaminetetraacetic acid ($CaNa_2$-EDTA, Solvitar (E385) Food) were obtained from Brenntag Nederland B.V. (Dordrecht, the Netherlands). Acetic acid (vinegar spirit 12%) was obtained from Carl Kühne KG (GmbH & Co., Hamburg, Germany). Lemon flavour was added to the oil phase. The soybean oil phase was added slowly to the aqueous phase while stirring at 5200 rpm using a L5M-A Silverson laboratory mixer with 1 mm hole emulsor screen (Silverson Machines Ltd., Chesham, United Kingdom). Once all oil was added, the speed was increased to 7200 rpm for 1 min and the beaker with the emulsion was

Table 1
Composition of low-fat mayonnaises prepared with four thickening agents. Each thickening agent was applied at three concentrations (low, medium, high) resulting in twelve low-fat mayonnaises. Concentrations are given as wt%.

	Microfibrillated cellulose (MFC)			Modified starch (MS)			Waxy corn starch (WCS)			Xanthan gum (XG)		
	low	medium	high	low	medium	high	low	medium	high	low	medium	high
Thickener	1.44	1.6	1.76	5.0	5.5	6.0	5.5	6.0	6.5	1.6	1.8	2.0
Water	67.9	67.8	67.6	64.4	63.9	63.4	63.9	63.4	62.9	67.8	67.6	67.4
Soybean oil	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Egg yolk	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Sucrose	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Acetic acid	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Salt (NaCl)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sorbic acid	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Lemon flavour	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
EDTA	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075

moved around to ensure complete homogenisation. The finished mayonnaises were transferred to 200 ml glass jars and stored at 4 °C until further use. Two batches of 2600 g were prepared for each mayonnaise.

2.2. Rheological characterisation

Rheological properties of mayonnaises were determined using a MCR 302 rheometer (Anton Paar, Graz, Austria) equipped with a parallel plate geometry (ø 50 mm) with a gap of 1 mm.

Shear viscosity was determined as a function of logarithmically increasing shear rate from 0.1 s^{-1} to 500 s^{-1} in 50 steps (10 s per data point). After loading, a waiting step of 5 min was applied to allow for structural relaxation of the sample before the start of the measurement. Measurements were performed in duplicate at 35 °C. Consistency index K and flow index n were determined using the Ostwald-de Waele power law model: $\sigma = K \cdot \gamma^{n}$, where σ = shear stress (Pa), γ = shear rate (s^{-1}), K = consistency index (Pa·s^n) and n = flow index. This model was fitted to data in the entire shear rate range used. Data was also fitted to the Herschel-Bulkley model as this model is commonly used to describe the rheology of mayonnaises (e.g. Golchoobi et al., 2016; Lee, Lee, Lee, & Ko, 2013; Ma & Barbosa-Cánovas, 1995; Su, Lien, Lee, & Ho, 2010). This model however failed to describe the flow behaviour of mayonnaises with XG. We therefore chose to use the Ostwald-de Waele model, in order to use one single model that can describe the flow behaviour of all mayonnaises used in this study.

Strain sweeps were performed and G' and G'' were measured as a function of logarithmically increasing shear strain (0.01–100%) at constant oscillation frequency (1 Hz). Samples were pre-sheared at 100 s^{-1} for 1 min, followed by 2 min rest to allow for structural relaxation. Yield stress was determined from the strain sweeps as the stress applied at the intersect of G' and G''. Measurements were performed in triplicate at 35 °C.

2.3. Tribological characterisation

Tribological properties of the mayonnaises were determined using a MCR 302 rheometer (Anton Paar, Austria) equipped with a tribological cell (T-PTD-200). A ball-on-three-pins set-up was used, with a glass ball and polydimethylsiloxane (PDMS) pins. All measurements were performed in triplicate at 35 °C and a normal force F_N of 1N was applied. Each measurement consisted of three consecutive runs in which rotational sliding speeds were logarithmically increased from 0.0001 to 2200 rpm ($4 \cdot 10^{-5}$-10^{3} mm/s). Each run was preceded by a 5 min resting period in which a normal force of 1N was applied. Data from the second run was used for data analysis. Friction coefficients were defined as the ratio of the frictional force divided by the normal load. PDMS pins were replaced by new pins after each replicate of the entire set of samples to limit the effect of wear on the PDMS pins. New PDMS were run-in by one run with deionised water, followed by one run with one of the mayonnaises (MFC-low).

2.4. Confocal Laser Scanning Microscopy (CLSM)

Microstructures of low-fat mayonnaises were visualised using a Zeiss LSM 510-META confocal laser scanning microscope (Carl Zeiss AG, Oberkochen, Germany). The fat phase of all mayonnaises was stained with 0.0001% (w/v) Nile Red (Sigma-Aldrich, Saint-Louis, MO, USA). Different samples of mayonnaises thickened with MS and WCS were stained with 0.1% (w/v) Acridine Orange (Sigma-Aldrich, USA) in 0.1M phosphate buffer (pH 7) to visualise starch and proteinaceous materials. Calcofluor White (American Cyanamid, Wayne, NJ, USA; 0.002%) was used to stain cellulose in mayonnaises thickened with MFC. A drop of the stained mayonnaise was placed on an object slide and images were acquired using a Plan-Apochromat 63x/1.4 oil DIC objective for Calcofluor White and an EC Plan-Neofluar 40x/1.30 oil DIC objective for Nile Red and Acridine Orange. Excitation wavelengths were 543 nm for Nile Red, 488 nm for Acridine Orange and 405 nm for Calcofluor White.

2.5. Sensory evaluation

2.5.1. Participants

Participants between 18 and 50 y from Wageningen and surroundings were recruited online and through posters at the Wageningen University campus. Participants had a BMI between 18 and 30 kg/m^2, were non-smokers, proficient in reading English and were generally in good health with normal smell and taste functions. Participants had no allergies for any of the mayonnaise ingredients, were familiar with mayonnaise and consumed mayonnaise on a regular basis. Female participants were not pregnant or breastfeeding. A total of n = 80 participants (13 male, 67 female; mean age 25 ± 5 y; mean BMI 22 ± 2 kg/m^2) completed the study. Participants signed an informed consent form and completed a general questionnaire at the start of the first session. Participants received financial reimbursement upon completion of the study. The study did not meet the requirements to be reviewed by the Medical Research Ethical Committee of The Netherlands according to the "Medical Research Involving Human Subjects Act" of The Netherlands. The study was conducted in agreement with the ethics regulations laid out in the Declaration of Helsinki (2013).

2.5.2. Rate-All-That-Apply (RATA) method

Each participant evaluated all twelve mayonnaises in two test sessions of 30–45 min each. Six samples were evaluated in each test session. Samples were presented monadically in random order during the two test sessions. In the first test session participants tasted two example mayonnaises representing the range of mayonnaises to be evaluated (WCS-low and XG-high) in order to familiarise participants with the samples. Participants selected one of these mayonnaises to answer the example question to get acquainted with the sensory evaluation method. Mayonnaises were evaluated using the Rate-All-That-Apply (RATA) method. For each sample, participants indicated which sensory attributes were applicable to describe the perception of the sample, followed by indicating the intensity of the selected sensory attributes on a 9-point scale anchored from *low* to *high* intensity. Applicable attributes were selected from a list of 18 sensory attributes, which were divided over three categories: appearance, flavour and texture. Definitions of the sensory attributes were provided to the participants (Table 2). After evaluation of a sample, participants could leave any additional remarks in a separate comment box. Mayonnaises (15–20 g) were presented in 30 ml transparent plastic cups labelled with random 3-digit codes, which were taken from the fridge 30 min prior to the start of the test session. A spoon was used to taste the mayonnaises. Participants could expectorate mayonnaises after evaluation. Crackers and water were provided for palate cleansing after evaluation of each sample. Data was collected in Qualtrics (Qualtrics, USA).

2.6. Data analysis

Rheological and tribological data were reported as mean values with standard deviation, and differences between low-fat mayonnaises were assessed using one-way ANOVA and Tukey post-hoc tests. Intensity scores from sensory evaluation were reported as mean values with standard error. An intensity score of 0 was assigned to sensory attributes that were not selected by the participants. Two-way repeated measures ANOVA was performed on each of the sensory attributes (fixed factors: thickener type, concentration, thickener type:concentration interaction; random factor: participant). Bonferroni post-hoc tests were performed to determine statistically significant differences between samples. Principal Component Analysis (PCA) was performed and a bi-plot with 95% confidence ellipses was created. Multiple Factor Analysis (MFA) was performed to determine relationships between sensory, rheological and tribological properties of the mayonnaises. Data was analysed using RStudio (version 4.0.2) using the packages lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017), emmeans (Lenth, 2021), factoextra (Kassambara & Mundt, 2020) and FactoMineR (Lê, Josse, & Husson, 2008). A significance level of $\alpha = 0.05$ was used.

Table 2
Sensory attributes used to evaluate twelve low-fat mayonnaises using RATA together with definitions, and examples of products high in intensity of the respective attribute.

Attribute	Definition	Examples of products
Appearance		
Glossiness	The product has a shiny appearance, light is reflected from the surface of the product.	Olives, icing, custard
Sliminess	The product is thick, slippery and cohesive.	Gelatin pudding, oysters, raw egg white
Smoothness	The texture of the product is smooth and homogeneous; absence of lumps and grains.	Custard, milk, water (smooth) Cottage cheese (not smooth)
Thickness	The degree to which the product flows/deforms.	Greek yoghurt (thick) Water (not thick)
Yellowness	The intensity of the yellow colour.	Cauliflower, milk (white) Mustard, vanilla custard (yellow)
Flavour		
Fatty flavour	The intensity of the taste of fat.	Butter, whipped cream, French fries
Lemon flavour	The degree to which the product tastes like lemon.	Lemons, lemon zest, lemon curd
Saltiness	The intensity of the salt taste.	Salt, cheese, meat
Sourness	The intensity of the sour taste; acidity.	Citrus fruits, vinegar, yoghurt
Sweetness	The intensity of the sweet taste.	Sugar, lemonade
Texture		
Creaminess	The degree to which the product provides a silky, rich, full mouthfeel.	Ice cream, whipped cream
Melting	The degree to which the product becomes thin and fluid and distributes itself in the mouth.	Ice cream, chocolate
Mouthcoating	The feeling that a layer of the product remains behind on the palate (after swallowing).	Butter, oil, chocolate
Pulpiness	The product has a pulpy, mushy structure; the texture of the product is fibre-like.	Apple sauce, orange juice with pulp
Sliminess	The product is thick, slippery and cohesive in the mouth.	Gelatin pudding, oysters, raw egg white
Smoothness	The texture of the product is smooth and homogeneous; absence of lumps and grains.	Custard, milk, water (smooth) Cottage cheese (not smooth)
Stickiness	The degree to which the product sticks to the palate and teeth.	Honey, marshmallow, toffee
Thickness	The amount of force needed to make the sample flow or deform in the mouth.	Greek yoghurt (thick) Water (not thick)

3. Results & discussion

3.1. Flow properties

Flow curves of low-fat mayonnaises thickened with different concentrations of microfibrillated cellulose (MFC), modified starch (MS), waxy corn starch (WCS) and xanthan gum (XG) are shown in Fig. 1. All mayonnaises displayed shear-thinning behaviour, which can also be observed from their flow index (Table 3). As expected, shear viscosity and consistency index K of the mayonnaises increased with increasing concentration of thickener (Table 3), which is consistent with results from previous studies on mayonnaises thickened with various biopolymers (e.g. Bortnowska & Tokarczyk, 2009; Golchoobi et al., 2016; Heggset et al., 2020; Lee et al., 2013; Ma & Barbosa-Cánovas, 1995; Mozafari, Hosseini, Hojjatoleslamy, Mohebbi, & Jannati, 2017; Mun et al., 2009; Su et al., 2010). Differences in viscosity and consistency index between thickener concentrations (low, medium, high) were small, which reflects the moderate variation in thickener concentrations used in the mayonnaises (Table 1). A narrow range of thickener concentrations was used in this study to represent concentrations used in commercial low-fat mayonnaises. Mayonnaises thickened with MFC and WCS generally had lower shear viscosities than mayonnaises thickened with MS or XG. Although applied in higher concentrations (Table 1), addition of WCS resulted in lower shear viscosities than addition of MS, which can be attributed to the improved resistance to shear and acidity of cross-linked MS (Chen, Kaur, & Singh, 2018). On the other hand, shear viscosities of mayonnaises thickened with MFC and XG were similar at shear rates $>100\ s^{-1}$ due to more pronounced shear-thinning behaviour of XG-thickened mayonnaises (Table 3). This can also be observed from the flow index n, as a lower flow index n indicates stronger shear-thinning behaviour. Our results support findings of Mozafari et al. (2017), who concluded that addition of xanthan gum to low-fat mayonnaises resulted in lower flow indices.

3.2. Viscoelastic properties

Storage modulus G' of all mayonnaises was larger than loss modulus G'' up to strains of 5% (Fig. 2, Table 3), indicating that all mayonnaises exhibited solid-like behaviour in the linear viscoelastic region. The magnitude of G' and G'' increased with increasing concentrations of biopolymers, which is in accordance with previous studies on mayonnaises thickened with MFC (Heggset et al., 2020) or xanthan gum (Ma & Barbosa-Cánovas, 1995). An increase in thickener concentration results in the formation of a stronger network in the aqueous phase of the low-fat mayonnaises, which is reflected in larger G' and G''. Differences are observed when comparing the different biopolymers used to thicken the low-fat mayonnaises. Highest G' and G'' were observed for mayonnaises thickened with MFC and lowest G' and G'' for mayonnaises thickened with waxy corn starch. These values of G' and G'' in

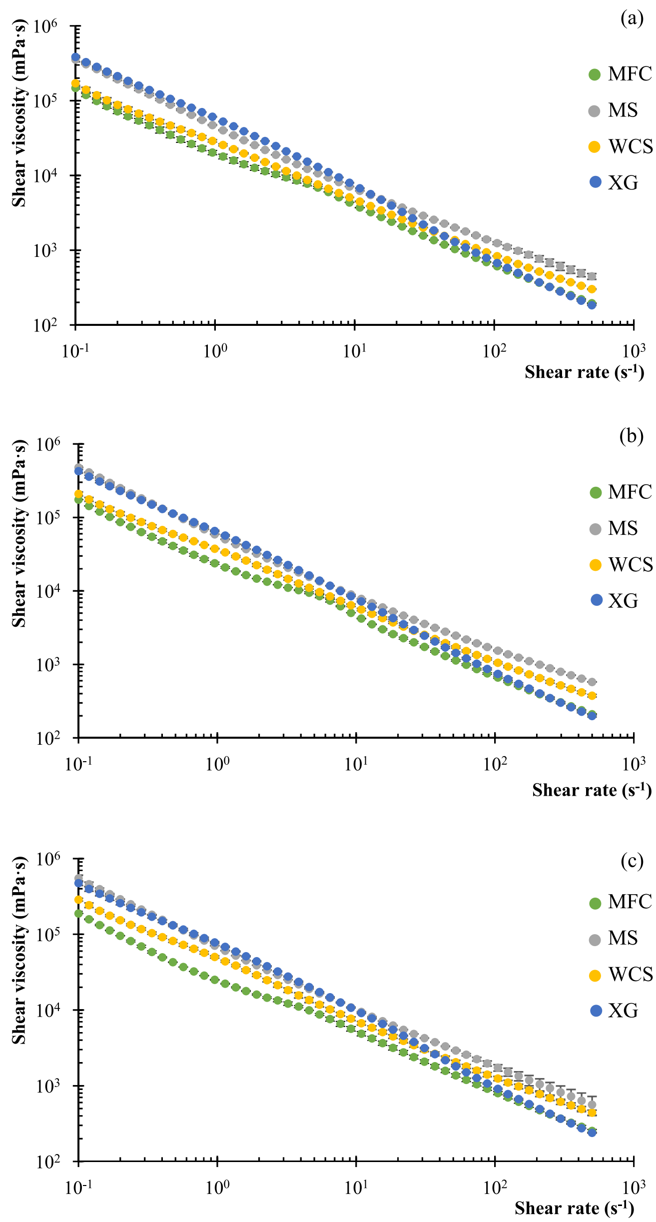

Fig. 1. Mean shear viscosity of low-fat mayonnaises with (a) low, (b) medium and (c) high concentrations of microfibrillated cellulose (MFC; green), modified starch (MS; grey), waxy corn starch (WCS; yellow) and xanthan gum (XG; blue) (2 replicates, error bars represent standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

MFC-thickened mayonnaises are in agreement with those found by Golchoobi et al. (2016) and Heggset et al. (2020), considering that these studies used lower concentrations of MFC (1 wt% and 0.25–0.42 wt%, respectively).

Yield stress (σ_y) was determined from the crossover point between *G'* and *G"* (Table 3). Yield stress of low-fat mayonnaises generally increased with increasing concentration of thickener, which is in accordance with previous studies on fluids thickened with MFC (Agoda-Tandjawa et al., 2010; Iotti, Gregersen, Moe, & Lenes, 2011; Lowys, Desbrieres, & Rinaudo, 2001), starch (Evans & Haisman, 1980; Ross, Tyler, Borgognone, & Eriksen, 2019), xanthan gum (Marcotte, Hoshahili, & Ramaswamy, 2001; Ross et al., 2019; Song, Kim, & Chang, 2006) and mayonnaises thickened with xanthan gum (Ma & Barbosa-Cánovas, 1995). Mayonnaises thickened with MS and XG exhibited the highest yield stresses, whereas yield stress of those thickened with MFC or WCS were at least 3 times smaller. The lower yield stress of low-fat mayonnaises with MFC or WCS cannot be attributed solely to a structural difference between MFC or WCS and the other biopolymers, because these mayonnaises also differ in shear viscosities (Fig. 1).

3.3. *Tribological properties*

Tribological properties of the low-fat mayonnaises thickened with different biopolymers are shown in Fig. 3 and Table 3. For all low-fat mayonnaises the boundary and mixed friction regimes are observed. The boundary regime occurs at low speeds or high loads, when the surfaces of the tribo-pair are in direct contact with each other and the lubricant (mayonnaise) is excluded from the gap (Stokes, 2012). Friction in the boundary regime therefore depends on the ability of (constituents of) the sample to form a lubricating boundary film, for example by surface adsorption. Although differences between mayonnaises in this regime are small, friction in the boundary regime was mainly affected by the type of thickener rather than the concentration of thickener ($\mu_{BR\ (max)}$; Table 3). Friction coefficients were higher for mayonnaises thickened with MFC (0.17–0.19) compared to the other thickeners (0.10–0.12). We hypothesise that polymer adsorption occurred in mayonnaises thickened with MS, WCS and XG, whereas cellulose microfibrils were unable to form a boundary lubricating film on the tribological surfaces. The presence of starch lowers boundary friction, which has been attributed to the formation of an amylose film on the surface and/or a ball-bearing effect provided by intact starch granules (Morell, Chen, & Fiszman, 2017; Yakubov et al., 2015; Zinoviadou, Janssen, & De Jongh, 2008). Xanthan gum reduces friction by adsorption on PDMS and formation of a hydrated film (Stokes et al., 2011). The large particle size (*i.e.* several micrometers in length) of MFC and their aggregates are expected to hinder its entrainment in the gap (Lavoine et al., 2012; Lundahl, Berta, Ago, Stading, & Rojas, 2018), which consequently inhibits formation of a lubricating film and results in high boundary friction.

In the mixed regime, friction is affected by boundary lubrication and the lubricant's bulk viscosity (Stokes, 2012). Although the differences are small, lower friction coefficients are generally observed at higher biopolymer concentration (Fig. 3), which is consistent with earlier findings by Cassin, Heinrich, and Spikes (2001), Malone, Appelqvist, and Norton (2003) and Garrec and Norton (2012). For mayonnaises thickened with MS or XG the hydrodynamic regime is observed at sliding speeds above 100 mm/s. In this regime the surfaces of the tribo-pair are fully separated by a layer of fluid and friction solely depends on bulk viscosity (Stokes, 2012). Minor differences are observed in friction coefficient at the start of the hydrodynamic regime, with low-fat mayonnaises thickened with MFC being slightly less lubricating. The onset of the mixed and hydrodynamic regimes shifts to lower sliding speeds for mayonnaises with highest shear viscosities, *i.e.* mayonnaises with MS or XG (Figs. 1 and 3). This has previously been described (Chojnicka, de Jong, de Kruif, & Visschers, 2008) and is expected to result from a combination of the samples' shear viscosity and adsorption at the tribological surface (Bongaerts, Fourtouni, & Stokes, 2007; Stokes, 2012; Stokes et al., 2011). Polymer adsorption can improve the wetting properties of the surfaces, thereby facilitating entrainment of the lubricant into the contact, which shifts the transitions to other regimes to lower velocities. Secondly, more viscous fluids will be entrained more easily than low viscous ones, enabling an earlier transition from the mixed to the hydrodynamic regime (Cassin et al., 2001). The latter may also explain the discrepancy between our current results and previous results on aqueous MFC dispersions (Blok et al., 2021). The higher viscosity of mayonnaise potentially promoted the entrainment of MFC between the tribopairs, while the continuous phase of simple aqueous MFC dispersions could not facilitate this. Moreover, shear-induced flocculation of MFC (Karppinen et al., 2012) may have been hindered by the viscosity of mayonnaise, thereby limiting the formation of

Table 3
Rheological and tribological parameters of low-fat mayonnaises thickened with microfibrillated cellulose (MFC), modified starch (MS), waxy corn starch (WCS) and xanthan gum (XG) at low, medium and high concentration. Values are given as means (±SD). Consistency index (K) and flow index (n) were determined using the Ostwald-de Waele model. Yield stress σ_y was determined as stress applied at the intersect of G' and G'' during a strain sweep at 1 Hz. $\mu_{BR(max)}$ represents the maximum friction coefficient in the boundary regime, $\mu_{HDR(start)}$ is the friction coefficient at the start of the hydrodynamic regime.

	η^{-1}_{10s} (mPa·s)	η^{-1}_{50s} (mPa·s)	η^{-1}_{100s} (mPa·s)	K (Pa·s^n)	n (−)	σ_y (Pa)	G' (Pa)	G'' (Pa)	$\mu_{BR(max)}$ (−)	$\mu_{HDR(start)}$ (−)
MFC-low	3726 ± 2^{h}	1036 ± 10^{g}	611 ± 7^{e}	21.5 ± 1.4^{g}	0.24 ± 0.01^{ab}	12.9 ± 1.4^{g}	491 ± 22^{c}	71 ± 1^{b}	0.19 ± 0.03^{a}	0.12 ± 0.02^{ab}
MFC-medium	4209 ± 48^{gh}	1135 ± 29^{fg}	661 ± 17^{e}	25.3 ± 0.2^{fg}	0.22 ± 0.01^{abc}	11.8 ± 1.1^{g}	529 ± 18^{b}	76 ± 6^{b}	0.19 ± 0.01^{a}	0.13 ± 0.01^{a}
MFC-high	4878 ± 326^{f}	1370 ± 72^{e}	799 ± 39^{de}	27.6 ± 0.3^{f}	0.24 ± 0.01^{ab}	15.3 ± 0.7^{f}	711 ± 27^{a}	101 ± 3^{a}	0.17 ± 0.01^{a}	0.11 ± 0.02^{abc}
MS-low	6222 ± 8^{de}	2008 ± 24^{c}	1243 ± 50^{b}	47.2 ± 0.4^{d}	0.21 ± 0.01^{bc}	44.1 ± 1.5^{e}	280 ± 7^{e}	25 ± 4^{e}	0.12 ± 0.01^{b}	0.09 ± 0.01^{cd}
MS-medium	7793 ± 44^{b}	2468 ± 26^{b}	1540 ± 29^{a}	60.1 ± 0.4^{b}	0.21 ± 0.00^{bc}	56.6 ± 0.7^{c}	323 ± 3^{d}	28 ± 1^{de}	0.12 ± 0.01^{b}	0.10 ± 0.02^{abcd}
MS-high	9435 ± 107^{a}	2925 ± 52^{a}	1729 ± 170^{a}	71.5 ± 0.5^{a}	0.19 ± 0.02^{c}	60.5 ± 0.4^{b}	315 ± 3^{d}	32 ± 4^{de}	0.12 ± 0.01^{b}	0.10 ± 0.00^{abcd}
WCS-low	4458 ± 0^{fg}	1367 ± 5^{e}	834 ± 8^{cde}	27.2 ± 1.1^{f}	0.26 ± 0.01^{a}	6.8 ± 0.5^{h}	140 ± 1^{i}	13 ± 0^{f}	0.10 ± 0.01^{b}	0.09 ± 0.00^{cd}
WCS-medium	5577 ± 201^{e}	1723 ± 54^{d}	1054 ± 31^{bc}	34.7 ± 0.2^{e}	0.25 ± 0.01^{a}	6.5 ± 0.4^{h}	173 ± 3^{ghi}	15 ± 0^{f}	0.10 ± 0.01^{b}	0.09 ± 0.00^{bcd}
WCS-high	6705 ± 377^{cd}	2044 ± 125^{c}	1246 ± 80^{b}	45.4 ± 2.0^{d}	0.23 ± 0.00^{abc}	6.2 ± 0.5^{h}	203 ± 10^{fg}	16 ± 1^{f}	0.11 ± 0.00^{b}	0.09 ± 0.01^{bcd}
XG-low	6729 ± 79^{cd}	1291 ± 11^{ef}	675 ± 5^{e}	54.4 ± 0.5^{c}	0.08 ± 0.00^{d}	51.1 ± 0.1^{d}	155 ± 1^{hi}	32 ± 2^{de}	0.12 ± 0.01^{b}	0.08 ± 0.01^{d}
XG-medium	7190 ± 87^{bc}	1433 ± 48^{e}	742 ± 23^{de}	58.7 ± 0.8^{b}	0.08 ± 0.01^{d}	60.6 ± 0.2^{b}	186 ± 3^{fgh}	35 ± 3^{d}	0.12 ± 0.00^{b}	0.08 ± 0.01^{d}
XG-high	9119 ± 115^{a}	1803 ± 19^{d}	912 ± 14^{cd}	69.7 ± 2.3^{a}	0.09 ± 0.01^{d}	69.3 ± 0.6^{a}	222 ± 3^{f}	43 ± 3^{c}	0.12 ± 0.00^{b}	0.08 ± 0.01^{d}

[a-i]: Different superscript letters indicate significant differences between samples.

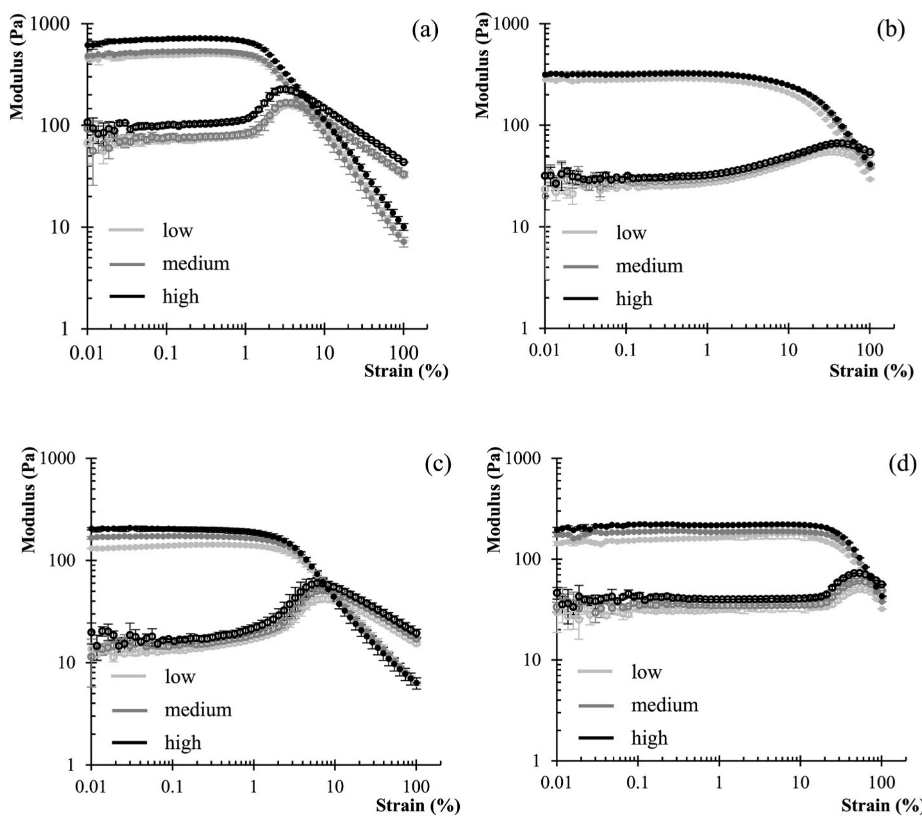

Fig. 2. Mean storage (G', filled symbols) and loss modulus (G'', open symbols) of mayonnaises thickened with (a) microfibrillated cellulose (MFC), (b) modified starch, (c) waxy corn starch and (d) xanthan gum at low, medium and high concentration.

sheared gel particles that are expelled from the tribological gap.

Although tribological properties of the mayonnaises were determined to speculate about their potential lubricating effect in the mouth, it should be noted that the tribology set-up used mimicked oral conditions to a limited extent. Friction properties of the mayonnaises were determined at 35 °C to simulate the oral temperature and PDMS pins were selected as these are frequently used to crudely mimic the human tongue. Saliva was not included in the tribological experiments performed in this study, which is why the tribological data and its correlations with the sensory properties require careful interpretation. Saliva serves as a lubricant in the mouth and its presence therefore affects the lubricating effect of foods upon their consumption (e.g. Morell et al., 2017). This effect is especially consequential for foods thickened with starch, as starch is hydrolysed by α-amylase in saliva (Torres et al., 2019). The resultant loss of viscosity is expected to increase friction in the mixed and boundary regime (Stokes, 2012), which might in turn affect sensory perception. This study did not include saliva in the tribological experiments because the flow rate and composition of human saliva shows large inter- and intra-individual variation (Dodds, Johnson, & Yeh, 2005; Mosca et al., 2019; Neyraud, Palicki, Schwartz, Nicklaus, & Feron, 2012). This variation makes it challenging to draw generalisable conclusions from tribological data obtained with human saliva.

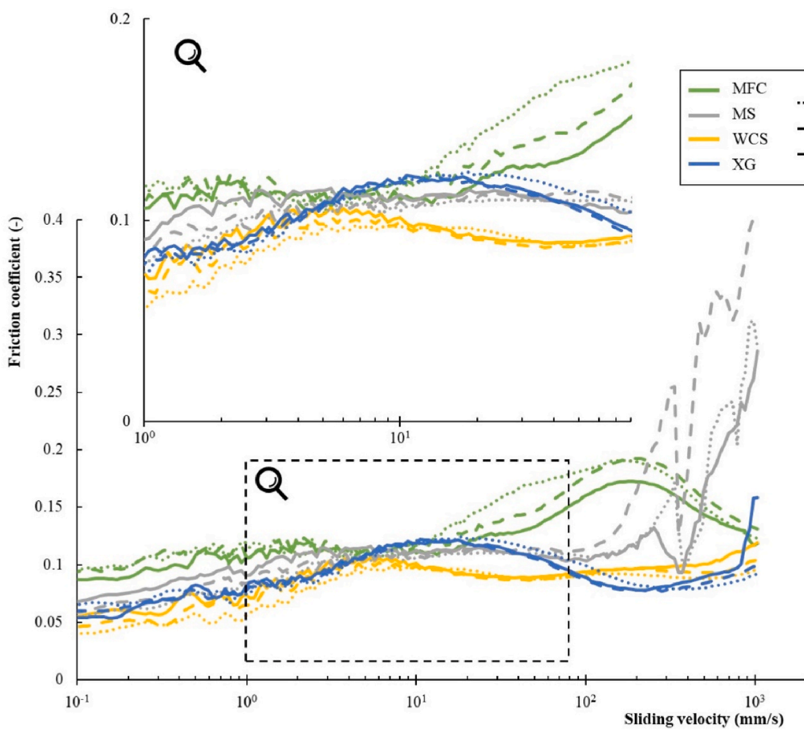

Fig. 3. Mean friction coefficients (triplicates) as a function of sliding speed of low-fat mayonnaises thickened with microfibrillated cellulose (MFC; green); modified starch (grey); waxy corn starch (yellow) or xanthan gum (blue). Dotted lines represent lowest concentration of thickener, dashed lines medium and solid lines highest concentration of thickener (See Table 1 for composition of the low-fat mayonnaises). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Microstructure

Fig. 4 shows CSLM images of low-fat mayonnaises containing the highest concentration of thickener (MFC-high, MS-high, WCS-high, XG-high). Oil droplets were generally smaller than 20 µm and were largest in mayonnaises thickened with MFC, followed by those thickened with XG. Addition of MFC or XG moreover resulted in polydisperse emulsions, whereas more monodisperse emulsions with smaller oil droplets (<5 µm, with the exception of a few large oil droplets) were obtained upon addition of MS or WCS to low-fat mayonnaises. As opposed to the uniform distribution of small oil droplets in MS-thickened mayonnaises, voids and clusters of aggregated oil droplets can be observed in mayonnaises thickened with WCS. The latter furthermore show uneven distribution of protein and starch throughout the emulsion, whereas a homogeneous network of starch and protein is present in mayonnaises with MS. Modification of starch is usually performed to improve its functional properties, including retrogradation and resistance to high temperature, high shear or low pH (Chen et al., 2018). The relatively low pH of the mayonnaises (pH 3.6–3.9) could have affected the strength of the non-modified WCS network in the continuous phase of the mayonnaise, resulting in oil droplet aggregation (Fig. 4e and f). This in turn can have an effect on the rheological properties of the mayonnaises, such as shear viscosity or yield stress (Fig. 1, Table 3). MFC did not only form a microfibril network in the continuous phase of MFC-thickened mayonnaises, but was also present around the oil droplets (Fig. 4b). There, MFC can act as an emulsifier on the oil-water interface, according to earlier studies in which the emulsifying properties of MFC have been established (Choublab & Winuprasith, 2018; Nomena et al., 2018; Winuprasith & Suphantharika, 2013, 2015).

3.5. Sensory properties

Mean intensities of appearance, flavour and texture attributes of the low-fat mayonnaises are shown in Table 4. Type of thickener affected all sensory attributes, except for visual thickness (A-Thick) and sweetness (F-Sweet). The concentration of thickener significantly affected smooth and thick appearance, fatty and lemon flavour and smooth, sticky, thick, mouthcoating and melting texture. The Principal Component Analysis (PCA) bi-plot shows the position of the twelve mayonnaises in the sensory space (Fig. 4). The first three principal components explain 40.6% of the total variation between the mayonnaises. Mayonnaises thickened with XG are separated from mayonnaises thickened with MFC, MS or WCS, which indicates that sensory perception of XG-thickened mayonnaises is different from the other mayonnaises. Mayonnaises thickened with MFC are located close to mayonnaises thickened with WCS and MS, which implies that sensory perception of mayonnaises thickened with MFC is similar to mayonnaise thickened with WCS and MS.

3.5.1. Appearance

Mayonnaises thickened with MS were perceived as the glossiest, whereas mayonnaises thickened with MFC were the least glossy (Table 4). Although yellowness intensities of the mayonnaises were generally low, addition of MFC resulted in a slight increase of yellowness. The larger oil droplet size of MFC-thickened mayonnaises (Fig. 4) might have caused this difference in appearance. Larger oil droplets lead to increased yellowness and reduced light scattering efficiency, resulting in decreased glossiness (Chantrapornchai, Clydesdale & McClements, 1998, 1999; Winuprasith & Suphantharika, 2015). Visual smoothness generally decreased for higher concentrations of thickener, except for mayonnaises thickened with XG. These mayonnaises had a less smooth but slimier appearance than the other mayonnaises. As anticipated, visual thickness increased with increasing thickener concentration, yet it was not affected by the type of thickener used. Participants did not observe differences in visual thickness between mayonnaises thickened with different biopolymers although flow properties and shear viscosities of the mayonnaises differed (Fig. 1), suggesting that the rheological differences between mayonnaises differing in the type of thickener added were too small to cause changes in visual thickness.

3.5.2. Flavour

No perceptual differences between the twelve mayonnaises were found for sweet and salty taste, and no clear trend in terms of fatty flavour intensity was observed. As the same concentrations of salt, sugar and fat were used in all mayonnaises, this was expected. Mayonnaises

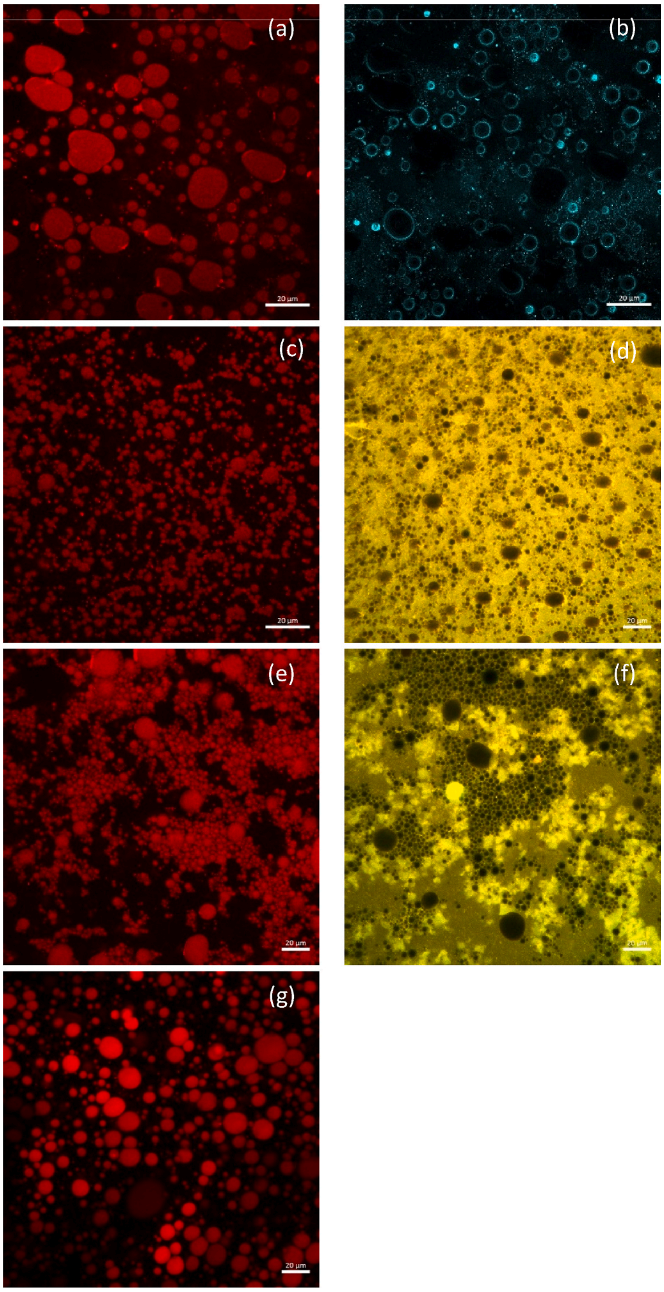

Fig. 4. Confocal laser scanning microscopy (CLSM) images of mayonnaises containing MFC (a,b), modified starch (c,d), waxy corn starch (e,f) and xanthan gum (g). The left column shows mayonnaises stained with Nile Red to visualise the fat phase, the right column shows the same mayonnaises stained with either Calcofluor White to visualise MFC (Fig. 4b) or stained with Acridine Orange to visualise starch and protein (Fig. 4d,f). Scale bars correspond to 20 μm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

thickened with XG had lower sourness and lemon flavour intensities compared to mayonnaises thickened with MFC, MS or WCS. We hypothesise that this is caused by the texture of mayonnaises thickened with XG, as multiple participants indicated that these mayonnaises had a cohesive gel-like texture that did not distribute well in the mouth upon oral processing. The cohesiveness of these mayonnaises might have resulted in a smaller surface area that is in contact with the tongue and saliva, and consequently might have reduced flavour release from the matrix. Our results confirm those of Pangborn, Gibbs, and Tassan (1978) who observed that xanthan gum suppressed sourness and flavour intensity in thickened beverages. Furthermore, several participants mentioned the presence of an off-flavour for mayonnaises thickened with WCS, which is in accordance with previous findings (Lotong, Chun, Chambers IV, & Garcia, 2003; Matta, Chambers IV, Garcia, & Helverson, 2006).

3.5.3. *Texture*

As anticipated, perceived thickness increased with increasing concentrations of thickener. Highest thickness intensities were found for mayonnaises thickened with MS, whereas lowest intensities were found for mayonnaises thickened with MFC. This was expected, since mayonnaises thickened with MFC also had the lowest shear viscosities (Fig. 1). Similar to thickness, mouthcoating and stickiness intensities generally increased with increasing thickener concentration, which is in line with results of Ross et al. (2019). Perceived mouthcoating was slightly higher for mayonnaises thickened with MS compared to the other mayonnaises. Highest stickiness intensities were found for mayonnaises thickened with MS and XG, while MFC was the least sticky. This is in line with previous studies that reported high adhesiveness or stickiness in samples thickened with starch (Nguyen, Kravchuk, Bhandari, & Prakash, 2017; Ong, Steele, & Duizer, 2018) and xanthan gum (Blok et al., 2021; Bortnowska & Tokarczyk, 2009). Mayonnaises thickened with MFC, MS or WCS were very similar in terms of creaminess, pulpiness, sliminess and smoothness (Table 4, Fig. 5). Mayonnaises thickened with XG differentiated themselves from the other mayonnaises by high sliminess and low creaminess, melting and smoothness intensities. This confirms earlier work in which foods thickened with XG imparted high sliminess (Blok et al., 2021; Gössinger et al., 2018; Matta et al., 2006), but low creaminess and smoothness (Nguyen et al., 2017; Terpstra et al., 2009). Although pulpiness intensities were generally low, pulpiness increased upon addition of XG. Pulpiness was included as a sensory texture attribute since MFC consists of insoluble fibres. Model foods thickened with MFC have previously been reported to be pulpier than those thickened with xanthan gum (Blok et al., 2021). However, in the current study higher pulpiness was observed for mayonnaises with XG, which is also reflected in Fig. 5. This is consistent with findings that XG induced heterogeneity in mayonnaises (Terpstra et al., 2009), considering their definition of heterogeneity was similar to our definition of pulpiness. An alternative explanation could be that participants did not experience pulpiness in any of the mayonnaises and hence used this attribute to evaluate the aforementioned cohesive, gel-like texture of XG-thickened mayonnaises. This would confirm earlier findings, as products thickened with XG were found to exhibit cohesiveness (Ross et al., 2019; Tobin et al., 2020) and cohesiveness of mayonnaises increased with increasing concentrations of XG (Bortnowska & Tokarczyk, 2009).

3.6. *Linking sensory to rheological and tribological properties of low-fat mayonnaises*

In order to link sensory characteristics to rheological and tribological properties of the low-fat mayonnaises with different thickeners, Multiple Factor Analysis (MFA) was performed (Fig. 6). Parameters located close to each other are positively correlated, whereas parameters opposing each other are negatively correlated. Since oral and visual thickness perception are located close to several shear viscosity parameters, these are positively correlated, as anticipated (e.g. Akhtar, Stenzel, Murray, & Dickinson, 2005; Cutler, Morris, & Taylor, 1983). Yield stress and consistency index K are positively correlated with shear viscosity at low shear rates (η at 10 s^{-1}), which indicates that mayonnaises with higher viscosity at low shear rates also had higher yield stress and consistency index K. Flow index n is negatively correlated with sliminess, suggesting that stronger shear-thinning mayonnaises were perceived as slimier. This is in contrast with previous work in which sliminess was found to be associated with higher n-values (*i.e.* weaker shear-thinning behaviour) (Szczesniak & Farkas, 1962; Wood, 1974) or small deformation viscosity

Table 4
Mean intensities (±SE) of appearance, flavour and texture attributes obtained from RATA (n = 80) of all mayonnaises. Samples in the same row containing the same letter are not significantly different from each other. Main effects (two-way ANOVA) of thickener type, concentration and their interaction with corresponding F- and p-values (n.s. = not significant; *p < 0.05; **p < 0.01; ***p < 0.001) are reported.

	Microfibrillated cellulose (MFC)			Modified starch (MS)			Waxy corn starch (WCS)			Xanthan gum (XG)			Two-way ANOVA effects					
	low	medium	high	low	medium	high	low	medium	high	low	medium	high	Thickener type		Concentration		Interaction	
Appearance													*F*(3,869)	*p*	*F*(2,869)	*p*	*F*(6,869)	*p*
Glossy	4.3 ± 0.2[d]	4.0 ± 0.2[d]	3.9 ± 0.2[d]	7.3 ± 0.2[a]	7.1 ± 0.2[a]	7.1 ± 0.2[ab]	6.0 ± 0.2[c]	5.8 ± 0.2[c]	5.6 ± 0.2[c]	5.9 ± 0.2[c]	6.3 ± 0.2[bc]	6.2 ± 0.2[c]	*F*=173.7	***	*F*=1.0	n.s.	*F*=1.3	n.s.
Slimy	4.0 ± 0.3[cd]	4.1 ± 0.3[cd]	3.8 ± 0.2[d]	4.6 ± 0.3[bcd]	4.6 ± 0.3[bcd]	4.5 ± 0.3[cd]	4.9 ± 0.2[abc]	4.7 ± 0.3[bcd]	4.6 ± 0.3[bcd]	5.4 ± 0.2[ab]	5.4 ± 0.2[ab]	5.7 ± 0.2[a]	*F*=34.9	***	*F*=0.2	n.s.	*F*=0.6	n.s.
Smooth	6.9 ± 0.2[abc]	6.0 ± 0.2[de]	5.6 ± 0.2[def]	7.5 ± 0.2[a]	7.3 ± 0.2[a]	7.1 ± 0.2[ab]	6.4 ± 0.2[bcd]	6.2 ± 0.2[cd]	5.8 ± 0.2[de]	4.8 ± 0.2[fg]	5.3 ± 0.2[efg]	4.5 ± 0.3[g]	*F*=99.5	***	*F*=14.2	***	*F*=3.0	**
Thick	6.0 ± 0.2[ab]	6.2 ± 0.2[ab]	6.5 ± 0.2[a]	5.8 ± 0.2[ab]	6.3 ± 0.2[ab]	6.4 ± 0.2[a]	5.5 ± 0.2[b]	6.0 ± 0.2[ab]	6.5 ± 0.2[a]	5.8 ± 0.2[ab]	6.2 ± 0.2[ab]	6.4 ± 0.2[a]	*F*=0.8	n.s.	*F*=15.9	***	*F*=0.6	n.s.
Yellow	2.7 ± 0.2[ab]	2.7 ± 0.2[ab]	3.1 ± 0.2[a]	2.0 ± 0.2[c]	2.1 ± 0.2[c]	2.1 ± 0.2[c]	2.3 ± 0.2[bc]	2.0 ± 0.1[c]	1.9 ± 0.2[c]	2.3 ± 0.2[bc]	2.5 ± 0.2[bc]	2.5 ± 0.2[bc]	*F*=26.9	***	*F*=0.9	n.s.	*F*=2.4	*
Flavour																		
Fatty	5.0 ± 0.2[abc]	4.8 ± 0.2[bc]	5.2 ± 0.2[abc]	5.4 ± 0.2[abc]	5.7 ± 0.2[a]	5.6 ± 0.2[ab]	4.7 ± 0.2[c]	5.0 ± 0.2[abc]	5.4 ± 0.2[abc]	4.7 ± 0.2[c]	5.0 ± 0.2[abc]	5.0 ± 0.2[abc]	*F*=9.1	***	*F*=3.7	*	*F*=0.8	n.s.
Lemon	5.9 ± 0.2[a]	5.5 ± 0.2[ab]	5.4 ± 0.2[ab]	5.2 ± 0.2[ab]	5.5 ± 0.2[ab]	5.0 ± 0.2[bc]	5.8 ± 0.2[ab]	5.4 ± 0.2[ab]	5.1 ± 0.2[ab]	4.2 ± 0.2[cd]	4.2 ± 0.2[cd]	4.0 ± 0.3[d]	*F*=36.4	***	*F*=4.6	*	*F*=1.0	n.s.
Salty	3.7 ± 0.2[a]	4.3 ± 0.3[a]	4.0 ± 0.2[a]	4.2 ± 0.2[a]	3.9 ± 0.2[a]	4.1 ± 0.2[a]	4.3 ± 0.3[a]	4.1 ± 0.2[a]	4.2 ± 0.2[a]	3.7 ± 0.3[a]	3.5 ± 0.2[a]	3.6 ± 0.3[a]	*F*=6.5	***	*F*=0.0	n.s.	*F*=1.4	n.s.
Sour	4.9 ± 0.2[a]	4.8 ± 0.2[a]	4.4 ± 0.2[abc]	4.4 ± 0.3[abc]	4.7 ± 0.2[a]	4.5 ± 0.3[ab]	4.9 ± 0.2[a]	4.6 ± 0.2[a]	4.7 ± 0.2[a]	3.6 ± 0.2[c]	3.6 ± 0.2[c]	3.7 ± 0.2[bc]	*F*=23.2	***	*F*=0.5	n.s.	*F*=1.0	n.s.
Sweet	3.1 ± 0.2	3.1 ± 0.2	3.2 ± 0.2	3.2 ± 0.2	3.2 ± 0.2	3.2 ± 0.3	3.3 ± 0.2	3.1 ± 0.3	3.2 ± 0.2	3.0 ± 0.2	3.0 ± 0.2	2.9 ± 0.2	*F*=1.4	n.s.	*F*=0.1	n.s.	*F*=0.1	n.s.
Texture																		
Creamy	6.4 ± 0.2[a]	6.4 ± 0.2[a]	6.3 ± 0.2[a]	6.4 ± 0.2[a]	6.7 ± 0.2[a]	6.8 ± 0.2[a]	6.0 ± 0.2[a]	6.0 ± 0.2[a]	6.3 ± 0.2[a]	4.4 ± 0.2[b]	5.0 ± 0.2[b]	4.7 ± 0.2[b]	*F*=72.6	***	*F*=1.5	n.s.	*F*=1.0	n.s.
Melting	5.6 ± 0.2[a]	5.4 ± 0.2[ab]	5.3 ± 0.2[ab]	5.4 ± 0.2[ab]	4.7 ± 0.2[bcd]	4.6 ± 0.2[bcd]	5.7 ± 0.2[a]	4.8 ± 0.2[abc]	5.0 ± 0.2[abc]	4.3 ± 0.3[cd]	4.6 ± 0.3[bcd]	3.9 ± 0.2[d]	*F*=24.3	***	*F*=9.1	***	*F*=2.3	*
Mouth-coating	4.7 ± 0.2[cd]	4.8 ± 0.2[cd]	5.2 ± 0.3[abcd]	5.1 ± 0.3[abcd]	5.9 ± 0.2[ab]	6.1 ± 0.2[a]	4.6 ± 0.2[d]	5.2 ± 0.3[abcd]	5.6 ± 0.2[abc]	4.6 ± 0.2[d]	5.0 ± 0.3[bcd]	4.9 ± 0.3[cd]	*F*=11.5	***	*F*=12.4	***	*F*=1.0	n.s.
Pulpy	0.7 ± 0.2[d]	0.8 ± 0.2[bcd]	0.8 ± 0.2[cd]	0.6 ± 0.1[d]	0.7 ± 0.1[d]	0.8 ± 0.2[cd]	0.9 ± 0.2[bcd]	0.8 ± 0.2[d]	0.7 ± 0.2[d]	1.5 ± 0.3[ab]	1.5 ± 0.2[abc]	2.2 ± 0.3[a]	*F*=33.3	***	*F*=2.1	n.s.	*F*=1.9	n.s.
Slimy	3.5 ± 0.3[b]	3.5 ± 0.2[b]	3.8 ± 0.2[b]	3.8 ± 0.3[b]	4.4 ± 0.3[b]	4.1 ± 0.3[b]	3.8 ± 0.3[b]	3.9 ± 0.3[b]	3.9 ± 0.3[b]	5.6 ± 0.3[a]	5.8 ± 0.3[a]	5.9 ± 0.3[a]	*F*=67.0	***	*F*=2.0	n.s.	*F*=0.6	n.s.
Smooth	7.2 ± 0.2[a]	6.9 ± 0.2[a]	6.9 ± 0.2[a]	7.6 ± 0.1[a]	7.3 ± 0.2[a]	7.2 ± 0.2[a]	7.2 ± 0.2[a]	6.9 ± 0.2[a]	6.9 ± 0.2[a]	5.5 ± 0.3[bc]	5.9 ± 0.2[b]	4.8 ± 0.3[c]	*F*=86.3	***	*F*=7.2	***	*F*=2.6	*
Sticky	2.9 ± 0.2[d]	3.0 ± 0.3[cd]	3.5 ± 0.3[bcd]	3.7 ± 0.3[bcd]	4.4 ± 0.3[ab]	4.7 ± 0.3[a]	3.3 ± 0.2[cd]	3.3 ± 0.3[cd]	3.8 ± 0.3[abcd]	3.7 ± 0.3[bcd]	3.9 ± 0.3[abc]	3.9 ± 0.3[abc]	*F*=15.8	***	*F*=8.2	***	*F*=1.1	n.s.
Thick	4.4 ± 0.2[e]	4.7 ± 0.2[cde]	5.4 ± 0.2[abc]	5.2 ± 0.2[bcde]	6.2 ± 0.2[a]	6.2 ± 0.2[a]	4.5 ± 0.2[de]	5.3 ± 0.2[abcd]	5.6 ± 0.2[ab]	4.8 ± 0.2[bcde]	5.2 ± 0.2[bcde]	5.7 ± 0.2[ab]	*F*=16.8	***	*F*=30.1	***	*F*=1.1	n.s.

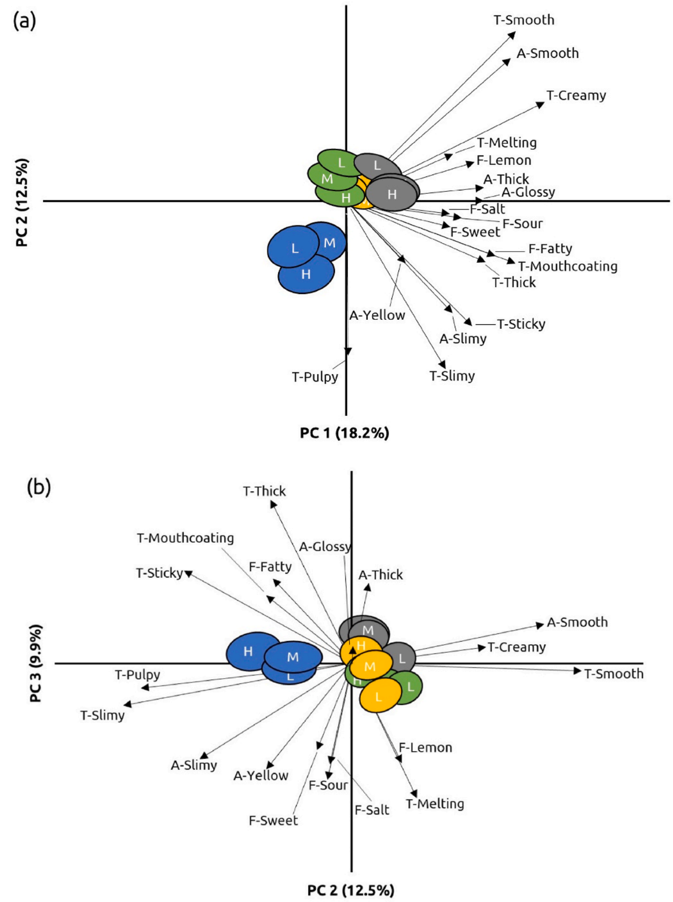

Fig. 5. Principal Component Analysis (PCA) bi-plots displaying loadings for the appearance, flavour and texture attributes and scores for the twelve low-fat mayonnaises thickened by microfibrillated cellulose (MFC; green), modified starch (grey), waxy corn starch (yellow) and xanthan gum (blue) with their respective 95% confidence ellipses. Letters in circles correspond to the concentration of thickener used: low (L), medium (M) and high (H) thickener concentration. Figure (a) displays principal components (PC) 1 and 2; (b) displays PC 2 and 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

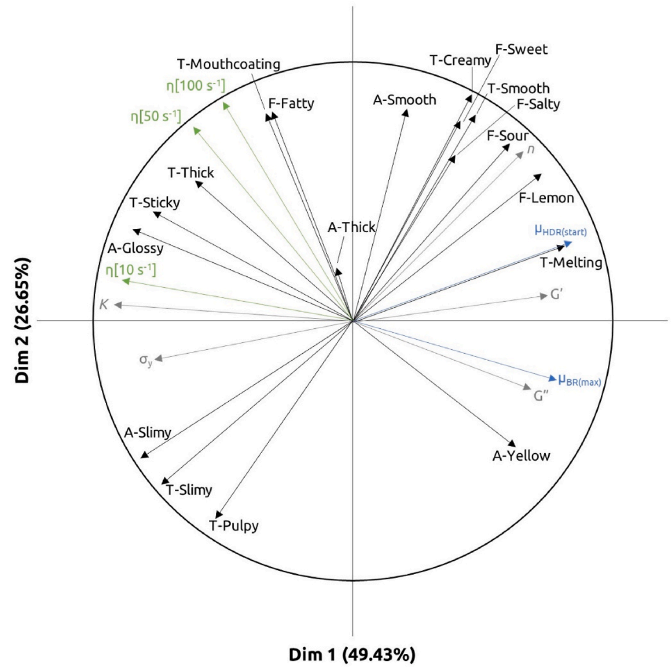

Fig. 6. Multiple Factor Analysis (MFA) plot including all sensory attributes (black), shear viscosity parameters (η at 10, 50 and 100 s^{-1}; green), rheological parameters (consistency index K, flow index n, storage modulus G', loss modulus G'' and yield stress σ_y; grey) and friction parameters (maximum μ in the boundary regime ($\mu_{BR(max)}$) and μ at the start of the hydrodynamic regime ($\mu_{HDR(start)}$); blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at 50 rad s^{-1} (Richardson, Morris, Ross-Murphy, Taylor, & Dea, 1989). Many of the flavour and taste attributes (F-Lemon, F-Sour, F-Salty, F-Sweet) are located close to each other and opposite to sliminess, suggesting that samples with low sliminess generally had higher flavour intensities. This correlation might be driven by the XG-thickened mayonnaises as these were slimy and had lower flavour intensity. This correlation might therefore be specific for the current sample set and might not be generalisable to other foods. Sliminess and pulpiness are moreover placed opposite of smoothness and creaminess, which implies that mayonnaises with higher pulpiness and sliminess were perceived as less smooth and less creamy. The fact that creaminess is negatively correlated with pulpiness is consistent with findings of Terpstra et al. (2009), considering the definition they used to evaluate the homogeneity of mayonnaises is similar to the definition used for pulpiness in the current study.

A strong positive correlation between friction at the start of the hydrodynamic regime ($\mu_{HDR(start)}$) and melting texture was found. Friction in the hydrodynamic regime predominantly depends on the shear viscosity of the material between the surfaces (Stokes, 2012), it is therefore expected that a higher friction coefficient at the start of the hydrodynamic regime is caused by a lower shear viscosity of the mayonnaise. As shear rates between the tribological surfaces are estimated to exceed 1000 s^{-1}, no data is available on the viscosity of the mayonnaises in the tribological gap. However, it can be reasonably assumed that mayonnaises that are more viscous at a shear rate of 500 s^{-1} (highest shear rate applied in this study during the rheological characterisation) also have higher viscosity at higher shear rates. Less viscous mayonnaises might have been perceived as more melting, as these rapidly become thin in the mouth and melting texture was defined in this study as 'the degree to which the product becomes thin and fluid and distributes itself in the mouth'. This corresponds with results from a study by de Wijk and colleagues, in which 'melting' was regarded as the semantical opposite of 'thick' (de Wijk et al., 2003). Maximum friction coefficient in the boundary regime ($\mu_{BR(max)}$) is negatively correlated with a sticky texture, indicating that mayonnaises with higher friction in this regime were less sticky. While this is inconsistent with findings of Devezeaux de Lavergne et al. (2016), de Wijk and Prinz (2005) also concluded that increased friction generally resulted in decreased sensations of stickiness of custard desserts. In the boundary regime the surfaces of the tribo-pair are in contact and thus exclude the sample from the tribological gap. The friction in this regime is therefore largely determined by the properties of the surfaces, although these can be affected by adsorption of molecules to the surfaces (Stokes, 2012). Adsorption of biopolymers on (one of) the surfaces could reduce friction in the boundary regime by film formation on the one hand, and might induce stickiness on the other hand. It should be noted that the correlations reported between instrumental and sensory parameters depend on the experimental conditions used. In this work, low-fat mayonnaises were not mixed with saliva for the rheological and tribological characterisation and friction properties were determined using a glass ball and PDMS pins, which mimics oral conditions only to a very limited extent. We acknowledge that addition of saliva or salivary amylase is known to change tribological properties of starch thickened foods (Torres et al., 2019). The correlations reported in Fig. 6 therefore might change when other tribological surfaces are used or upon inclusion of saliva or salivary amylase in the experiment, especially for the starch containing mayonnaises.

4. Conclusions

The aim of this study was to determine the effect of type and concentration of thickener on rheological, tribological and sensory properties of low-fat mayonnaises. Independent of thickener type, higher biopolymer concentrations generally led to increased shear viscosities, G' and G'', and yield stress. Increasing the biopolymer concentration moreover enhanced perception of several sensory texture attributes, including thickness, stickiness and mouthcoating. Biopolymer concentration only had a minor effect on tribological properties of the mayonnaises, whereas larger differences were observed between the types of thickener. Rheological properties of low-fat mayonnaises strongly depended on the type of biopolymer used. Addition of xanthan gum resulted in low-fat mayonnaises with strong shear-thinning behaviour and high yield stress compared to mayonnaises with modified starch, waxy corn starch or MFC, despite having comparable shear viscosities ($>10\ s^{-1}$). Mayonnaises thickened with xanthan gum were furthermore sensorially different from the other mayonnaises due to higher sliminess and pulpiness, but lower creaminess, smoothness and melting intensities. Sensory texture characteristics of mayonnaises with MFC closely resembled those of mayonnaises thickened with waxy corn starch and modified starch, despite differences in microstructure, rheological and tribological properties (*i.e.* lower shear viscosity and yield stress, higher G', G'' and boundary friction, larger oil droplet size). We therefore conclude that MFC can be used as thickener in low-fat food mayonnaise as a substitute for conventionally used modified starch without greatly affecting sensory properties of the mayonnaise. The use of natural fibers such as MFC offers several benefits compared to the use of (modified) starch, including a low nutritional density, the potential of being used as a clean-label thickener and the possibility to use agricultural waste streams for its production.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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