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PLANT-BASED YOGURTS:
TEXTURE PERCEPTION AND
CONSUMER RESPONSES

Maija Greis

ACADEMIC DISSERTATION

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ABSTRACT

The present study concentrates on the prospects of texture perception and consumer acceptance of plant-based (PB) yogurts. This thesis lays a cornerstone for the dynamic texture profile and physicochemical properties of PB yogurts in relation to dairy yogurts. The study contributes to the understanding of the basis of the texture and mouthfeel of PB yogurts.

Temporal dominance of sensations (TDS) with consumers (*n*=87) was used to analyze the dynamic mouthfeel. Following TDS, overall and mouthfeel liking were evaluated using a 7-point hedonic scale. Some PB yogurts were found to be similar by their mouthfeel profile and equally liked as dairy yogurts. Physicochemical properties of the yogurts were also analyzed. Significant differences in flow behavior and small deformation rheology were found between them. Among PB yogurts, thick, creamy, thin, and watery mouthfeel sensations were strongly associated with steady shear rates and apparent viscosity. Large deformation rheology proved to be a useful tool to study PB yogurts.

The role of selected factors on mouthfeel perception was studied. Generic descriptive analysis (GDA) and TDS with a trained panel were conducted to study the influence of aroma compounds possibly congruent with sweetness perception (*n*=10 panelists × 4 sessions). Unflavored and flavored (vanilla; 0.05%; 0.1%; lemon: 0.025%; 0.05%) samples were included. The aromas modified the perceived sweetness in PB yogurts; however, aroma and perceived sweetness did not impact the mouthfeel.

The role of product information, visual experience, and cross-cultural differences in mouthfeel perception and consumer acceptance were studied with two identical consumer studies: in the US (*n*=101) and in Finland (*n*=96). Six blueberry-flavored yogurts were blended in varying plant-to-dairy proportions. Selected texture-related attributes were studied first by appearance and, after tasting, by mouthfeel using the Rate-all-that-apply (RATA) and Just-about-right (JAR) methods. The results showed that product information did not have an impact on the texture perception. The interpretation of mouthfeel descriptors such as creamy can vary depending on the culture, language and the yogurt market. The perception of texture characteristics was emphasized differently by visual experience and mouthfeel, depending on sample and texture characteristics. In overall acceptance, clear differences were found between the samples: PB-labeled samples with a higher dairy content were most liked, but there were no differences between the countries. Interestingly, the PB-labeled yogurt (50:50) was more liked compared to the same yogurt labeled as dairy yogurt, indicating that consumers have different expectations toward PB and dairy yogurts. Creamy was found to be the main driver of liking among the PB-labeled yogurts in the US and in Finland.

While this thesis focuses on PB yogurts with oat as the main plant ingredient, the results will benefit product development and research on other types of PB yogurts, as well as providing insight to the sensory and physicochemical methods suitable for studying food texture and structure with semisolids. Future studies should focus on the effect of various food ingredients on the texture of PB yogurts, and on the preferences of segments of the consumer population.

TIIVISTELMÄ

Tutkimus keskittyy kasvipohjaisten jogurttien rakenteen aistimiseen ja hyväksyttävyyteen. Työ avaa kasvipohjaisten jogurttien rakenteen ja suutuntuman perusteita.

Ensimmäisessä osatyössä selvitettiin kasvipohjaisen jogurtin rakenteen ajallisia muutoksia ja fysikaalis- kemiallisia ominaisuuksia suhteessa maitojogurttiin. Kuluttajaraati (n=87) arvioi viiden kasvi- ja kahden maitopohjaisen jogurtin suutuntumaominaisuuksia syönnin aikana TDS-menetelmällä (engl. Temporal dominance of sensations). Suutuntuma- ja kokonaismiellyttävyyttä arvioitiin 7-portaisella asteikolla. Osa kasvipohjaisista jogurteista koettiin yhtä miellyttäviksi suutuntuman osalta kuin maitopohjaiset jogurtit. Lisäksi selvitettiin jogurttien fysikaalis-kemiallisia ominaisuuksia. Kasvi- ja maitopohjaisten jogurttien välillä havaittiin merkittäviä eroja muun muassa virtauskäyrissä. Kasvipohjaisissa jogurteissa paksu, kermainen, ohut ja vetinen suutuntuma olivat vahvasti yhteydessä tasaiseen leikkausnopeuteen ja viskositeettiin.

Erilaisten tekijöiden roolia suutuntuman havaitsemisessa tutkittiin eri tavoin. Koulutettu raati arvioi kuvailevan analyysin ja TDS-menetelmän avulla aromiyhdisteiden vaikutusta koettuun suutuntumaan kasvipohjaisilla jogurteilla (n=10 arvioijaa × 4 arviointikertaa). Tutkimuksessa arvioitiin maustamattomia ja maustettuja (vanilja: 0.05%; 0.1%; sitruuna: 0.025%; 0.05%) jogurtteja. Aromit voimistivat makeuden kokemusta, mutta aromi itsessään tai näytteen koettu makeus ei vaikuttanut koettuun suutuntumaan.

Jogurtteihin liittyvä kuluttajatutkimus toteutettiin Yhdysvalloissa (n=101) ja Suomessa (n=96). Kiinnostuksen kohteena oli erityisesti tuotetiedon ja jogurtin aistittavien ominaisuuksien vaikutus koettuun suutuntumaan. Kuusi mustikanmakuista jogurttia valmistettiin sekoittamalla maito- ja kasvipohjaista jogurttia eri suhteissa. Valittuja rakenneominaisuuksia arvioitiin ensin ulkonäön ja sitten suutuntuman perusteella kahdella menetelmällä (RATA, engl. Rate-all-that-apply ja JAR, engl. Just-about-right). Tuotteista annetut tiedot eivät vaikuttaneet koettuun rakenteeseen. Ominaisuuksista erityisesti kermaisuus koettiin eri tavalla maasta riippuen, mikä todennäköisesti johtui englannin- ja suomenkielisten termien ja jogurttimarkkinoiden eroista. Maiden välillä ei ollut eroja miellyttävyyden arvioinnissa. Näytteiden välillä havaittiin kuitenkin selkeitä eroja kokonaismiellyttävyydessä: maitopohjaisen jogurtin osuuden kasvaessa näytteiden miellyttävyys vahvistui. Näyte, joka sisälsi puoliksi maito- ja puoliksi kasvipohjaista jogurttia ja joka tarjoiltiin kasvipohjaisena jogurttina, oli pidetympi kuin sama näyte, kun sen kerrottiin olevan maitopohjainen. Tulos osoittaa, että kuluttajien odotukset kasvipohjaisia jogurtteja kohtaan ovat erilaiset kuin maitopohjaisia jogurtteja kohtaan. Kermaisuus oli kasvipohjaisiksi jogurteiksi nimetyissä näytteissä kokonaismiellyttävyyden kannalta tärkeä ominaisuus sekä Yhdysvalloissa että Suomessa.

Työssä käytettyjen kasvipohjaisten jogurttien pääainesosana oli kaura, mutta tuloksia voidaan hyödyntää myös muiden kasvipohjaisten jogurttien tuotekehityksessä ja tutkimisessa. Tutkimus tarjoaa tietoa puolikiinteiden elintarvikkeiden rakenteen tutkimisen menetelmistä. Tulevissa tutkimuksissa tulisi keskittyä tarkemmin eri raaka-aineiden ja rakenteen vuorovaikutuksiin sekä kuluttajasegmenttien mieltymyksiin.

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Berlin, January 2023,

Maija Greis

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

I Greis, M., Sainio, T., Katina, K., Kinchla, A. J., Nolden, A., Partanen, R., & Seppä, L. (2020). Dynamic texture perception in plant-based yogurt alternatives: Identifying temporal drivers of liking by TDS. *Food Quality and Preference,* 86, 104019.

II Greis, M., Sainio, T., Katina, K., Nolden, A. A., Kinchla, A. J., Seppä, L., & Partanen, R. (2022). Physicochemical properties and mouthfeel in commercial plant-based yogurts. *Foods*, 11(7), 941.

III Greis, M., Kukkonen, R., Lampi, A. M., Seppä, L., Partanen, R., & Sandell, M. (2022). The impact of vanilla and lemon aromas on sensory perception in plant-based yogurts measured with static and dynamic methods. *Foods*, *11*(14), 2030.

IV Greis, M., Seppä, L., Puputti, S. Nolden, A. A., Kinchla, A. J. & Sandell M. What if plant-based yogurts were like dairy yogurts? Texture perception and liking of plant-based yogurts among US and Finnish consumers. Revised version and resubmitted to Food Quality and Preference.

The publications are referred to in the text by their Roman numerals. The articles are reprinted with permission of their copyright holders.

RESEARCH INPUT AND AUTHORSHIP OF ARTICLES (I-IV)

I This study formed the topic for Taru Sainio's master's thesis. The planning of the study and the data analysis were carried out by Taru Sainio and Maija Greis. Taru Sainio was responsible for preparing the samples and collecting the data. Maija Greis was responsible for drafting and writing the manuscript. The study was supervised by Dr. Laila Seppä, Professor Kati Katina, and Dr. Riitta Partanen who also offered comments and suggestions on the manuscript. Professor Alissa Nolden and Professor Amanda Kinchla contributed to the manuscript by providing comments and suggestions.

II This study partly formed the topic for Taru Sainio's master's thesis. The planning of the study and the data analysis were carried out by Taru Sainio and Maija Greis. Taru Sainio was responsible for preparing the samples and collecting the data. Maija Greis was responsible for additional data analyzes, and for drafting and writing the manuscript. The study was supervised by Dr. Laila Seppä, Professor Kati Katina, and Dr. Riitta Partanen who also offered comments and suggestions on the manuscript. Professor Alissa Nolden and Professor Amanda Kinchla contributed to the manuscript by providing comments and suggestions.

III This study partly formed the topic for Roosa Kukkonen's master's thesis. The planning of the study was carried out by all authors. Roosa Kukkonen was responsible for collecting the data and preparing the samples. Maija Greis was responsible for additional data analyzes, and for drafting and writing the manuscript. Dr. Anna-Maija Lampi was responsible for conducting the GC-MS analyzes. The study was supervised by Dr. Laila Seppä, Dr. Riitta Partanen, and Professor Mari Sandell who also offered comments and suggestions on the manuscript.

IV The planning of the study was carried out by all authors. Maija Greis was responsible for preparing the samples, collecting the data in the US and in Finland, data analysis and for drafting and writing the manuscript. The study was supervised by Dr. Laila Seppä, Dr. Sari Puputti, and Professor Mari Sandell who also offered comments and suggestions on the manuscript. Professor Alissa Nolden and Professor Amanda Kinchla contributed to the study by providing comments and suggestions on the research plan, data analysis, and manuscript.

ABBREVIATIONS

ANOVA	Analysis of variance
CATA	Check-all-that-apply
D	Dairy
DSI	Domain-specific innovativeness scale
FIN	Finland
FNS	Food neophobia scale
G'	Storage modulus
G"	Loss modulus
GDA	Generic descriptive analysis
JAR	Just-about-right
MF	Mouthfeel
n	Number of panelists in a panel or substudy
NVA	Negative vegetarian attitude
ºBrix	Soluble solids
p	Level of significance
PB	Plant-based
PC	Principal component
PCA	Principal component analysis
PLS	Partial least squares regression
RATA	Rate-all-that-apply
SUS	Background question on sustainability
TDS	Temporal dominance of sensations
TTA	Total titratable acidity
US	United States
VE	Visual experience

1 INTRODUCTION

Yogurt has been an important part of the human diet for thousands of years and goes by many names worldwide. It is considered a healthy, tasty, and nutritious food, supplying essential vitamins and minerals. It is traditionally produced by bacterial fermentation of milk, thus prolonging its shelf life. The word yogurt is believed to have come from the Turkish word "yoğurmak," which means to thicken, or coagulate, referring to the structure and texture of the food.

In recent years, various fermented plant-based (PB) yogurts, using soy, rice, almond, and coconut milk as a base for the product, have appeared on the market for those consumers who prefer a vegetarian or vegan lifestyle and those with a milk allergy (Mäkinen et al., 2016). Typically, the acceptance of PB yogurt is believed to be best achieved when the product has similar sensory properties as the dairy product (Craig & Brothers, 2021). However, due to the different macromolecules that form their structures, mimicking the texture of a dairy yogurt is challenging. In this thesis, the word yogurt will be used for PB yogurts, although, in Europe and the US, companies are not allowed to market their PB products using the word "yogurt" according to the European Union (EU) and Food and Drug Administration (FDA).

Nowadays, oat is highly accepted by consumers due to its health benefits (Banovic et al., 2018; Brückner-Gühmann, Banovic, et al., 2019). The FDA and EU have authorized health claims for oat's beta-glucan on lowering blood cholesterol levels and improving blood sugar management (EFSA 2020; FDA 1997). Northern countries like Finland, Scotland and Canada have a long tradition of using oat in various foods. Examples of oat-based spoonable snacks have already been on the market in Finland since 1995, while several new oat-based yogurts have appeared on the market over the past years (Fineli, 2022).

An essential step toward acceptance is that a food product meets consumers' sensory demands and expectations (Lawless & Heymann, 2010). Sensory properties are highlighted as one of the most influential factors determining food acceptance, and within these, taste and flavor are typically the most studied. Interestingly, food texture has been under less investigation. However, texture plays a crucial role in acceptance in many food products, particularly semisolid products. For example, food texture is a primary reason for rejecting or accepting food (Werthmann et al., 2015; Scott & Downey, 2007).

This thesis is based on the studies performed during 2019−2022, presented in four original publications. The thesis focuses on texture perception and consumer responses related to PB yogurts. The studied products are referred to as "plant-based" instead of "oat-based" yogurts, as oat is usually not the only plant ingredient in them. The thesis characterizes the temporal nature of mouthfeel perception and physicochemical properties of PB yogurts, determines the role of product information, visual experience, and added aroma compounds on mouthfeel perception. In addition, consumer acceptance of PB yogurts among US and Finnish consumers is examined.

The dynamic mouthfeel profiles present valuable scientific information for future research on PB yogurts because no such dataset has been available before in Finland or elsewhere. The results provide information on whether there are ways to influence the mouthfeel perception in PB yogurts. In addition, by examining the role of product information on the mouthfeel and overall liking, we will understand if there are different expectations for PB and dairy yogurts. The literature review first discusses the definitions of texture, structure, and mouthfeel of food in general. Then it concentrates on PB yogurts, i.e., their composition, physicochemical properties, and sensory quality. Finally, selected factors contributing to consumer responses and the sensory methods relevant to this work will be reviewed.

2 REVIEW OF THE LITERATURE

2.1 Texture and mouthfeel of food

2.1.1 Definitions of structure, texture, and mouthfeel

Over the years, the definition of food texture has undergone many changes (Bourne, 2002; Chen, 2007; Christensen, 1984; Funami & Nakauma, 2022; Guinard & Mazzucchelli, 1996; Melito 2018; Kilcast, 2004; Wilkinson et al., 2000). Primarily, there has been confusion with the expressions of texture and structure, as the terms have been used for similar purposes. **Figure 1** presents the relationship between structure, texture, and mouthfeel according to the literature. Food texture is regarded as a multidimensional sensory property influenced by the food's structure, rheology, and surface properties, and mouthfeel refers to the tactile aspects of texture perception. Texture can be divided into visual, tactile, and auditory textures, which are perceived by different senses: sight, touch, and sound. Mouthfeel, in contrast, refers to the tactile aspect of texture perception, and the surface of the oral cavity is responsible for perceiving it.

In 2002, one of the most cited texture scientists, Dr. Alina Szczesniak, defined food texture as a sensory property and a multi-parameter attribute that derives from the structure of the food (Szczesniak, 2002). By defining food texture as a sensory property, she highlighted that texture is detected by several senses and that textural characteristics of food could be measured only by sensory assessment tests. However, the link between texture and structure is vital. Food texture is firmly influenced by the interactions of food macromolecules such as proteins, polysaccharides, and lipids. Thus, instrumental methods designed to measure rheological and mechanical properties may be used to establish parameters that relate to relevant sensory textural characteristics (Chen & Opara, 2013). According to Knoop (2011), three types of texture sensations can be differentiated. Kinesthetics express texture perception during mastication, while somesthetics is perceived sensations by other tactile stimulation and does not require oral manipulation of the food. The third sensation describing food texture is trigeminal which detects temperature, astringency and pungency (e.g., CO_2 stimulation). Yet, there is no single receptor type that can detect texture perception, although trigeminal somatosensory receptor neurons transmit trigeminal sensations. In this thesis mastication refers to eating while yogurt is mixed in the mouth with saliva, leading to continuous transition of the structure.

Others have described food texture as a collective term of sensory experiences originating from visual, audio, and tactile stimuli (Chen & Stokes, 2012), or a multidimensional sensory property that is influenced by the food's structure, rheology, and surface properties (Kravchuk et al., 2012). Furthermore, the International Organization for Standardization ISO (1994) defines texture as follows: the texture is "all the mechanical, geometrical and surface attributes of a product perceptible utilizing mechanical, tactile, and, where appropriate, visual and auditory receptors." Mouritsen & Styrbæk (2017) describes texture as: "the texture of a particular food is determined by its physical state at the time and the physical properties associated with that state".

Mouthfeel, in contrast, is perceived on the oral cavity surfaces by mechanoreceptors. Mouthfeel tends to change less dramatically than other oral-tactile texture properties (Lawless & Heymann, 2010). Many mouthfeel characteristics are not necessarily related to the rheology or product breakdown. However, some of the mouthfeel characteristics are related to the force of the breakdown. Examples of these properties are viscosity and stickiness. de Wijk et al. (2006) indicated that each texture dimension has attributes that are either related to surface properties or bulk properties of the food bolus. Thus, the role of the mouthfeel properties is highlighted in the characterization of liquids and semisolids. In 1966, Szczesniak classified mouthfeel attributes into 11 groups, as presented in **Table 1.** According to the classification, for instance, the coating of the oral cavity–related characteristics (e.g., fatty, oily) are different from body-related characteristics (e.g., watery, light) (Szczesniak, 2002).

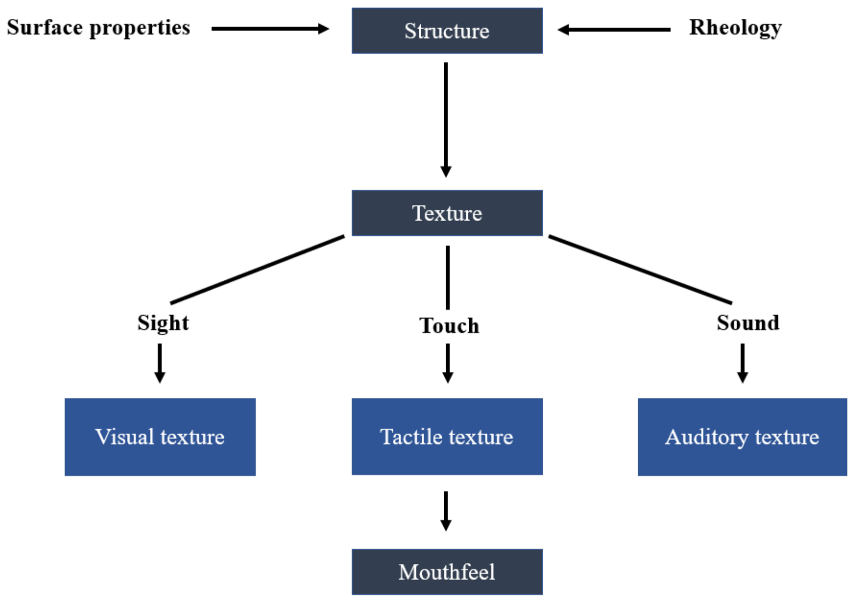


Figure 1. Illustration of the definitions of structure, texture, and mouthfeel. Structure, texture, and mouthfeel are considered food material properties; more precisely, texture and mouthfeel are considered as sensory properties. Food texture is regarded as a multidimensional sensory property influenced by the food's structure, rheology, and surface properties. Texture can be divided into visual, tactile, and auditory textures. These are perceived by different senses: sight, touch, and sound. Mouthfeel refers to the tactile aspect of texture perception, and the surface of the oral cavity is responsible for perceiving it.

Table 1. Classification of mouthfeel properties according to Szczesniak (1966).

No.	Classification	Examples of descriptors
1	Viscosity related	Thick, Thin
2	Feel of soft tissue surfaces related	Smooth, Pulpy
3	Carbonation related	Bubbly, Foamy
4	Body related	Watery, Heavy, Light
5	Chemical related	Astringent, Numbing, Cooling
6	Coating of the oral cavity related	Clinging, Fatty, Oily
7	Resistance to tongue movement related	Slimy, Sticky, Pasty
8	Mouthfeel after-feel related	Clean, Lingering
9	Physiological after-feel related	Filling, Refreshing
10	Temperature related	Hot, Cold
11	Wetness related	Wet, Dry

Typically, mouthfeel attributes are split into mouthfeel and after-feel characteristics, such as de Wijk et al. (2003) described. The most cited mouthfeel characteristics are perhaps astringency, puckering sensation, cooling, numbing, and mouth coating. After-feel properties are similar to those perceived during mastication. In semisolids, the feeling in the mouth after swallowing has been described as slimy with the following definition "product leaves a feeling of thick mucus in the mouth that is difficult to remove/swallow, typically caused by dairy products," as the instructions for the descriptive panel in de Wijk et al. (2003) clarified. Devezeaux de Lavergne et al., (2015) classified mouthfeel properties into first and second bites, chew down, and after-feel groups. Mouthfeel properties can also be very distinctive for solid, semisolid, and liquid foods due to the different oral processing behaviors needed to masticate the food. For example, the attribute brittle is seldom used for semisolid foods. Instead, it can be used, for example, with cookies, describing how quickly it breaks when crushed with the teeth (Mouritsen & Styrbæk, 2017).

Table 2 and **Table 3** present a few attributes and definitions describing the mouthfeel of various semisolid foods used in studies. For these tables, the selected attributes are divided into viscosity related, softness related, resistance to tongue movement related, and body related, which are adapted from Szczesniak's classification. The tables show that attributes generated in the different studies for similar products have a significant overlap. For example, the attribute thickness and firmness are defined the same way for vanilla custards and yogurts. In addition, some differences exist between the same attributes, primarily with more complex ones. For example, the attribute creamy is defined similarly for yogurts, emulsion-filled gels, and vanilla custards in different studies.

Table 2. Viscosity and softness related mouthfeel attributes and their definitions for semisolid food products as reported in the following publications.

Attribute	Definition	Sample	Reference
Viscosity related			
Thickness	Represents the thickness of the food in the mouth after the food is compressed via up and down motions of the tongue against palate	Vanilla custards	(de Wijk et al., 2003)
Thickness	Resistance to flow in the mouth before saliva modifies the sample	Low-fat pot-set yogurt	(Nguyen et al., 2017)
Firmness	Describes the resistance of the yogurt when it is crushed between the tongue and the palate	Fat-free strawberry yogurt	(Lesme et al., 2020)
Liquid	Describes the tendency of yogurt to flow in the mouth	Fat-free strawberry yogurt	(Lesme et al., 2020)
Viscous	Describes a smooth and homogenous texture with an intermediate thickness	Fat-free strawberry yogurt	(Lesme et al., 2020)
Softness related			
Smooth/grainy	Degree to which the food contains granules detected by moving the tongue parallel to the palate	Vanilla custards	(Devezeaux de Lavergne 2015)
Smooth	Slippery	Emulsion-filled gels	Devezeaux de Lavergne 2015
Creaminess	Silky smooth sensation in the mouth	Low-fat pot-set yogurt	(Nguyen et al., 2017)
Creamy/soft	Range of sensation typically associated with fat content such as full and sweet taste, compact, smooth, not rough, not dry, with a velvety (not oily) coating. Food disintegrates at moderate rate.	Vanilla custards	(de wijk et al., 2003)
Creamy	Product feels full, soft, velvety	Emulsion-filled gels	Devezeaux de Lavergne 2015
Fatty	Fatty and oily layer on oral tissues lubricating food transport in the mouth and stimulating saliva production	Vanilla custards	(de Wijk et al., 2003)
Fatty	Oil-like	Emulsion-filled gels	Devezeaux de Lavergne 2015
Oily coating	Oily coating in the mouth after swallowing	Low-fat pot-set yogurt	(Nguyen et al., 2017)

Table 3. Resistance to tongue movement and particle related, and body related mouthfeel attributes and their definitions for semisolid food products as reported in the following publications.

Attribute	**Definition**	**Sample**	**Reference**
Resistance to tongue movement and particle related			
Sticky	Food is pulled apart by downward movement of the tongue and the resulting threads are sensed as sticky by the tongue, palate, and throat making swallowing difficult	Vanilla custards	de Wijk et al., 2003
Sticky	Clinging in the mouth	Emulsion-filled gels	Devezeaux de Lavergne et al., 2015
Stickiness	Degree to which the sample sticks to the teeth and palate	Low-fat pot-set yogurt	Nguyen et al., 2017
Heterogeneity	Food is sensed simultaneously as thick and thin (or "cloudy" or "flocky") in the mouth while food is mixed with saliva. Various parts of the food seem to melt at different rates.	Vanilla custards	Devezeaux de Lavergne, van de Velde, et al., 2015
Dry/mealy	Food seems to absorb saliva making it difficult to swallow while it is compressed between the tongue and palate. Surface of mouth feels rough.	Vanilla custards	de Wijk et al., 2003
Brittleness	Sensation linked to the difficulty of mixing the yogurt with saliva when it loses its thickness	Fat-free strawberry yogurt	Lesme et al., 2020
Graininess	Describes the presence of particles or granules	Fat-free strawberry yogurt	Lesme et al., 2020
Body related			
Lumpy	Product has small soft lumps	Emulsion-filled gels	Devezeaux de Lavergne et al., 2015
Lumpiness	Number of soft lumps or graininess present in the sample	Low-fat pot-set yogurt	Nguyen et al., 2017
Airy	Food is perceived by tongue as airy/foamy and disintegrates easily after the food is compressed against the palate	Vanilla custards	de Wijk et al., 2003
Moist	Watery	Emulsion-filled gels	Devezeaux de Lavergne et al., 2015
Melting/becoming thin (slow–quick)	Foods becomes thin in the mouth and spreads throughout the mouth at different rates	Vanilla custards	de Wijk et al., 2003
Melting	Dissolves, structure disappears like in ice cream	Emulsion-filled gels	Devezeaux de Lavergne et al., 2015
Melty	Rate at which the yogurt loses thickness in the mouth. Tendency to create a paste in the mouth.	Fat-free strawberry yogurt	Lesme et al., 2020

2.1.2 Dynamic texture perception

To explain the acceptance and liking of food products, understanding the dynamic sensory perception is essential (Chen & Stokes, 2012; Koc et al., 2013). Texture perception of semi-solid food gels is a dynamic process since the structure of food alters during mastication due to oral processing and chemical breakdown in the mouth (Devezeaux de Lavergne et al., 2015; Hutchings & lillford, 1988). The previous literature on mouthfeel properties of semi-solid food has focused on dairy yogurts (Nguyen et al., 2017), soybean and dairy custards (Engelen et al., 2003), vanilla custards (de Wijk et al., 2003) and various emulsion-filled gels (Devezeaux de Lavergne et al., 2015). Nguyen et al. (2017) demonstrated that the initial dominant perception was related to the viscosity properties. As for the chronology of the attributes during mastication, it has been shown that sensations of those bulk-dominated texture features were detected relatively quickly. In contrast, sensations related to surface properties were detected more slowly (Chen & Stokes, 2012; de Wijk et al., 2011).

The processing of semi-solid foods such as spoonable yogurts and puddings in the mouth is very different from solid foods. As described by Hutchings & Lillford (1988), semi-solid foods are modified in the mouth with the help of the tongue, pressing the food against the hard palate while the structure changes simultaneously. Saliva is secreted when eating semi-solid foods. Nevertheless, the effect of saliva on food cohesion is not the same as in solid foods, as Laguna et al. (2021) reviewed.

Although widely accepted, the function of the tongue when eating semi-solid foods has not been extensively investigated. Takahashi & Nakazawa, (1991) studied gels with different gelatin content and changes in palate pressure during eating. Although the study was conducted with a small sample size (n=2), it gave indications of the tongue's function when eating different gels with varying gelatin content (1−5%). The researchers suggested that concentrations lower than 4% would be crushed with the tongue, whereas teeth would break down concentrations higher than 4%. Ishihara et al. (2011) studied the activity of muscles coordinating tongue movements (n=9) electromyographically while consuming soft gels. Significant differences were found in the processing times of the gels in the mouth. The gels containing the same gelling agent were evaluated to be thicker and stayed in the mouth longer than the softer gels. They also concluded that the tongue seemed to be working continually during eating, i.e., there were no significant intervals in the tongue activity. In addition, no difference was observed in tongue activity during swallowing food and the masticating that takes place before swallowing, which means that the mastication and swallowing of food can happen simultaneously.

de Wijk et al. (2008) studied movements in the mouth while dairy puddings varying in viscosity, oil content, and roughness were masticated by participants (n=9). They captured the force of tongue and jaw muscles during eating by vibromyographic measurement. They demonstrated that the tongue and jaw movements change despite relatively small viscosity, oiliness, and roughness differences. For example, an increase in oil content caused decreased tongue activity, while increasing roughness increased tongue activity. Moreover, they also studied pleasantness and tongue movements. They concluded and showed that weak tongue movement after one second of placing the food inside the mouth was connected to a greater liking of the food. Thus, the tongue and mouth movements are affected by the texture of the food, such as viscosity, roughness, and hardness, as well as by pleasantness (de Wijk et al., 2008; Ishihara et al., 2011).

2.1.3 Factors contributing to texture

Several factors, both product and subject related, can influence texture perception. They can affect texture perception indirectly or directly, and some factors influence each other, making the process complex. **Table 4** highlights selected factors in each category. There is strong evidence from some of these factors and only weak evidence from some. The extensive literature demonstrates various product ingredients that are important determinants of the structure and thus influence texture perception—for example, thickeners, type of starch, oil, and water. Fat level is suggested to influence mouthfeel (de Wijk et al., 2006) and thermal perception (Engelen et al., 2003).

Texture can be also perceived outside the mouth by the appearance. Before the food enters the mouth, visual cues such as color and heterogeneity of the food product provide information on the texture. Santagiuliana et al. (2019) concluded that both visual and oral sensory cues impact texture and flavor perception of model cheeses. Furthermore, information can be obtained by handling the food, e.g., mixing the food by spoon or cutting an apple with a knife (Seppä et al., 2012).

Physiological factors, such as saliva amount and composition, have been widely studied. Oral processing behavior may impact the texture perception. For example, Devezeaux de Lavergne et al. (2015) suggested that different eating durations impact texture perception due to altered bolus properties in sausages. Jeltem et al. (2015) demonstrated that mouth behavior is actually the main driver of food choice after the food texture. Aguayo-Mendoza et al. (2019) stressed that rheological and mechanical properties of food determine oral processing behavior. There are still relatively few studies on the texture sensitivity in participants. However, Breen et al. (2019) studied the oral somatosensory acuity in participants eating chocolate. They concluded that it is related to particle size perception, whereas regarding chemesthesis there is more evidence on individual differences in the perception of astringency. For example, Roukka et al. (2021) concluded that people can be classified into different oral chemesthesis sensitivity groups based on their chemesthetic modality -specific intensity ratings.

Furthermore, the emotional state of the person eating the food, their social background, the time of day and their expectations could have an impact on food. A recent study by Ketel et al. (2020) studied the texture sensitivity between Dutch and Chinese participants, and no differences in the thickness sensitivity, saliva flow rates or lingual tactile thresholds between Dutch and Chinese participants were found. Personal characteristics, product information and food culture on consumer responses are discussed in more depth in the **section 2.3.**

Table 4. Classification of selected and possible factors affecting texture perception of food. Adapted from particularly (Cardello & Meiselman, 2018; Engelen et al., 2003; Piqueras-Fiszman & Spence, 2015).

Instrinsic product factors	**Extrinsic product factors**
Ingredients	Appearance
Fat	Packaging
Taste	Handling of the sample
Aroma	Cutlery, e.g., size of spoon
Production	Auditory cues from the sample
Modifications after production	
Temperature	
Particles	
Physiological characteristics	**Context factors and Personal characteristics**
Saliva	Environment: lightning, background noise, etc.
Mouth behavior	Product information
Swallowing	Culture
Dentition	Expectation
Sensitivity of the mouth	Time of day
Thermal perception	Mood, emotions
	Gender, age
	Personality, Attitudes

Aroma, taste, and texture interactions

Interactions between texture and aroma can originate from physicochemical and cognitive factors. These can be learned associations between the stimuli, our expectation, and the attention given to the stimuli (Knoop, 2011; Lawrence et al., 2009). The impact of texture on aroma release is well known (Pangborn & Szczesniak, 1974). There is a decrease in aroma and taste perception due to the increased viscosity, e.g., by adding hydrocolloids. This results in lower volatile mobility at the food–air interface (Pangborn et al., 1993). The same phenomenon has been demonstrated in many food matrices (Baines & Morris, 1987; Cook et al., 2003; Kälviäinen et al., 2000; Koliandris et al., 2010; Lethuaut et al., 2003; Saint-Eve et al., 2006). There is still a limited number of studies on whether this effect can be reversed, with aroma influencing the perceived texture of food. The addition of aromas could be a tool to overcome undesired texture characteristics, for example, in sugar, salt, and fat-reduced products, but also PB alternatives with weak consumer acceptability.

Some aroma–texture interactions have been proved with varying aroma compounds and foods (Bult et al., 2007; de Wijk et al., 2003; Kora et al., 2003; Roudnitzky et al., 2011; Saint-Eve et al., 2004; Weel et al., 2002). For instance, Saint-Eve et al. (2004) demonstrated how fruity aroma decreased thickness perception in low-fat stirred yogurts. In addition, the taste–texture interaction in model dairy desserts is more studied than aroma–texture interactions. For example, a study by Lethuaut et al. (2003) observed an interaction between sucrose and thickness perception, but no common rule was applied. **Table 5** presents examples of aroma, taste, and texture interactions in liquid and semisolid foods.

Table 5. Examples of aroma, taste and texture interactions in liquid and semi-solid food products. GDA refers to generic descriptive analysis.

Sensory relationship	**Food product**	**Variables**	**Panel and Method**	**Effect**	**Reference**
Taste - texture	Model dairy desserts	Sweetness and carrageenan composition	*n*=19, trained panel	Sweetness–texture interaction was observed. Sucrose concentration increased mouthfeel attribute intensities.	Lethuaut et al., 2003
Flavor – oral texture	Vanilla custards	Diacetyl, benzaldehyde, vanillin, caffeine	*n*=7, trained panel	Some flavorants resulted in increased viscosities, whereas others resulted in decreased viscosities	de Wijk, et al., 2003
Aroma – oral texture	Milk-like foods	Cream odor (butter buds) and thickeners (spatial and time)	*n*=11, trained panel, Gaseus pulps (retro-ortho) and mouth	The odor stimulus increased the intensities of thickness and creaminess (retronasally and swallowed).	Bult et al., 2007
Texture - taste	Model dairy desserts	Benzaldehyde, two levels of sweetness	*n*=61, consumer panel	Texture and aroma did not interact, but taste–aroma interactions were detected	Tournier et al., 2009
Olfaction - taste, trigeminal and texture	Viscous model system	Olfactory (odorants peach and mint), taste (citric acid), trigeminal (cooling agent).	*n*=10, trained panel	Olfaction had an impact on coldness/trigeminal	Labbe et al., 2007
Olfaction - texture	Low fat stirred yogurts	Six aroma compounds	*n*=16, sorting, free choice profiling, GDA	Yogurts presenting fatty notes were perceived as thicker. Yogurts flavored with a mixture of aromas were perceived as thinner compared to those flavored with only one aroma compound.	Saint-Eve et al., 2004
Texture - taste, flavor	Model cheese	Dry matter, fat, salt, (blue cheese aroma with propylene glycol)	*n*=10, GDA	Olfactory perception modified texture perception, but only for model cheeses with low fat and low dry-matter conditions	Saint-Eve et al., 2009
Texture-taste, texture-aroma, and aroma-taste	Custard desserts	Varying viscosities	*n*=77, consumer test	Taste and aroma did not impact texture perception, texture affected the taste but not the aroma intensity	Tournier et al., 2009
Ortonasal and retronasal – tactile	Milk and thickened milk	Butter aroma	*n*=18, psychophysical and an electrophysiological method	Interaction occurred between texture and odor, with cross-modal interaction found for both ortho and retronasal olfactory	Roudnitzky et al., 2011
Texture - taste	Viscous solutions	Dextran and guar gum (polysaccharides)	*n*=9, trained panel	Saltiness perception was related to low shear viscosity	Koliandris et al., 2010

2.2 Plant-based yogurts

2.2.1 Overview

In recent years, consumer demand for cow's milk alternatives has increased due to the rising awareness of sustainable food production and medical reasons such as lactose intolerance and milk allergies. Specifically, the market is developing rapidly in western countries as PB alternatives are gaining popularity. An excellent example is fermented PB semi-solid yogurt alternatives which have recently challenged dairy-based yogurts. Consumers often choose PB yogurts as a substitute for dairy yogurt. They can offer a sustainable option, particularly when formulated into nutritionally adequate products (Mäkinen et al., 2016). The design of PB yogurts has gained high appeal due to the new possibilities offered by the worldwide market (FONA 2018; Montemurro et al., 2021). Moreover, developing countries consider PB yogurts an economical alternative to dairy products (Coda et al., 2017). Dollar sales of PB yogurt grew 76% over 2018−2021 in the US. The market is expected to grow in Europe and in the US at least until 2030. In addition, over the past 15 years the number of Americans following PB diets has increased 300% (FONA 2021; Craig & Brothers, 2021).

Table 6 shows the literature on PB yogurts from 2010 to 2022. Most of the published literature relates to various technological aspects like fermentation, development processes, and physicochemical properties of PB yogurts. Less studies has focused on sensory perception and consumer acceptance of the products and only a tiny part of the published papers on PB yogurts are about oat-based yogurts. In addition, most of the research is on liquid drinkable PB yogurts (these are not included in **Table 6**).

Table 6. Research publications on plant-based (PB) yogurts published between 2010 and 2022, with the main ingredient and focus of the research included. The listed publications are limited to semi-solid yogurts, and liquid yogurts are not included.

Ingredient	Focus of the research	Reference
Oat	Physicochemical, consumer	Walsh et al., 2010
Soy	Fermentation	Park et al., 2012
Soy	Sensory, consumer	Al-Nabulsi et al., 2014
Almond	Development	Bernat et al., 2015
PB review	Overview	Mäkinen et al., 2016
Lupin	Physicochemical	Hickisch et al., 2016
Peanut	Technological	Bansal et al., 2016
Cereal-based	Fermentation	Peyer et al., 2016
Maize	Fermentation	Descalzo et al., 2018
PB review	Overview	Jeske et al., 2018
Quinoa	Development	Zannini et al., 2018
Soy	Fermentation	Hwang et al., 2018
Oat	Overview	Brückner-Gühmann et al., 2019
Oat	Development	Brückner-Gühmann et al., 2019
Brown rice	Development	Cáceres et al., 2019
Soy	Fermentation	Rui et al., 2019
PB review	Overview	Min et al., 2019
Several different	Physicochemical, sensory	Grasso et al., 2020
Coconut	Physicochemical, sensory	Amirah et al., 2020
Soy	Technological	Dias et al., 2020
Millet	Technological	Song et al., 2020
Quinoa	Development	Väkeväinen et al., 2020
Oat	Physicochemical	Raikos et al., 2020
Potato	Technological	Levy et al., 2021
PB review	Overview	Montemurro et al., 2021
Several different	Consumer acceptance	Gupta et al., 2021
PB review	Nutrition	Boukid et al., 2021
Coconut	Physicochemical, sensory	Pachekrepapol et al., 2021
Oat	Heat treatment	Demir et al., 2021
Several different	Nutrition	Craig & Brothers, 2021
Pea	Nutritional, technological	Pontonio & Rizzello, 2021
Several different	Sensory & physicochemical	Gupta et al., 2022
Several different	Quality & consumer	Gupta et al., 2022
Potato (PI)	Technological	Levy et al., 2022
Soybean and quinoa	Physicochemical, sensory	Huang et al., 2022

2.2.2 Composition

PB yogurts are formulated globally from cereals such as oat, rice, maize, wheat, and barley. Additionally, coconut, almond, and cashew are employed, while a significant number are formulated from legumes like soy, pea, fava bean, and hemp protein or have a blend that includes a legume. According to Craig & Brothers (2021), around one-third of PB yogurts in the western US have 5g or more of protein per serving, while a small number (4%) have 10–

11 g protein/serving. Usually, products including a legume have higher protein levels, and oat-based yogurts have lower protein levels, than other plant ingredients. **Table 7** compares the nutritional values of dairy, oat- and soy-based yogurts. It is evident from the table that the protein content in oat yogurt is typically significantly lower, and carbohydrate and fiber typically higher than in soy and dairy. Due to their high solubility in water, foaming properties, and emulsifying activities, plant-protein isolates are considered texture improvers. To obtain a protein network similar to dairy yogurt, the technological potential of different plant-protein isolates as structuring agents have been investigated by several authors (Montemurro et al., 2021). The use of oat protein concentrate and oat protein isolate was proposed by Brückner-Gühmann et al. (2019). Protein-rich fractions from legumes, lupin protein isolates (Hickisch et al., 2016), and potato protein isolates (Levy et al., 2021) have been used successfully in PB yogurts.

Oat is a high-protein cereal that grows well in northern regions (Mäkinen et al., 2016), and is employed for making PB yogurt beverages (Åman et al., 2004; Coda et al., 2017; Luana et al., 2014; Walsh et al., 2010). Oat is a good source of unsaturated fatty acids, high quality proteins, and antioxidants (e.g., phenolic compounds and avenanthramides) (Luana et al., 2014). In addition, β-glucans—soluble fiber found in oat—have positive health benefits such as reducing blood glucose levels after meals and reducing blood cholesterol (EU, 2020). Nevertheless, due to the unpleasant off flavor resulting from lipolytic enzymes in oat-based dairy alternatives, thermal treatment is usually needed to increase sensory acceptability (Molteberg et al., 1996; Montemurro et al., 2021). **Table 8** shows the nutritional values of commercial flavored oat-based yogurts in the US and Finland, demonstrating minor differences, including lower fat and carbohydrate contents of the yogurts in Finland compared to the US yogurts.

To compare with oat, soy is the most used plant-protein source in the food industry due to its low production costs and good nutritional value (Al-Nabulsi et al., 2014; Montemurro et al., 2021). Its benefits include high protein content and quality, functional properties (Phillips et al. 2011), and the ability to be fermented. However, it has some challenges, e.g., allergens, beany flavor, consumer attitudes toward GMOs (genetically modified organisms) and sustainability issues related to the production chain (Heron et al., 2018; Montemurro et al., 2021).

Table 7. Protein, fat, carbohydrates, sugar and fiber content (g/100g) in various non-flavored dairy, oat and soy yogurts. Various dairy yogurts with fat level between 1.5−4g/100g are included in the table.

Yogurt type	Protein, g/100g	Fat, g/100g	Carbohydrates, g/100g	Sugars, g/100g	Fiber, g/100g	Reference
Dairy	8.7	4.0	n/a	2.7	0	Gupta et al., 2021
Dairy	5.1	1.5	6.1	6.1	0	Grasso et al., 2020
Dairy	4.2	2.5	5.0	5.0	0	Fineli, 2022
Dairy	3.0	2.4	4.8	4.8	0	Fineli, 2022
Dairy	3.0	3.5	4.8	4.8	0	Fineli, 2022
Dairy	3.0	3.9	4.8	4.8	0	Fineli, 2022
Mean	*4.5*	*2.8*	*5.1*	*4.7*	*0.0*	
Oat	2.5	1.8	11.2	1.6	1.5	Fineli, 2022
Oat	2.2	0.8	8.4	2.3	1.0	Fineli, 2022
Oat	1.7	2.3	9.9	0.2	1.3	Fineli, 2022
Oat	2.1	1.9	12.0	2.5	0.13	Fineli, 2022
Oat (20)**	3.0 (3–3)	3.5 (3.0–4.8)	19 (19–20)	9 (7–9)	1.0 (1–2)	Craig & Brothers, 2021)
Mean	*2.0*	*1.7*	*9.8*	*1.7*	*0.9*	
Soy	4.9	3.9	n/a	1.7	n/a	Gupta et al., 2021
Soy	4.0	2.3	2.1	2.1	1.0	Grasso et al., 2020
Soy	4.6	2.6	1.0	0.4	0.1	Grasso et al., 2020
Soy	6.2	3.4	2.5	2.5	1.5	Fineli, 2022
Soy(11)**	6.0 (6–6)	3 (2.5–3.5)	20 (18.5–23.5)	9.0 (7–9)	1 (1–2)	Craig & Brothers, 2021
Mean	*4.9*	*3.1*	*1.9*	*1.7*	*0.9*	

Table 8. Protein, fat, carbohydrate (carboh.), sugar and fiber content (g/100g) of commercial flavored plant-based oat yogurts in the US and Finnish markets.

United States	Protein, g/100g	Fat, g/100g	Carboh., g/100g	Sugar, g/100g	Fiber, g/100g
Chobani, Vanilla	2.0	2.0	14.0	8.7	0.7
So Delicious, Strawberry-Rhubarb.	2.0	0	11.3	6.0	1.3
Oatly, Strawberry	2.0	4.7	14.7	7.3	0.7
Nancy's, Vanilla	4.0	6.0	12.7	5.3	2.0
Mean	2.5	3.2	13.2	6.8	1.2
Finland					
Oddlygood, Raspberry	1.2	1.4	15.0	8.4	n/a
Fazer Aito, Strawberry-Banana	3.5	1.8	9.9	5.4	0.9
Elovena, Strawberry	1.4	2.9	15.0	8.5	0.7
Planti, Strawberry-Lemon	3.5	1.9	10.0	8.1	n/a
Mean	2.4	2.0	9.9	7.6	0.8

The nutritional value of PB yogurts is mainly due to the raw materials that form their structure. Many PB yogurts claim that they are fortified with calcium, iodine, and B12 vitamins. However, a study by Craig & Brothers (2021) showed that the majority of the non-dairy yogurt alternatives in the US were not fortified: only 45% of the PB yogurts had calcium levels fortified to at least 10% of daily value (DV), while only about one in five had adequate vitamin D and B12 fortification at the 10% DV level. They found that yogurts based on oat, soy, or a coconut–legume mix had the best fortification levels. Furthermore, the numbers for % (DV) are often rounded to the nearest 5% in the US. Additionally, numbers are rounded without decimals for macronutrients, such as sugars, fats, protein, and dietary fiber. This procedure contrasts with European practices, where decimals commonly appear on the nutrition label (Craig & Brothers, 2021).

2.2.3 Production

In recent years, PB yogurt with a comparable protein structure to dairy yogurt has been attempted to be developed. Nevertheless, the low protein content and different coagulation properties of plant ingredients make the process more challenging and time-consuming. Therefore, the optimal texture in PB yogurts is usually achieved with additives like hydrocolloids, protein extracts, and emulsifiers. Nevertheless, these do not always meet the growing trend of clean-label products (Food product with the label not listing ingredients that may be perceived by consumers as undesirable) (Jeske et al., 2018). The functional properties inherent to PB ingredients often possess a lower gelling strength compared to animal-based systems; hence, the gelling structures are enhanced through the use of hydrocolloids (Brückner-Gühmann, Banovic, et al., 2019; Ercili-Cura et al., 2015; Jeske et al., 2018; Martens, 1992).

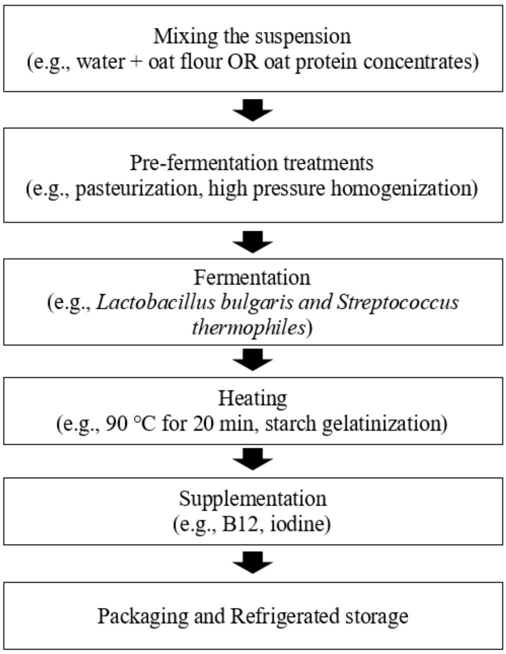


Figure 2. An example of a simplified flow chart of processing plant-based oat yogurt. Adapted from the Bruckner et al. (2019), Montemurro et al. (2021) and Demir et al. (2021).

Fermentation has been widely explored with plant-derived ingredients (Gobbetti et al., 2019). It has been observed to positively affect such ingredients' nutritional, sensory, and technological properties. Thus, the proper selection of microbial starters is of primary importance in obtaining high-quality products (Leroy & de Vuyst, 2004). Lactic acid bacteria are considered the best candidates for PB yogurts due to their safe and traditional use in food fermentations (Montemurro et al., 2021). In conventional yogurts, fermentation of cow milk is usually done by *Streptococcus thermophilus* and *Lactobacillus delbrueckii subsp. bulgaricus* until the pH is lower than 4.5. The same starters are usually used for PB yogurts, which are generally made by fermenting aqueous extracts or flour–water suspensions of cereal, pseudo cereals, legumes, and flours (Mäkinen et al., 2016). **Figure 2** presents a possible process flow of an oat-based yogurt adapted from Brückner-Gühmann et al. (2019) and Montemurro et al. (2021).

Moreover, a proper heat treatment is required to gelatinize the starch to increase the viscosity of the final product. This is usually conducted before the fermentation (Coda et al., 2012; Pontonio & Rizzello, 2021). The process is influenced, for example, by the starch content and the branching of the molecule (Lund, 1984). Furthermore, various combined technologies have been reported. For instance, high-pressure homogenization coupled with thermal treatment led to the best texture of an almond PB yogurt (Bernat et al., 2015). Another study reported that homogenization reduced droplet size, which increased protein solubilization in soy yogurts (Cruz et al., 2007).

2.2.4 Physicochemical properties

Rheology is often used to understand the texture properties of various yogurts. Thus, rheological parameters are often linked to sensory properties. There is extensive literature exploring the relationship between dairy yogurts' rheological properties and sensory attributes (Cutler et al., 1983; de Wijk et al., 2003; Ercili-Cura et al., 2015; Frøst & Janhøj, 2007; Harte et al., 2007; Janssen et al., 2007; Jørgensen et al., 2015; Nguyen et al., 2017; Sonne et al., 2014). Other physicochemical parameters have also been successfully linked to mouthfeel in dairy yogurts. Particle size–related parameters have been shown to influence the creamy mouthfeel (Kilcast & Clegg, 2002; Krzeminski et al., 2013; Laiho et al., 2017; Lett et al., 2016; Sonne et al., 2014). In addition, reducing sugar in dairy yogurt has been shown to decrease viscosity, resulting in a thin and watery mouthfeel (Sodini et al., 2004).

There is less evidence of the connection between physicochemical parameters and sensory properties of PB yogurts. Huang et al. (2022) studied the physicochemical and sensory properties of quinoa-fortified soy yogurts. They concluded that quinoa enhanced the textural and rheological properties of the yogurt. Furthermore, starch, the primary component in carbohydrates, has been proven to increase storage modulus (G′) by formatting a network gel-like structure in dairy and coconut yogurts (Pachekrepapol et al., 2021). Grasso et al. (2020) studied the physicochemical and sensory properties of commercial PB yogurts made from soy, coconut, cashew, almond, hemp, and a reference dairy yogurt. They showed that one of the soy-based yogurts was similar to the dairy yogurt in apparent viscosity and water-holding capacity. Nevertheless, other PB yogurts, e.g., hemp yogurts, showed different rheological and textural parameters to the other PB products, connecting this to the agar and rice starch components of the hemp formulation. Their results emphasize that hydrocolloids in formulation significantly affected the rheology in PB yogurts (Foster & Wolf, 2010; Grasso et al., 2020).

Many studies explore the consumer acceptance and physicochemical properties of different PB yogurts (Brückner-Gühmann, Banovic, et al., 2019; Grasso et al., 2020; Mårtensson et al., 2001; Gupta et al. 2021). Brückner-Gühmann et al. (2019) investigated rheological properties, sensory perception, and consumer acceptability of lactic acid fermented, oat-based gels. They demonstrated that a gel with a higher total solids content was perceived as creamier than a gel with a lower total solids content. A recent study aims to understand the sensory acceptability and textural properties in Australian commercial dairy and PB samples (Gupta et al. 2021). The selected soy, coconut, and dairy yogurts showed wide variations in their microstructure and rheology. Notably, these previous studies did not include oat-based yogurts in their experiments.

2.2.5 Sensory quality

The sensory properties of PB yogurts are strongly affected by their ingredients and formulations. Plant matrices are usually characterized with attributes such as bitter, beany, astringent and off flavor (Cheng et al., 1990). Other characteristics used for PB ingredients include "earthy," "dairy," "cereal," or "savory" attributes (Lorusso et al., 2018). Some unpleasant odors and flavors have been associated with the unprocessed forms of plant ingredients (Craig & Brothers, 2021; Montemurro et al., 2021). For example, "bitterness" could derive from phenolic compounds found in the outer layers of whole grains (Peyer et al., 2016). In particular, in oat, a suitable heating treatment is used to inactivate lipolytic enzymes. If this is not done, the oat will remain bitter in taste (Klensporf & Jeleń, 2008). Thus, in most cases, PB yogurts are flavored with various aroma compounds that mask the unpleasant off flavors. Craig & Brothers (2021) observed that PB yogurts are flavored with over 35 various flavors in the US. Wu et al. (2005) reported that the inclusion of strawberry or orange jam in a soy yogurt improved the overall acceptability, flavor, aroma, and taste compared to the unflavored control. Grasso et al. (2020) found out that flavored yogurts (soy- and coconut-based) were similar to dairy yogurt in all sensory descriptor results (appearance, odor, flavor, texture, and overall acceptability). They suggested that sugars and fruity aromas probably played a prominent role in masking unusual smells and flavors of the products. It is evident that different consumer groups appreciate different kinds of products. Furthermore, volatile compounds are responsible for odor perception. Many of the volatile organic compounds in PB yogurts can be found in dairy yogurts. For example, diacetyl, acetaldehyde, acetone, and ethanol are found in both types of yogurts (Irigoyen et al., 2012; Montemurro et al., 2021).

From a product perspective, properties such as visual appearance, flavor, and texture are of primary importance to establish consumer sensory and hedonic responses (Pascua et al., 2013; Wei et al., 2012; Wilkinson et al., 2000; Zellner et al., 2010). Typically taste and flavor properties are stressed over texture properties in sensory evaluations. Nevertheless, a few studies have focused on the texture properties of PB yogurts. For example, Demir et al. (2021) studied the constancy on the spoon and consistency in the mouth of oat-based yogurts with a trained panel. Brückner-Gühmann et al. (2019) studied chewy, adhesive, sticky, creamy, smooth, and dry mouthfeel attributes in oat-based gels using the CATA (Check-all-that-apply) method with consumers. Some challenges appear in the sensory evaluations conducted for PB yogurts. For example, the panel size is often too small to provide valuable results, or hedonic responses are studied with a trained panel. **Table 9** shows sensory characteristics and evaluation methods used with various PB yogurts.

Table 9. Yogurt type, sensory characteristics, and used sensory evaluation methods with various plant-based yogurts.

Yogurt type	Characteristics	Sensory evaluation method	Reference
Oat yogurt	Appearance, consistency on the spoon, consistency in mouth, flavor, acidity, oat-like flavor, overall acceptability	Trained panel, 9-point hedonic scale, *n*=7	Demir et al., 2021
Oat-based gels	Overall liking	9-point hedonic scale, *n*=101	Brückner-Gühmann et al., 2019
	Bitter, sour, soft, moist, chewy, adhesive/sticky, creamy, oat, salty, sweet, dry mouthfeel, porous, intense taste, chalky, smooth, floury	CATA, *n*=101	
Soy yogurt	Sour, bitter, astringency, beany, butter, raisin, yogurt, firm, smooth	Trained panel, 5- and 7-point intensity scales, *n*=10	Cheng et al., 1990
Soy yogurt	Color, flavor, aroma, taste, texture, consistency and overall impression	9-point hedonic scale, *n*=61	Al-Nabulsi et al., 2014
Coconut yogurt	Overall liking	9-point hedonic scale, *n*=40	Amirah et al., 2020
Coconut yogurt	Flavor, aroma, color, texture, overall acceptability	9-point hedonic scale, *n*=30	Pachekrepapol et al., 2021
Coconut, soy, cookies, berry yogurts	Overall liking, emotions	9-point hedonic scale, CATA (emojis), facial expressions, *n*=62	Gupta et al., 2022
Soy, coconut, almond, cashew, hemp yogurts	Appearance, odor, flavor, texture, overall acceptability	Hedonic test, 0–10-line scale, *n*=25	Grasso et al., 2020
Almond, soy, coconut yogurts	Sweet, sour, aftertaste, mild aroma, strong aroma, thick, runny, lumpy, good texture, bad texture, heavy, light, creamy, smooth, grainy, chalky	Perceptual mapping, *n*=32	Gupta et al. 2021
Almond, soy, coconut yogurts	Odor, appearance, taste, overall liking, mouthfeel	9-point hedonic scale, blinded, *n*=117	Gupta et al. 2021

2.3 Factors contributing to consumer responses

2.3.1 Demographics

Consumer acceptance of food depends on several factors, consumers' demographics and personal characteristics being of primary importance. Age is a significant predictor of food preference and choice, specifically in children and older people (Rozin, 2007). The sense of smell is also affected by aging, resulting in altered flavor perception. There are minor gender differences in the ability to identify basic tastes, expect in bitterness (Michon et al., 2009), and preference for sweetness is more common among women.

Food preferences develop from an early age. Preferences established as early as two years of age can predict preferences in later life (Michon et al., 2009). Moreover, a new study by Ustun et al. (2022) showed that the diet of pregnant women already exposes fetus to various flavors. The study has important implications for understanding the earliest evidence for fetal abilities to sense and discriminate different flavors. Furthermore, Michel et al. (2021) demonstrated that being younger was associated with higher taste, healthiness, and environmental friendliness ratings for the pea burger. The finding might be attributed to young people being more open and interested in trying new food and thus being already more likely to consume meat alternatives (Hoek et al., 2011; Siegrist & Hartmann, 2020; Slade, 2018). In addition, a report on the vegan yogurt market declared that PB yogurts are particularly popular among millennials (Vegan Yogurt Market, 2020).

As age is the important driver of food preference, it is essential that sensory scientists are able to measure preferences of consumers in different age groups. Laureati et al. (2020) developed a child-friendly tool to explore individual differences in texture preferences. The tool identified subgroups of children (9–12 years) with different texture preferences (hard- vs. soft-likers). They found that hard-likers were less neophobic and consumed more healthy food than soft-likers.

Some differences in gender have also been found concerning food preference (Rozin, 2007). Men and women differ in terms of preferences for food with different sensory properties. Women are more likely to choose pale, bland food and foods that are associated with healthiness, while men may favor rich, strong tastes, red meat, and higher fat products (Kähkönen & Tuorila, 1999). Furthermore, Siegrist et al. (2015) demonstrated that women show more sustainable food consumption patterns than males.

2.3.2 Food culture

Culture, through a combination of environment, mobility, and economic and political systems, strongly influences food preferences (Mela, 1999) and is probably the best predictor of food preferences or attitudes (Rozin, 2007). Different textures in different cultures are favored, such as stickiness in Japan (Tanaka, 1986). Preferences for certain flavors, for example, can even be seen internationally in the types of dishes that are traditional in countries.

Consumer studies are more and more executed in multiple countries due to the possibility of conducting online surveys. Moreover, the increased interest in the global market potential of food products has led to an increased number of cross-cultural studies (Slater & Yani-de-Soriano, 2010). Michel et al. (2021) studied meat eaters' attitudes and expectations for burgers containing beef, pea, or algae protein in Germany, France, and the United Kingdom and noticed that the country did not significantly influence the expectation for the burgers. Laureati et al.

(2020) identified country-related differences in children's texture preferences. Finland and Sweden had a higher proportion of children with a tendency to prefer hard and particulate food than Southern countries, like Italy and Spain. Furthermore, Cattaneo et al. (2020) studied oral processing behaviors across Chinese and Danish consumers. They concluded that Asian and Caucasian populations differed in oral food processing behavior, and Asians were characterized by larger numbers of "soft processing likers." Cross-cultural research has received criticism that there is a lack of studies from Asian or African countries, as most studies in this field have been conducted in developed countries, primarily in selected European countries or North America (Siegrist & Hartmann, 2020).

2.3.3 Product information

Information about food can influence consumer behavior and food liking. Product information usually comes from various sources: the brand, the label, nutrition claims, information about technology, or processing and advertising (Cardello & Schutz, 2005). The possible link between information and its effect on hedonic ratings of food is through the consumer's expectations.

Descriptive information, like product information, has a more significant role in unfamiliar new products than in familiar food products (Piqueras-Fiszman & Spence, 2015; Shankar et al., 2009; H. Tuorila et al., 1998; Vidal et al., 2013). For example, the product's name has been shown to affect the liking ratings of foods (Guinard et al., 2001; Hubbard et al., 2016; Liu et al., 2017; Pliner & Pelchat, 1991; Torres-Moreno et al., 2012). Torres-Moreno et al. (2012) evaluated the influence of label information on dark chocolate acceptability and demonstrated that premium brands generated higher expectations than store brands. Nevertheless, there are fewer studies on the impact of product information on sensory responses like perceived texture properties. Adise et al. (2015) investigated consumers' willingness to try animal and vegan versions of foods (chocolate milk, macaroni, cheese, chicken tenders, or meatballs) that they were told were vegan substitutes for animal products or actual animal products. They found that respondents liked foods more if told they were vegan. Siegrist (2008) highlighted that to increase acceptance of novel foods, credible information and education regarding the benefits have to be provided, not just the results of the studies.

2.4 Sensory methods relevant to this study

2.4.1 Temporal dominance of sensations

Since food texture is a multidimensional sensory property (Szczesniak, 2002), temporal methods, e.g., temporal dominance of sensations (TDS), have been developed to study the dynamics of eating (Lawless & Heymann, 2010; Pineau et al., 2009). TDS is a sensory method that studies the sequence of dominant sensations of a product during a specific period (di Monaco et al., 2014; Pineau et al., 2009). It focuses on the determination of the most "dominant" sensation over time (Pineau et al., 2009) or the sensation that catches the most attention at a time point during mastication. In a TDS evaluation, typically the sample is placed in the mouth and a panelist selects the most dominant attribute from a list of attributes during mastication. In general, the list of attributes is randomized and balanced across participants, and it is recommended that the list of attributes should not be longer than 8–10 attributes (Pineau et al., 2009). TDS results are usually presented as curves on a plot, where the y-axis represents the dominance rate (the percentages of assessors who chose the same dominant attribute simultaneously) and the x-axis represents the time presented in seconds or standardized across participants (Pineau et al., 2009). Usually, two levels are marked on the curves to aid in the interpretation of the curves: the chance level (p_0), the dominance rate below which an attribute was obtained by chance, and the significance level (P_s), the minimum dominance rate level to be considered significantly higher than p_0.

TDS helps to show the interactions between the attributes and sequences of sensations (Déléris et al., 2011; di Monaco et al., 2014). When TDS is conducted with another sensory methodology (e.g., descriptive analysis), it is more effective than TDS alone and adds an extra dimension to the sensory evaluation of foods (Labbe et al., 2007). For example, Velázquez et al. (2020) used TDS to study the sugar reduction in vanilla milk desserts in children. In another work, TDS showed its potential to underline aroma–taste interactions during coffee drinking by pairing TDS with in vivo nose-space measurements (Charles et al., 2015). Saint-Eve et al. (2011) concluded that time-dependent methods could help understand the relationship between cross-modal interactions. They studied the texture–aroma interaction in model candies, using TDS associated with descriptive analysis. Furthermore, a review of aroma perception in dairy products showed that temporal methods could provide accurate descriptions of aroma perception (Gierczynski et al., 2011).

There has been a continuous dialogue on the meaning of dominance and how the evaluation practices and results of TDS should be interpreted when conducted with a trained panel versus consumers (Nguyen et al., 2018; Varela et al., 2018). The method is still undergoing improvements, particularly in data analysis. An example of using TDS data is to study the temporal drivers by considering the TDS data as CATA data and using penalty-lift analysis, as proposed by Ares et al., 2014; Meyners (2016).

2.4.2 Descriptive sensory profiling

Descriptive sensory profiling is a sophisticated sensory method that results in a specification of the sensory attributes of usually a series of products (Lawless & Heymann, 2010; Stone & Sidel, 2004). Lawless & Heymann state that "it is widely used at various research and product development stages, for example, in quality control, product optimization, and determining sensory-instrumental relationships" (Lawless & Heymann, 2010; Murray et al., 2001). There are various methods of descriptive sensory profiling, including the Sensory Spectrum, Flavor Profile Method, and Quantitative Descriptive Analysis (Lawless and Heymann, 2010). Generic descriptive analysis uses elements of these methods to fulfill specific project objectives (Murray et al., 2001).

In descriptive sensory profiling, a trained panel quantifies the intensity of pre-determined attributes on scales accurately. The panelists (usually 8−20) need to have good sensory acuity and motivation (Murray et al. 2001). Training begins with developing or adapting a shared sensory language or lexicon elicited from exposure to a spectrum of essential and interesting products. Panelists are trained to use a common frame of reference to provide context (Lawless and Heymann, 2010; Murray et al. 2001). The references for attributes are usually a "chemical, spice, ingredient, or a product" used to characterize an attribute or attribute intensity (Rainey, 1986). Reference standards are then used to achieve mutual context. It has been concluded that panels perform better with product-specific standards, while the external standards, e.g., chemical standards, can also be helpful.

Attributes are usually rated on graphic line scales with labeled anchors. Panelists do the evaluation individually, usually in isolated sensory booths. The evaluation session is usually replicated up to four times. The results of descriptive sensory profiling can be presented in the form of "spider-web" or bar charts (Lawless & Heymann, 2010; Stone & Sidel, 2004). Usually, analysis of variances (ANOVA) with repeated measures is performed, where product, panelist, and replication interactions are calculated. Moreover, multivariate methods, like principal component analysis (PCA), are usually used to characterize how products differ across all attributes and products (Lawless and Heymann, 2010). Training a sensory panel usually takes hours, thus the economic and time-consuming aspect of descriptive profiling can be an issue for the food industry and academic organizations (Varela & Ares, 2014).

2.4.3 Rate-all-that-apply, Check-all-that-apply, and Just-about-right scales

Several consumer-based sensory profiling methodologies have been developed as more rapid and flexible alternatives to descriptive analysis (Meyners & Castura, 2016; Varela & Ares, 2014). CATA is gaining popularity and is already widely used in the industry and academia. It is a quick and easy approach to obtain consumer-based sensory product characterization (Ares et al., 2015). CATA questions consist of a list of terms from which consumers select all those that they consider applicable to describe the sample. CATA provides reliable data when applied to a wide range of consumer products (Ares et al., 2015; Jaeger et al., 2013; Meyners & Castura, 2016). A disadvantage of CATA is that it does not allow a direct measurement of the intensity of the sensory attributes, which could potentially hinder discrimination among products that have similar but slightly different sensory characteristics. However, past research has shown that sensory product characterizations elicited from consumers using CATA questions are reliable and comparable to those generated by trained assessors (Dooley et al., 2010; Jaeger et al., 2013; Varela et al., 2018). Self-reported consumer measures confirm that CATA questions are perceived as easy and not tedious (Varela et al., 2018; Vidal et al., 2013).

Ares et al. (2014) introduced the RATA (Rate-all-that-apply) method, which was developed from CATA. Various rating scales are introduced, including a 3-pt intensity scale with anchors 1="low," 2="medium" and 3="high" and a 5-pt applicability scale with end-point anchors 1="slightly applicable" and 5="very applicable." RATA questions have been found to increase the identified differences among samples. Ares et al. (2014) showed that RATA questions led to an increase in the total number of selected terms when compared to CATA. The reduced time investment, costs, and low training requirements of consumers are vital advantages of the

RATA scale. Over the years, RATA has gained in popularity and is currently widely used in academia and industry.

The JAR (Just-about-right) scale measures consumer's reaction to a specific attribute (Lawless & Heymann, 2010; Varela & Ares, 2014). It is a popular scale that combines intensity and hedonic judgments (Rothman and Parker, 2009). The JAR rating scale has been included in the questionnaire, often in conjunction with liking and sensory intensity scales. The JAR scale is bipolar, with the end anchors labeled "Too little" and "Too much" of a specific attribute or a phrase such as "Too sweet" and "Not sweet enough." The center choice is usually rephrased as "just-about-right."

There has been a continuous debate that the JAR could be interpreted as a reference point for intensity rather than acceptance (Gacula et al., 2007). Popper et al. (2004) reported that the presence of JAR questions in the questionnaire affects overall liking. One potential problem is that consumers often show halo effects, in which one crucial attribute can affect the ratings of other, logically unrelated attributes. Another limitation is that JAR scales assume that all the consumers must have a consensus understanding of the evaluated attributes (Rothman and Parker 2009), limiting the use of the JAR scale to a few simple attributes that are widely understood, such as sweetness and saltiness. Furthermore, complex attributes like "creamy," which are made up of several combined qualities, should be avoided.

3 AIMS AND HYPOTHESES

3.1 Aims

This thesis aims to define texture perception and consumer acceptance of plant-based yogurts.

Detailed aims are as follows:

1. To characterize the mouthfeel and physicochemical properties of plant-based yogurts (Studies I-II);

2. To determine the selected factors on texture and mouthfeel perception, including product information, visual experience, added aroma and cross-cultural differences (Studies III and IV);

3. To examine the consumer acceptance of plant-based yogurts among Finnish and US consumers (Studies I and IV);

4. To define the relative importance of different texture properties on overall liking (Studies I and IV).

Four independent research papers (Studies 1-IV) were conducted during this PhD; however, this synthesis does not directly follow the order of the papers.

3.2 Hypotheses

1. Plant-based and dairy yogurts have a similar mouthfeel profile (Study I);

2. The structure of plant-based yogurt varies from dairy yogurt: oat-based structures are predominantly carbohydrate gels and thus provide a fine-stranded network compared to dairy yogurts that provide a distinguishable particle gel system attributed to the network of protein particles and protein-covered fat droplets (Study II);

3. The enhanced sweetness perception by the added aroma enhances the perceived thickness (Study III);

4. Finnish consumers are more familiar with oat-based products than US consumers. Familiarity has a positive impact on the acceptability of plant-based yogurts (Study IV);

5. The first perceived mouthfeel properties during mastication are the key drivers of liking in semi-solid plant-based food. Creaminess is the main driver of liking among texture properties on overall liking (Study I and IV).

4 MATERIALS AND METHODS

4.1 Overview

This thesis is comprised of three sections (A-C); section A investigates the mouthfeel perception and physicochemical properties in PB yogurts (Studies I-II). Section B determines the role of product information (Study IV), visual experience (Study IV), and added aroma (Study III) on mouthfeel perception, and section C examines the consumer acceptance of PB yogurts among consumers in the US and Finland (Studies I and IV). **Table 10** presents the four aims and methods of the thesis under the sections.

Table 10. Methods of the studies divided according to the four aims of the thesis. In particular, the aim (1–4), measurements, and the original articles of each of the studies (I–IV).

Aim		Methods	Studies
Section A: Dynamic mouthfeel perception and instrumental structural properties			
1.	To characterize the dynamic mouthfeel perception and physicochemical properties of plant-based yogurts	1) Dynamic mouthfeel perception: Temporal dominance of sensations (TDS) (n=87) 2) Instrumental structure: Rheological measurements, pH, soluble solids, °Brix (Table 18)	I–II
Section B: The role of selected factors on mouthfeel perception			
2.	To determine selected factors on texture and mouthfeel perception, including product information, visual experience, aroma, and cross-cultural differences	1) Intensity of texture and mouthfeel properties by consumer study (RATA) (*n*=197) 2) Intensity of texture and mouthfeel properties with trained panelists (GDA) and TDS (n=10x4 sessions) 3) Color, volatile profile and apparent viscosity (Table 18)	III–IV
Section C: Consumer acceptance of plant-based yogurts among Finnish and US consumers			
3.	To examine the consumer acceptance of plant-based yogurts among consumers in the US and in Finland	Hedonic responses (9-point hedonic scale), Demographics: consumption habits of the product types, and neophobia (Study I: n=87; Study IV: *n*=197)	I and IV
4.	To define the relative importance of different texture properties on overall liking	Sensory and hedonic responses by consumer study (TDS; CATA; RATA; 9-point hedonic scale). Demographics and attitude scales. (Study I: n=87; Study IV: *n*=197)	I and IV

However, to describe all the material and methods effectively, this chapter follows a different order by first summarizing the study samples, sensory study participants, and procedures of all the sensory studies (Studies I, III, and IV). The instrumental measurements of Study II are described at the end, before the data analysis.

4.2 Yogurt samples

A total of 18 PB and dairy samples were involved in the studies. **Table 11** shows the samples in Studies I–IV. In Studies I–II, seven commercially available dairy or PB yogurts were selected for the study based on preliminary experiments (*n*=10x3). In Study III, the unflavored fermented oat-based yogurt base was flavored with two aroma mixtures provided by Valio (Valio Ltd., Helsinki, Finland). After preliminary experiments (*n*=3), low and high aroma concentrations of vanilla and lemon were included in the evaluation to determine if the aroma's intensity would impact the samples' sensory properties (**Table 11**). For Study IV, blueberry-flavored fermented dairy yogurt (Valiojogurtti®, Valio) and PB yogurt alternative (Oddlygood, Valio) were used. After preliminary experiments (*n*=15), five blended yogurt samples with different plant-to-dairy ratios (PB:D %) were included in the evaluation. **Table 11** shows the PB:D ratios and the product information of the samples. In all the studies, the samples were fermented products. Although the samples are commercially labeled as oat-based yogurt alternatives, in this thesis they are referred to as PB since they also include other PB proteins, e.g., pea and potato protein. **Tables 12** and **Table 13** show the samples' macro components and other additives.

Table 11. The samples in three experimental sensory studies; the number of samples, the codes used in the thesis, product specification and the product information condition in the analysis. Abbreviations D refers to dairy-based and PB to plant-based.

Sample	Code	Product specification	Product information condition
Study I–II: Various unflavored, commercial D (dairy) and PB (plant-based) yogurts			
1	D1	D yogurt	3-digit code
2	D2	D yogurt	3-digit code
3	P1	PB yogurt	3-digit code
4	P2	PB yogurt	3-digit code
5	P3	PB yogurt	3-digit code
6	P4	PB yogurt	3-digit code
7	P5	PB yogurt	3-digit code
Study III: Unflavored PB yogurt base			
8	U-0	Unflavored PB yogurt F, 0.05% water	3-digit code
9	L-1	U-0 + 0.025% lemon	3-digit code
10	L-2	U-0 + 0.05% lemon	3-digit code
11	V-1	U-0 + 0.05% vanilla	3-digit code
12	V-2	U-0 + 0.1% vanilla	3-digit code
Study IV: Blueberry-flavored commercial D and PB yogurt			
13	PB100	100% PB: 0% D	Plant-based yogurt
14	PB75	75% PB: 25% D	Plant-based yogurt
15	PB50	50% PB: 50% D	Plant-based yogurt
16	PB50-D	50% PB: 50% D	Dairy yogurt
17	PB25	25% PB: 75% D	Plant-based yogurt
18	PB0-D	0% PB: 100% D	Dairy yogurt

Table 12. Macro-components, salt, oat, and berry content in the evaluated yogurts in Studies I–IV. Abbreviations D refers to dairy-based and PB to plant-based.

		Fat g/100ml	Carb. g/100ml	Sugar g/100ml	Fiber g/100ml	Proteins g/100ml	Salt g/100ml	Oat content, %	Berry content, %
Study I–II	D1	2.5	4.1	4.1	0	4.2	0.10	0	0
	D2	4	4.1	4.1	0	4.0	0.10	0	0
	P1	2.2	9.9	4.6	1	1.7	0.07	12.0	0
	P2	2.4	11.1	5.2	1	0.8	0.12	8.5	0
	P3	2.5	9.2	4.8	n/a	1.0	0.08	8.0	0
	P4	1.9	12	2.5	0.13	2.1	0.06	12.0	0
	P5	0.8	8.2	2.3	0	2.2	0.09	8.3	0
Study III	Base	0.8	8.2*	2.3*	0	2.2	0.09	8.3	0
Study IV	PB	1	16	9.5	0	1.6	0.08	8.3	4
	D	2	9.6	9.5	0	3.4	0.10	0	5

*In Study III, the listed macro-components in the table are based on the ingredients listed on the package. However, the sample used in the study was not the final commercially available product. Instead, the sample did not include the jam (carbohydrate + sugar), thus the final carbohydrate and sugar contents are lower than listed in the table.

Table 13. The yogurt base, thickeners, stabilizers, and oil content in the samples in Studies I–IV.

	Sample	Base	Thickener	Stabilizer	Oil
Study I–II	D1	dairy	none	none	milk fat
	D2	dairy	none	none	milk fat
	P1	oat base (water, oat 12%), potato protein	potato starch	Calcium carbonate (E170), Tricalcium phosphate (E341)	rapeseed oil
	P2	oat base (water, oat 8.5%)	modified starch, pectin	Potassium sorbate (E202)	canola oil
	P3	oat base (water, oat flakes 8%)	starch (corn, potato), pectin	Tricalcium phosphate (E341)	canola oil
	P4	water, oat 12%, potato protein	starch (tapioca, potato), xanthan, locust bean gum	none	canola oil
	P5	oat base (water, oat 8.2%), pea protein	modified potato starch	none	canola oil
Study III	Base	oat base (water, oat), pea protein		none	canola oil
Study IV	PB	oat base (water, oat), pea protein	corn starch	none	canola oil
	D	milk protein	none	none	milk fat

4.3 Sensory study participants

In Study I, the panel comprised 87 participants aged 20–59 years (**Table 14**). Before the evaluations, participants were informed that the samples would be fermented oat-based and dairy spoonable snacks. In Study III, the panel consisted of 10 members aged 24–29 years (mean value: 25 years). Before entering the panel, the ability to identify basic taste modalities and describe different aromas were tested. The aim of the study was not was not described in detail to the panelists. For Study IV, the recruitment in Finland was conducted according to the demographics in the US study. Before the evaluations, participants were informed that the samples would be plant- and dairy-based yogurts. Participants were recruited from university campuses and local consumer databases of sensory evaluation laboratories in both countries.

Table 14. Number of study participants, training, age, and gender of the panelists in Studies I, III, and IV.

Study	No. of panelists	Training	Age	Gender	Entering criteria
I	87	Semi-trained (10 min)	20–59 y	76 Women, 10 Men 1 N/A	>18 years old and without restrictions related to milk, lactose, or oat
III	10	Trained panel (5.5 h)	24–29 y (mean value 25 y)	9 Women, 1 Men	Detection taste modalities and ability to describe different aromas
IV	197	No training	18–75 y	133 Women, 63 Men, 1 N/A	18–75 years old, regular consumption of dairy yogurts, willingness to eat plant-based yogurts, no allergies

Studies I and III were conducted in the sensory laboratory at the University of Helsinki, Department of Food and Nutrition in Finland, and Study IV was conducted in the multisensory laboratory at the Flavoria® research platform in Turku, Finland, and at the sensory laboratory at the University of Massachusetts Amherst, Department of Food Science, MA, US. Studies I and III followed the ethical requirements of the sensory laboratory approved by the University of Helsinki Ethical review board in humanities and social and behavioral sciences (Statement 15/2020). For the US part (Study IV), the research protocol and panelists' recruitment for the study was approved by the institutional review board (IRB) of the University of Massachusetts Amherst. In Finland, the Flavoria study protocol was reviewed and ethically approved by the Ethics Committee for Human Sciences at the University of Turku, Humanities and Social Sciences Division (37/2021). Studies followed the European Union's General Data Protection Regulation (GDPR).

4.4 Sensory evaluation procedure

Figure 3 presents the flow chart of the three sensory evaluations (Studies I, III, and IV). In order to determine how the temporal mouthfeel profile changes during mastication, temporal dominance of sensations (TDS) was selected. In the TDS (Study I), consumers were instructed to evaluate the texture and mouthfeel properties of the samples during mastication and to select the term that caught their attention at each moment of the evaluation (Pineau et al., 2009). They were instructed to consume the sample for at least 5 s and no more than 40 s. The attributes and scales used are presented in **Table 15** and **Table 16**, respectively.

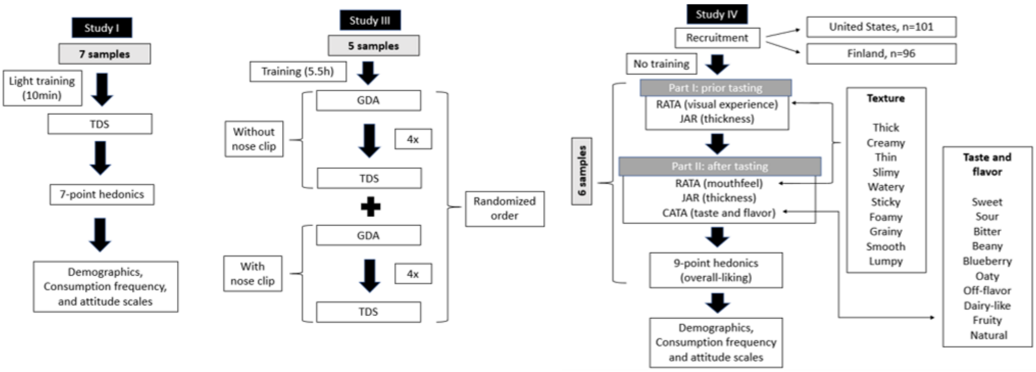


Figure 3. Flow chart of the three experimental designs for Studies I, III, and IV. CATA refers to Check-all-that-apply, GDA to generic descriptive analysis, JAR to Just-about-right, RATA to Rate-all-that-apply, and TDS to Temporal dominance of sensations.

Study III consisted of generic descriptive analysis (GDA) and TDS methods with a trained panel. The original plan was to study the impact of aroma on mouthfeel with a consumer panel but it was not plausible due to the COVID restrictions. Nevertheless, the impact of the added aroma on mouthfeel was presumably small and a GDA with a trained panel proved to be a suitable choice. TDS with the same panel added an extra layer, providing a deeper understanding of sensory characteristics than descriptive sensory profiling alone. The vocabulary and evaluation techniques relevant to GDA were developed during training sessions. Panelists generated the lexicon and agreed on the references with the panel leaders. Nose clips were included in the study to detect the possible impact of aromas on mouthfeel among the flavored and unflavored samples. The evaluation was repeated four times (n=10×4). In addition, two different conditions within the session were used: the evaluation was conducted once with a nose clip and once without a nose clip. The nose clip condition was balanced between panelists. The TDS followed a similar procedure as in Study I except that the panelists were instructed to consume the sample for at least 5 s and no more than 30 s.

Study IV was a consumer study that aimed to determine the cross-cultural differences among US and Finnish consumers. Participants rated texture properties by visual experience (VE) using Rate-all-that-apply (RATA) and thickness using Just-about-right (JAR) methods before tasting the samples. After tasting, participants evaluated mouthfeel (MF) using the similar RATA method as well as taste and flavor with CATA. Thickness, sweetness, sourness, and bitterness were rated using the JAR method, followed by overall liking on a 9-point hedonic scale. The main focus in the study was in the acceptance of the samples and thus consumer study was more suitable compared to a trained panel. Despite the potential limitations of CATA and RATA, these methods were selected for their rapid and consumer friendly approach for profiling the samples. A more careful rationale for the used methods is provided in the chapter 6.4. The results of taste and flavor (CATA) profiles are presented and discussed in the Study IV.

Table 15. The sensory attributes used in Studies I, III, and IV divided by aroma, texture, taste, and flavor properties. In Studies I and III, the attributes had specific evaluation instructions. In Study IV, only the term was provided for the consumers.

English term	Finnish term	Study I	Study III	Study IV
Odor				
Aroma intensity	*hajun voimakkuus*		x	
Texture				
Thick	*paksu*	x	x	x
Creamy	*kermainen*	x	x	x
Thin	*ohut*	x	x	x
Watery	*vetinen*	x	x	x
Sticky	*tahmea*	x	x	x
Foamy	*vaahtomainen*	x		x
Melting sensation	*rakenteen oheneminen*		x	
Grainy	*rakeinen*			x
Slimy	*limainen*			x
Smooth	*sileä*			x
Lumpy	*paakkuinen*			x
Taste				
Sweet	*makea*		x	x
Sour	*hapan*			x
Bitter	*karvas*			x
Flavor				
Lemon	*sitruunainen*		x	
Vanilla	*vaniljainen*		x	
Grain-like	*viljainen*		x	
Beany	*hernemäinen*			x
Blueberry	*mustikan maku*			x
Oaty flavor	*kauran maku*			x
Off flavor	*sivumaku*			x
Dairy-like	*maitomainen*			x
Natural	*luonnollinen*			x
Fruity	*hedelmäinen*			x

In Studies I and IV, various demographic questions were collected after the sensory evaluation: age, gender, and food consumption frequencies. The evaluation conditions are presented in **Table 17.** Demographic-related questions (gender, age, and education) and yogurt consumption frequencies were asked after the tasting procedure. In addition, a domain-specific innovativeness (DSI) scale (Goldsmith & Hofacker, 1991; Huotilainen et al., 2006; Urala et al., 2005) with six questions on attitudes and willingness to purchase PB yogurt alternatives was used to gain an understanding on consumer's attitudes toward PB products in Studies I and IV. As food neophobia has been identified as a major barrier to accepting novel food alternatives like meat replacements (Tuorila & Hartmann, 2020), in Study IV participants filled in a 10-item questionnaire measuring individual food neophobia (FNS) (Pliner & Hobden, 1992). To assess participants' negative attitudes toward vegetarian and vegan lifestyles (NVA), four statements based on previous findings were included (Judge & Wilson, 2019; Michel, et al., 2021; Ruby et al., 2016). Finally, one question on the importance of sustainability (SUS) was asked. For the attitude scales and SUS question, panelists rated their levels of agreement for each of the statements on a 7-point scale from "1 strongly disagree" to "7 strongly agree."

Table 16. The sensory methods, scales, and measured properties used in three studies (I, III and IV). CATA refers to Check-all-that-apply, GDA to generic descriptive analysis, JAR to Just-about-right, RATA to Rate-all-that-apply, and TDS to Temporal dominance of sensations.

Method	**Scale**	**Measured property**	**Studies**
TDS #1	Choose one attribute at a time	Mouthfeel attributes (6)	I
TDS #2	Choose one attribute at a time	Mouthfeel; taste; flavor (6)	III
Pleasantness #1	7-point anchored scale 1=Dislike very much 7=Like very much	Mouthfeel liking Overall liking	I
Pleasantness #2	9-point structured hedonic scale 1=Dislike extremely 2=Dislike very much 3=Dislike moderately 4=Dislike slightly 5=Neither like nor dislike 6=Like slightly 7=Like moderately 8=Like very much 9=Like extremely	Overall liking	IV
Attribute intensity #1 (GDA)	Unstructured 10-cm line scale Right=Not at all Left=Very strong		III
Attribute intensity #2	RATA (4-point) 0=N/A 1=low 2=medium 3=high	Visual texture (10) and mouthfeel (10)	IV
Attribute volume #2	CATA 0=Not applicable 1=Applicable	Taste and Flavor (10)	IV
Attribute appropriateness	JAR (5-point) 1=too weak 3=just about right 5=too strong	Thickness* Sweetness Sourness Bitterness	IV

Table 17. The evaluation conditions in three studies (I, III, and IV).

Condition	Study I	Study III	Study IV
Location	Sensory Laboratory (ISO8589)	Sensory Laboratory (ISO8589)	Sensory laboratory, University of Massachusetts Amherst, MA, US. Flavoria® research platform, Turku, Finland.
Country	Finland	Finland	US, Finland
Nose clip	No	Yes	No
Light condition	Red light	Red light	Normal light
Presentation	Simultaneously	Simultaneously	Monadically
Randomization	Latin square	Latin square	Latin square
Temperature of the samples (°C)	10	12	8–10
Sample size (g)	40 g	30 g	45 g
Cup size	75 ml	75 ml	74 ml (2.5 oz)
Software	FIZZ Sensory Evaluation Software	RedJade Sensory Solutions LLC, Martinez, CA, US).	Compusense Cloud software (Guelph, ONT, Canada).
Palate cleanse	Water, corn snacks	Water, corn snacks	Water, water crackers
Incentives	Chocolate or cookies	Cookies	Chocolate or cookies

4.5 Instrumental measurements

Study II consisted of several various instrumental measurements (**Table 18**). The measurements included pH, titratable acidity (TTA), soluble solids, particle size, and rheological measurements including small and large deformation rheology. Study III included color measurements, volatile profile, and rheological measurements, namely, flow curves. A detailed description of the methods and pieces of equipment used in the analyzes is described in publications II-III.

Table 18. The measurements, the code for each measured parameter, explanation of the measurements, and used in the Studies II–III.

Measurement	Parameter code	Explanation	References
Study II			
Steady shear rate (SS)	SR10	η at 10 s^{-1} at t=10s	de Wijk et al., 2006; Janssen et al., 2007.
	SR50	η at 50 s^{-1} at t=10s	de Wijk et al., 2006; Janssen et al., 2007.
Flow curves (FC)	HL	The area of hysteresis loop between the upward and downward curves	Krzeminski et al., 2013
	n, K	Shear thinning index n and Consistency K were calculated from Power-law ($\eta=K*\dot{y}n^{1}$) from the upward flow curve	de Wijk et al., 2006; Janssen et al., 2007.
	ηapp10	Apparent viscosities (η_{app}) from the upward flow curve (Pas) calculated from Ostwald-de Waele, $\eta_{app} = K\dot{y}$^(n-^{1}), at shear rates 1.5, 5, 10, 25, 50 (s^{-1})	de Wijk et al. 2006; Janssen et al. 2007.
Dynamic strain sweeps (DSS)	G'LVE	Stress (G') at the end point of LVER, Pa	Mezger, 2006.
	γLVE	Strain (γ) at the end point of LVER	Mezger, 2006.
Dynamic frequency sweep (DFS)	G'	G' at 1 Hz, Pa (DFS G'1Hz)	de Wijk et al. 2006; Janssen et al. 2007.
	G"	G" at 1 Hz, Pa (DFS G"1Hz)	
Particle size	d[3,2]	Surface weighted particle size	Laiho et al., 2017.
	d[4,3]	Volume weighted particle size	Laiho et al., 2017.
	d[0,9]	90th percentile of the particles less than d[0,9]	Laiho et al., 2017.
Soluble solids	ºBrix	°Brix	
Acidity	pH	pH	
	TTA	Total titratable acidity	Wang et al., 2018.
Study III			
Flow curves (FC)	ηapp10	Apparent viscosities (η_{app}) from the upward flow curve (Pas) calculated from Ostwald-de Waele, $\eta_{app} = K\dot{y}$^(n-^{1}), at shear rate 10 (s^{-1})	de Wijk et al. 2006; Janssen et al. 2007.
Volatile profile	HS-SPME-GC-MS	headspace solid-phase microextraction coupled to gas chromatography with mass spectrometric detection	Damerau et al. 2014.
Color measurements		L*, a*, and b* values	

4.6 Data analysis

All statistical analyzes were performed with SPSS version 25 (SPSS Inc., Chicago, IL, US). Both Principal component analysis (PCA) and Partial least square regression (PLS-R) were analyzed using Unscrambler (Unscrambler 7.6 SR-1, Camo Asa, Oslo, Norway). TDS curves were carried out using XLSTAT-Sensory software (version 2019.3.22019; Addinsoft, Paris, France). All statistical effects and interactions were studied at the significance level *p=0.05*. Bonferroni correction was used for t-tests and are defined in the results. The data was analyzed with procedures as described in the original publications (I–IV). **Table 19** summarizes the data analysis.

Table 19. Methods and data analysis of each Study (I–IV). A more precise description of the data analysis is described in the original publications. ANOVA refers to Analysis of variance, CA correspondence analysis, CATA Check-all-that-apply, GDA generic descriptive analysis, MF mouthfeel, PCA Principal component analysis, PLS Partial least squares regression, RATA Rate-all-that-apply, SD standard deviation, SEM standard error of mean, and TDS to Temporal dominance of sensations, VE visual experience.

Study	Method	Data analysis
I	TDS	Dominance rates, chance level, significance level, attribute duration, one-way ANOVA, PCA
	Hedonic responses	Mean, SD, one-way ANOVA, CA, Penalty-lift analysis
II	Instrumental measurements	One-way ANOVA, PCA, PLS, Pearson correlations
III	GDA	Mean, SEM, one-way ANOVA, Pearson correlations, Three-way ANOVA (sample, panelist, session)
	TDS	Dominance rates, chance level, significance level
	Instrumental measurements	Mean, SD
IV	Hedonic responses	Mean, SD, one-way ANOVA, two-way ANOVA, t-tests
	RATA	Mean, SEM, difference (RATA) = MF-VE, one-way ANOVA, two-way ANOVA, t-tests
	Hedonic responses + RATA	PLS, Linear regression

To define the impact of product information on mouthfeel, additional analyzes were conducted. Paired t-tests were conducted for the countries separately for all the texture attributes apart from foamy, grainy, lumpy and smooth, with Bonferroni corrected *p*-value (<0.004). The differences in the JAR results of thickness evaluated by VE and MF were analyzed with t-tests in both countries separately. The results from both countries were also compared with independent t-tests, with Bonferroni corrected *p*-value (< 0.006).

For the Study I differences in DSI group and for the Study IV, differences in FNS, DSI, NVA and SUS groups in overall liking were analyzed. The sum for each scale was calculated and then by using 33rd and 66th percentile as cut-off points, the respondents were placed into three groups according to their responses in three scales (FNS, DSI, and NVA) and sustainability question (SUS) as Huotilainen et al. (2006) proposed for the DSI scale. For the DSI scale, the groups were called Laggards, Moderates, Innovators as proposed in Huotilainen et al. (2006). Independent t-tests were performed for the mean values of each attitude scales and sustainability question between the two countries. Multiple pairwise comparisons were performed for each three groups (33rd and 66th cut off-points) in overall liking with Tukey's Honest Significant Difference test (HSD) at 95% confidence level.

5 RESULTS

The results and discussion follow the three sections (A–C) as presented in **Table 10.** Section A investigates the mouthfeel perception and physicochemical properties in PB yogurts (Studies I–II). Section B determines the role of product information (Study IV), visual experience (Study IV), and added aroma (Study III) on mouthfeel perception, and section C examines the consumer acceptance of PB yogurts among consumers in the US and Finland (Studies I and IV).

5.1 Dynamic mouthfeel perception and physicochemical properties in plant-based yogurts (Studies I–II)

5.1.1 Characteristics of dynamic mouthfeel perception (Study I)

The results show that the perception of mouthfeel is a dynamic process in plant and dairy-based yogurts (**Figure 4**). More variation was found in the selected mouthfeel properties of PB yogurts compared to dairy yogurts, where thickness and creaminess were the only significantly dominant attributes. Two PB samples (P2 and P3) showed a similar pattern in thickness and creaminess as the dairy yogurts. In the other PB samples (P1, P4, and P5), thickness, creaminess, thinness, and wateriness were dominant during mastication. Watery and thin attributes were dominant at different time points for various PB samples, but most often were reported at the end of mastication.

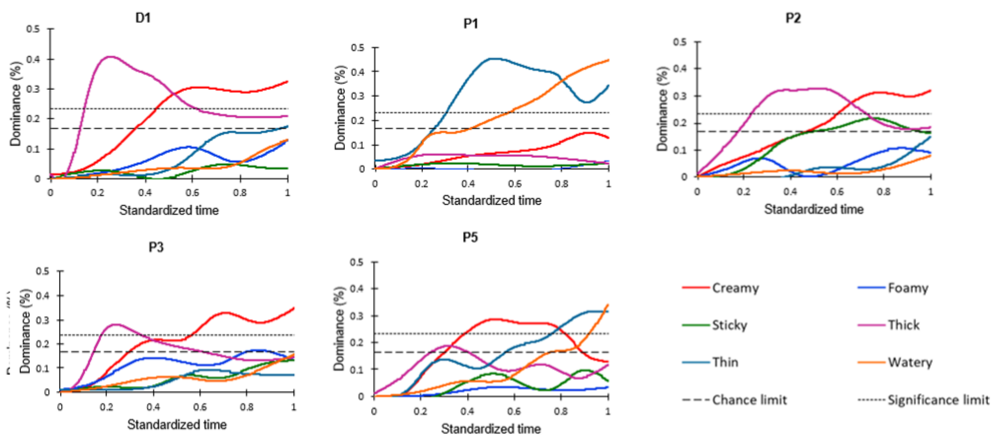


Figure. 4. Dominance curves of dairy yogurt (D1) and four selected plant-based yogurts (P1, P2, P3, and P5) plotted by standardized time with chance limit and significance limits (n=87). The Dominance curves of samples D1 and P4 are seen in the original publication I. The five samples are selected based on the differences in the TDS profile. The codes of the samples are in accordance with Tables 11.

Compared to the TDS curves, the duration period shows another dimension of the attributes which is time (**Table 20**). The findings revealed significant differences in the durations for each attribute. The results highlight that the time that thickness dominated in samples P2–P3 was comparable to dairy yogurts. The averaged durations show apparent differences in foaminess and stickiness even though these attributes were insignificant.

Table 20. Attribute duration (in seconds) averaged across participants (n=87) using non-standardized data. Different letters indicate significantly different (p<0.05) groups by Tukey's test. They correspond to the difference between the first click on the attribute and the click of the following one. These results indicate the temporal profile of texture descriptors but it does not reveal the order of the attributes. The D1–D2 refer to dairy yogurts and P1–P5 to various plant-based yogurts. The codes of the samples are in accordance with Tables 11.

	Creamy t(s)	Thick t(s)	Thin t(s)	Watery t(s)	Foamy t(s)	Sticky t(s)
D1	3.9 (a)	4.2 (abc)	1.3 (bcd)	0.6 (cb)	1.2 (ab)	0.4 (b)
D2	4.4 (a)	5.7 (a)	1.1 (dc)	0.3 (c)	0.5 (b)	0.7 (b)
P1	1.4 (b)	0.8 (e)	4.8 (a)	3.4 (a)	0.1 (b)	0.2 (b)
P2	3.7 (ab)	4.8 (ab)	0.6 (d)	0.5 (c)	1.3 (ab)	2.4 (a)
P3	4.6 (a)	3 (bcd)	0.9 (d)	0.9 (bc)	2.3 (a)	1.1 (b)
P4	2.6 (ab)	2.6 (cde)	2.5 (bc)	1.2 (bc)	0.5 (b)	1.3 (ab)
P5	3.5 (ab)	2.1 (ed)	2.6 (b)	1.7 (b)	0.4 (b)	0.9 (b)

5.1.2 Physicochemical properties (Study II)

The hysteresis loops, i.e., the area between the forward and backward curves describes the thixotropic properties of the samples (**Figure 5**). A greater area within the hysteresis loops was reported with dairy yogurts (D1–D2) compared to PB yogurts. The hysteresis loop for sample P2 showed that the forward and backward curves were partly overlapping (within 500–1000 s^{-1}), the backward curve being also partly higher than the forward curve, indicating reversible shear-thinning behavior.

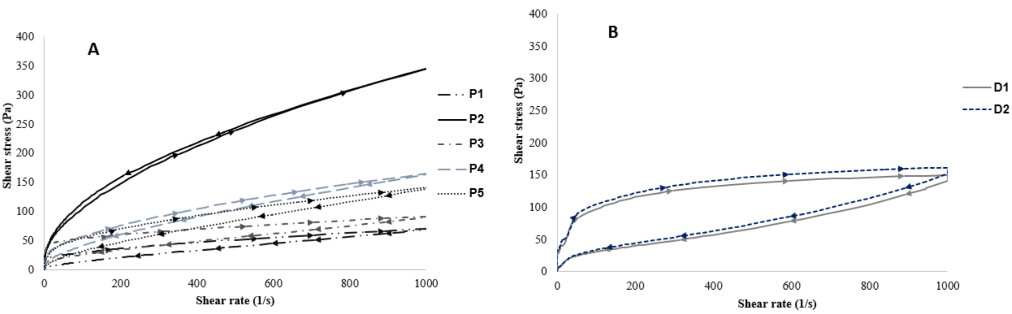


Figure 5. Hysteresis loops in A) plant-based yogurts (P1–P5) and B) dairy yogurts (D1–D2).

All samples had G′ > G″ and thus can be described as soft gels. There are significant disparities among the samples in the storage modulus, indicating that the samples represent a wide range of texture properties, particularly in rigidity. Dairy samples (D1–D2) and two of the PB samples (P2–P3) had the highest storage modulus (G'), indicating a more rigid structure compared to other products. Results from steady shear measurements indicate the same. Samples D1–D2 and P2–P3 were found to be more viscous at a steady shear rate of 10 s^{-1} compared to other samples. **Table 21** shows the results of selected instrumental measurements.

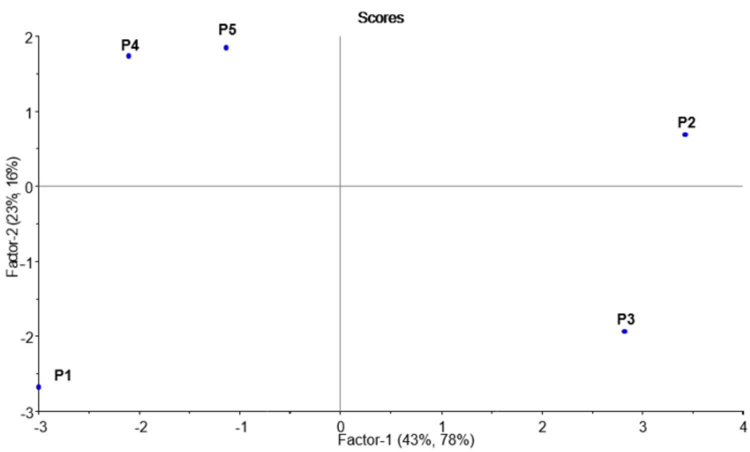
Table 21. The mean value and SD of selected rheological parameters of all the samples. Superscript letters indicate statistical difference among samples (p<0.05). The abbreviations of the of the sample codes are presented in the Table 11 and codes for the rheological parameters are presented in the Table 18.

	D1		D2		P1		P2	
SS10 (Pa s)	3.92	± 0.20^{b}	4.82	± 0.17^{a}	1.99	± 0.05^{d}	4.20	± 0.06^{b}
n (-)	0.31	± 0.01^{b}	0.28	± 0.01^{c}	0.15	± 0.01^{d}	0.35	± 0.00^{a}
K (Pa s^{n})	21.15	± 1.65^{b}	26.00	± 2.06^{a}	14.02	± 0.28^{c}	18.91	± 0.15^{b}
ηapp10 (1/s)	4.35	± 0.27^{b}	4.94	± 0.29^{a}	1.99	± 0.02^{d}	4.27	± 0.03^{b}
G' (Pa)	303.30	± 14.57^{a}	431.60	± 13.47^{b}	61.22	± 5.45^{e}	89.30	± 1.01^{d}
G” (Pa)	74.60	± 2.52^{a}	102.88	± 0.81^{b}	7.21	± 0.27^{de}	23.13	± 0.12^{d}
	P3		P4		P5			
SS10 (Pa s)	4.20	± 0.03^{b}	2.76	± 0.06^{c}	2.50	± 0.06^{c}		
n (-)	0.15	± 0.02^{d}	0.31	± 0.00^{bc}	0.36	± 0.01^{a}		
K (Pa s^{n})	27.94	± 1.18^{a}	13.52	± 0.08^{cd}	10.73	± 0.09^{d}		
ηapp10 (1/s)	3.97	± 0.02^{b}	2.75	± 0.01^{c}	2.45	± 0.03^{c}		
G' (Pa)	226.15	± 1.75^{c}	17.69	± 1.58^{f}	25.67	± 1.10^{f}		
G” (Pa)	14.81	± 0.06^{c}	8.53	± 0.67^{e}	10.51	± 0.23^{e}		

5.1.3 Relationship between the physicochemical properties and dynamic texture perception (Study II)

PLS regression visualizes the relationship between the mouthfeel attributes and the physicochemical properties among PB yogurts (**Figure 6**). Mouthfeel sensations represent the dominance durations for each attribute. Altogether, the PLS regression model explained 66% of the variation in the instrumental and 94% of the variation in the mouthfeel using the two first PCs.

a)



b)

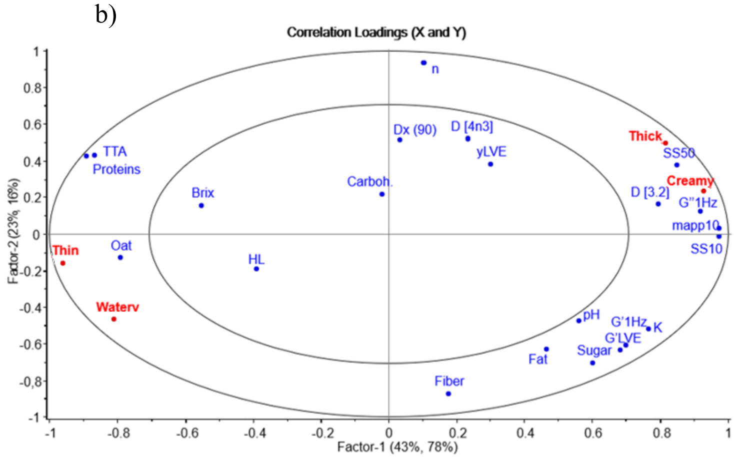


Figure 6. PLS regression bi-plots for scores (a) and for loadings (b) of sensory and physicochemical parameters for five plant-based (PB) yogurts. The abbreviations of physicochemical parameters are in accordance with Table 11. Samples P1–P5 represent different commercial PB (oat-based) yogurts and are accordance with Table 11.

Furthermore, Pearson correlations among PB samples indicate the positive or negative correlation between the instrumental measurements and mouthfeel properties. The PLS regression demonstrates that thickness and creaminess are associated with large deformation rheology. Pearson correlations also support this; all the mouthfeel sensations are correlated with both steady shear rates $10s^{-1}$ and $50s^{-1}$ and apparent viscosity (η_{app}) either positively (thick and creamy) or negatively (thin and watery). For example, creamy correlated positively with apparent viscosity, ηapp10 (0.893^{*}) and steady shear rate 10 (SS10) (0.908^{*}), and wateriness correlated negatively with apparent viscosity (ηapp10) (-0.884^{*}) and steady shear rates (SS50) (-0.894^{*}). Among small deformation tests, only the loss modulus (G″) was connected positively (0.812) with thickness and creaminess and negatively with thinness and wateriness. This indicates that the viscous properties are connected more strongly to the thickness and creaminess than the elastic properties.

5.2 The role of different factors on mouthfeel perception (Studies III–IV)

5.2.1 Product information and mouthfeel (Study IV)

Three-way ANOVA results showed differences among all six samples in all but grainy and smooth attributes in pooled results (n=197). Tukey's multiple comparison, however, showed no differences between the PB50 and PB50-D. Yet, closer investigation was conducted with paired t-tests for 14 attributes among the US and Finnish consumers. After Bonferroni correction, the differences were insignificant ($p>0.004$). The largest differences were found in thinness and thickness among the US consumers with $p=0.026$ and $p=0.008$, respectively. The results of the differences between MF and VE are presented in **Figure 7**. There were no differences between the two samples in any of the characteristics.

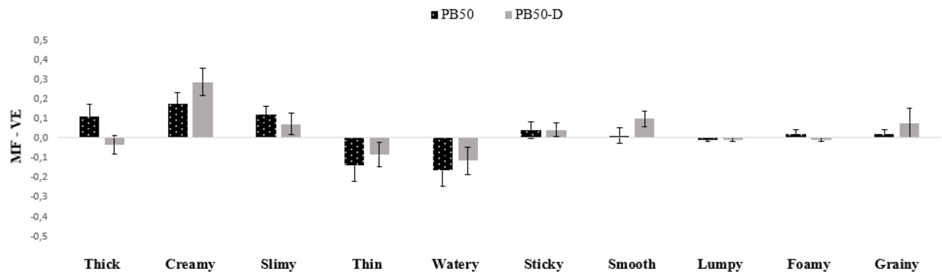


Figure 7. The visualization of the difference between mouthfeel (MF) and visual experience (VE) (MF-VE) in intensity of all texture attributes in samples PB50 and PB50-D in both countries together (*n*=197). If the difference is positive, the attribute is highlighted by mouthfeel (e.g., creamy) and if the difference is negative, the attribute is highlighted by visual experience (e.g., thin and watery). There was no difference between the samples in any of the attributes. PB50 refers to sample labeled as plant-based yogurt and PB50-D as sample labeled as dairy yogurt.

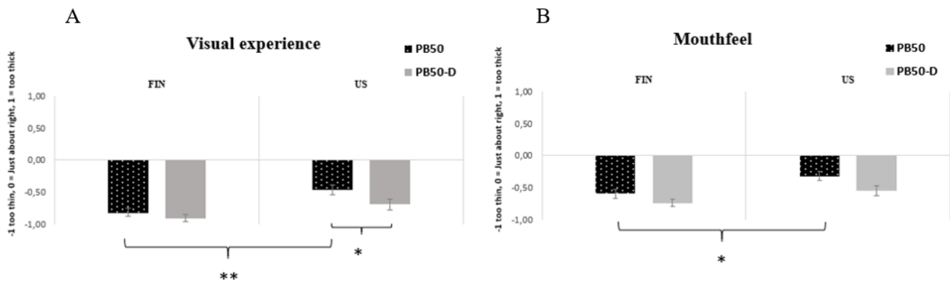


Figure 8. Mean value of the JAR scores of thickness (±SE) evaluated by visual experience (A) and by mouthfeel (B) for the two samples PB50 and PB50-D in Finland and in the US. JAR scores ranged from −2 ("too thin") to +2 ("too thick") and 0 ("just about right"). Mean values between the two sample were significantly different from each other (Bonferroni corrected $p<0.006$). PB50 refers to sample labeled as plant-based yogurt and PB50-D as sample labeled as dairy yogurt.

There were, however, differences in the JAR results of thickness evaluated by VE and MF among the US consumers (**Figure 8**). The PB50 sample was evaluated closer to the "just about right", compared to the PB50-D sample: [t(100)=-3.2, *p=0.002*]. Furthermore, there were differences between US and Finnish consumers in how the PB50 sample was rated in visual thickness: [t(96)=-4.0, $p<0.001$] and in mouthfeel thickness: [t(96)=-2.9, $p<0.001$].

5.2.2 Visual experience and mouthfeel (Study IV)

For all the attributes, when the difference is positive the mouthfeel was evaluated as stronger than the visual texture (**Figure 9**). When the difference is negative, the MF attribute was evaluated as weaker than by VE. For thickness, mouthfeel was perceived stronger than visual texture perception only in PB50. For creaminess, the results were highlighted in mouthfeel over visual texture for all the samples apart from PB100.

For sliminess, mouthfeel perception was stronger than visual texture for PB100–PB50. For descriptors thinness and wateriness, the perception was stronger in visual texture and mouthfeel depending on the sample. The significant difference was found between the PB100 and PB75, mouthfeel perception being stronger for PB100 and visual texture more intense for PB75.

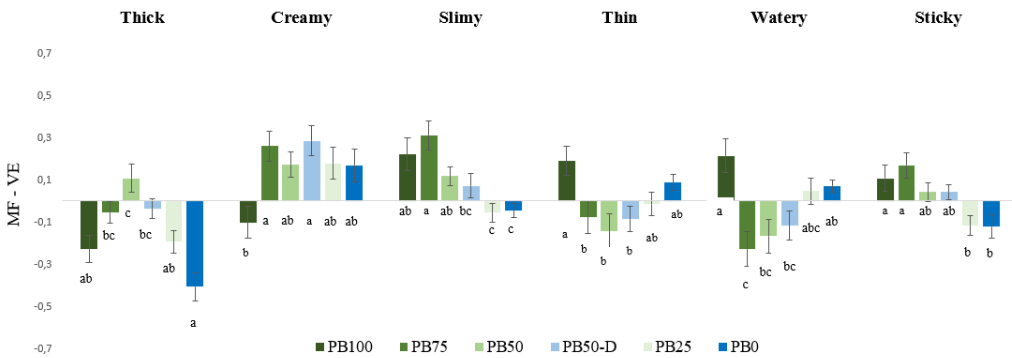


Figure 9. The difference between mouthfeel (MF) intensity and visual experience (VE) in intensity of thick, creamy, smooth, slimy, thin, watery and sticky for all the samples in both countries together (*n*=197). Different letters within an attribute are significantly different according to Tukey's post hoc test (p<0.05). The characteristics lumpy, grainy, foamy, and smooth are not included in the figure as there were no differences among samples. The sample codes are in accordance with Table 11.

5.2.3 Aroma and mouthfeel (Study III)

Clear differences between the samples were found in aroma intensity when the panelists did not use a nose clip: [F(4.35)=31.6, p<0.001] (**Figure 10**). In addition, differences were found in grain-like flavor [F(4.35)=38.9, p<0.001] and in sweetness [F(4.35)=2.5, p=0.041]. The sample with a higher vanilla content (V-2) was evaluated as the sweetest among the samples. No differences were found between the samples in any attributes when the panelists did not use a nose clip. The evaluation condition (the nose clip) affected the results only in sweetness in the sample V-2: [t(39)=2.815, p<0.008] with the Bonferroni corrected p-value (0.01). The sample was evaluated as sweeter when the nose clip was not used compared to the condition when the nose clip was used. Moreover, the Pearson correlation between the attributes in the GDA showed positive correlation between sweetness and texture thickness, stickiness and melting sensation (p<0.01).

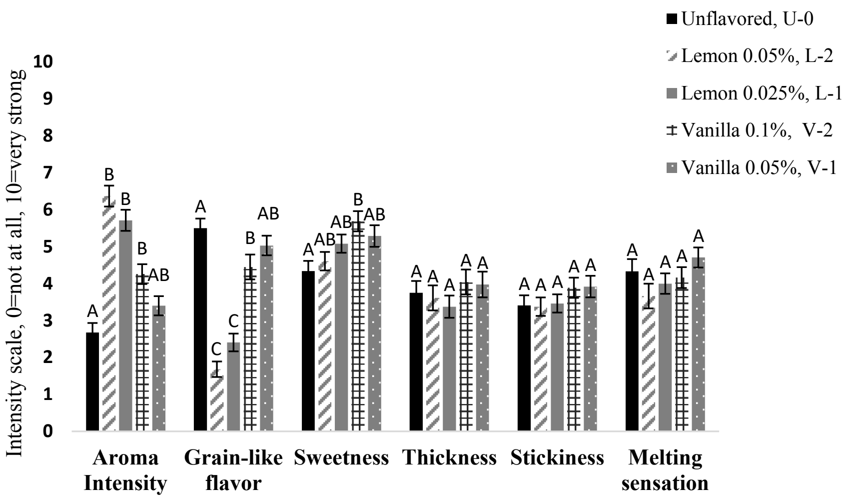


Figure 10. Intensities (mean) and the standard error of the mean (SEM) (n=4×10) of odor, flavor, and mouthfeel properties without a nose clip in samples U-0, L-2, L-1, V-2, and V-1, referring to unflavored, Lemon 0.05%, Lemon 0.025%, Vanilla 0.1%, and Vanilla 0.05%, respectively. Letters indicate a statistically significant difference between the samples: p<0.05 by Tukey's Honest Significant Difference test.

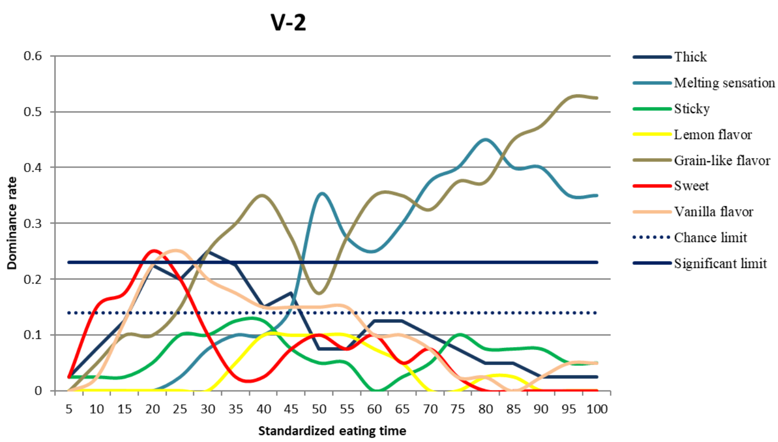


Figure 11. Dominant sensory properties during eating on a standardized time scale (0–100) evaluated without a nose clip (n=10x4) for the Vanilla sample with higher vanilla content (V-2).

The temporal sensory profile indicates the order of the significantly dominant attributes (**Figure 11**). With the nose clip on, mouthfeel properties were more highlighted, as thickness, stickiness, and melting sensations received the highest significant citation proportions, in respective order. Without the nose clip, the flavor properties dominated, apart from thickness, which had a lower citation proportion in vanilla samples compared to lemon samples. Moreover, the sweetness was dominant only in vanilla samples.

The volatile profiles (HS-SPME-GC-MS) of the unflavored, lemon and vanilla samples were different. The unflavored sample had the lowest numbers, while the vanilla had the highest number of detected compounds. In total, 6 out of 16 aroma compounds were found only in the vanilla samples, whereas 31 out of 35 were found only in the L-2. The volatile compounds found in the unflavored sample were the same as in the vanilla and lemon samples apart from acetic acid, found only in the U-0 sample, and nonanoic acid not found in the lemon samples. However, the color and apparent viscosity were measured to be similar between the samples. The apparent viscosity (10 s^{-1}) ranged from 3.37 to 3.45. The tables of volatile compounds, color, and viscosity measurements are presented in the original publication III.

5.2.4 Cross-cultural differences and mouthfeel (Study IV)

An independent t-test was conducted to study the differences between the Americans and Finns for each sample in each of the mouthfeel characteristics (**Figure 12**). Thus, 60 different t-tests were conducted and Bonferroni corrected alpha values were used. Instead of using p<0.05 (*), p<0.01 (**) and p<0.001 (***), p-values p<0.0008 (*), p<0.0002, (**), p<0.00002 (***) were used.

The most differences were found in creamy (PB100, PB75, PB50, and PB25). Consumers in the US evaluated the samples constantly creamier, while Finns evaluated the PB100 samples slimier (p<0.0002**) and less grainy (p<0.0008*). In addition, in sample PB0, the Finns evaluated the samples thinner (p<0.00002***) and less smooth (p<0.00002***) compared to the Americans. The p-values are Bonferroni corrected.

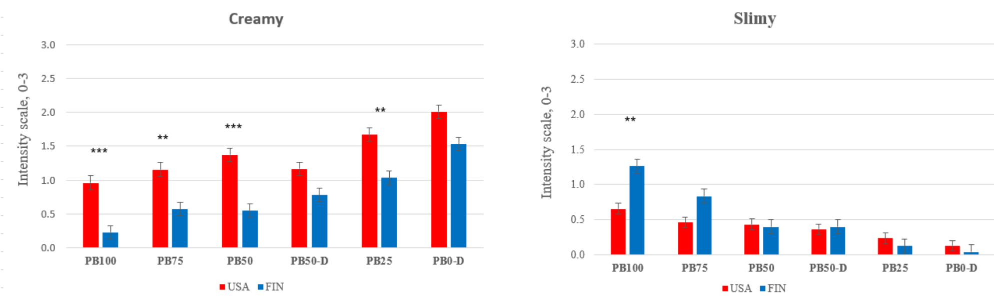


Figure 12. The creamy and slimy mouthfeel characteristics evaluated by the US (red) and Finnish (blue) consumers. After the Bonferroni correction, p-values are as follows: *$p \leq 0.0008$, **$p \leq 0.0002$, ***$p \leq 0.00002$. The sample codes are in accordance with Table 11.

5.3 Consumer perception of plant-based yogurts among consumers in Finland and in the US (Studies I and IV)

5.3.1 Consumer acceptance of plant-based yogurts (Studies I and IV)

In Study I, there were differences among products in overall liking [$F(6, 602)=4.56$; $p\leq 0.001$] and in mouthfeel liking [$F(6, 602)=4.92$; $p\leq 0.001$)] (**Table 22**). The dairy products were significantly more liked than the PB yogurt alternatives and Tukey's HDS post hoc test showed similarities in the two dairy yogurts in overall liking and mouthfeel liking. One of the oat products (P3) was as liked as the dairy product D2 by its mouthfeel properties. In addition, there was more variability in the liking scores of PB products compared to dairy yogurts.

When analyzing the liking scores among the dairy and PB products separately between the Laggards and Innovators based on the responses of the DSI scale, there was a significant difference between the two groups in overall liking [$t(2\ 8\ 8)=-2.541$; $p=0.012$] and in mouthfeel liking [$t(2\ 8\ 8)=-2.284$; $p=0.023$], for Laggards: 3.1 (±1.7) and 4.0 (±1.7) and for Innovators 3.6 (±1.8) and 4.5 (±1.7), respectively. No difference was found in dairy yogurts.

Table 22. The means and standard deviations in overall liking and mouthfeel pleasantness for each product individually. D1–D2 represent dairy yogurts with 2.5% (D1) and 4% (D2) fat levels. Samples P1–P5 represent different plant-based (PB) (oat-based) yogurts on the market. Different letters within each column indicate the significantly different ($p<0.05$) products by Tukey's Honest Significant Difference test (n=87). Samples D1–D2 refer to dairy yogurts and P1–P5 PB yogurts. The sample codes are in accordance with Tables 11. Superscript letters indicate statistical difference among samples ($p<0.05$).

Products	Overall liking		Mouthfeel liking	
D1	5.2±1.4	a	5.6±1.2	ab
D2	5.7±1.4	a	6.0±1.2	a
P1	2.4±1.3	c	3.0±1.6	d
P2	3.8±1.8	b	4.6±1.8	c
P3	3.7±1.8	b	4.9±1.7	bc
P4	3.3±1.6	b	4.3±1.5	c
P5	3.3±1.7	b	4.4±1.5	c

In Study IV, the one-way ANOVA in overall liking demonstrated differences among samples ($p<0.001$). When all the responses were merged (total, $n=197$), the samples PB100 and PB25 received the lowest and highest scores among the samples labeled as PB samples, 5.0 and 7.1, respectively (**Table 23**). The same yogurts (50:50) labeled as PB and dairy were equally liked in the US and Finland; however, when the data was merged, sample PB50-D was more liked than PB0 ($p<0.05$). The demographics, consumption frequencies, attitude questions, and scales were compared between those who liked samples (75th percentile) PB50 and PB50-D. There were no differences in any of the factors in the consumer groups. **Figure 13** visualizes the standard deviations of the liking results in each sample.

Two-way ANOVA showed significant effects of the main factor's samples ($p<0.001$) and country ($p=0.02$), but the interaction between samples and country was not significant

(p=0.981). The comparison between the two countries analyzed with independent t-tests showed no differences in any of the samples between the countries.

The Cronbach's alpha for the attitude scales were measured and the results indicate that the scales can be considered as reliable (NVA: 0.78; DSI: 0.82; FNS: 0.78). There were no differences between the mean values of each attitude scales and sustainability question between the two countries.

No significant differences in hedonic ratings were observed by gender or consumption frequency of dairy or PB yogurts or any of the attitude groups. However, there was a difference between age groups (≤30 and >30 years old) in samples PB100 [$F(1)=6.54$, $p=0.011$] and PB75 [$F(1)=4.78$, $p=0.030$]. Furthermore, there were statistical differences in DSI group between the Laggards and Innovators in the liking of sample PB100 [$F(2)=4.045$, $p=0.019$]. In addition, a difference was found in the sustainable question in the liking of sample PB100 [$F(2)=4.18$, $p=0.0179$], PB75 [$F(2)=3.44$, $p=0.034$], and PB25 [$F(2)=3.98$, $p=0.02$] (**Figure 14**).

Table 23. Average overall liking scores and standard deviations for the evaluated yogurts, for the US consumers (USA, n=101), Finnish consumers (FIN, n=96) and all respondents (Total, n=197). Overall liking scores were evaluated using a 9-point hedonic scale. Average values with different letters within a column are significantly different according to Tukey's post hoc test (p<0.05). The abbreviations of the samples are in accordance with Table 11. Superscript letters indicate statistical difference among samples (p<0.05).

	USA, *n*=101	**FIN, *n*=96**	**Total, *n*=197**
PB100	4.9 ± 1.9 d	5.1 ± 1.9 d	5.0 ± 1.9 d
PB75	5.6 ± 2.0 c	5.7 ± 1.9 c	5.7 ± 1.9 c
PB50	6.3 ± 1.7 b	6.5 ± 1.9 b	6.4 ± 1.8 b
PB50-D	5.8 ± 1.7 bc	6.1 ± 1.7 bc	5.9 ± 1.7 c
PB25	7.0 ± 1.3 a	7.2 ± 1.6 a	7.1 ± 1.5 a
PB0-D	6.9 ± 1.6 a	7.3 ± 1.4 a	7.1 ± 1.5 a

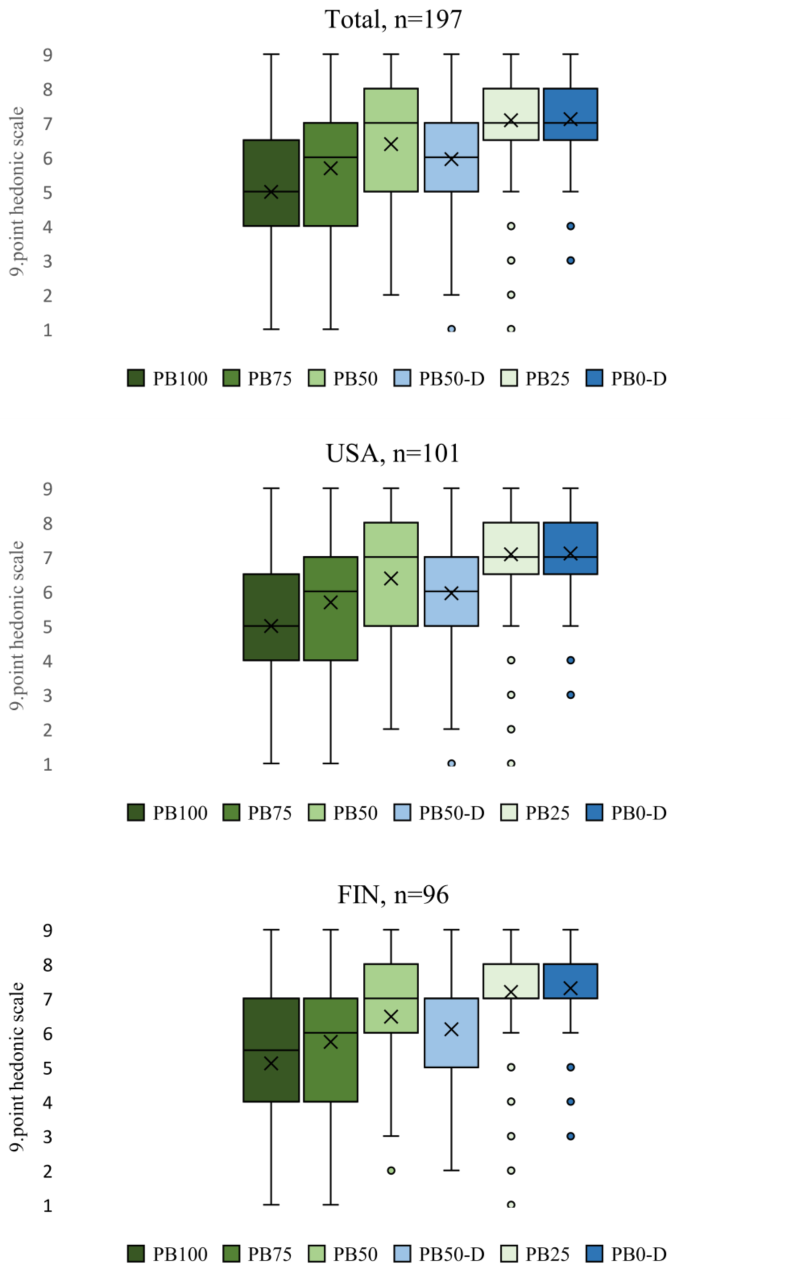


Figure 13. Box plots of the liking scores for all six samples (a) in total (*n*=197), (b) in the US (*n*=101), and (c) in Finland (*n*=96). The middle "box" represents the middle 50% of scores for the group. The abbreviations of the samples are in accordance with Table 11.

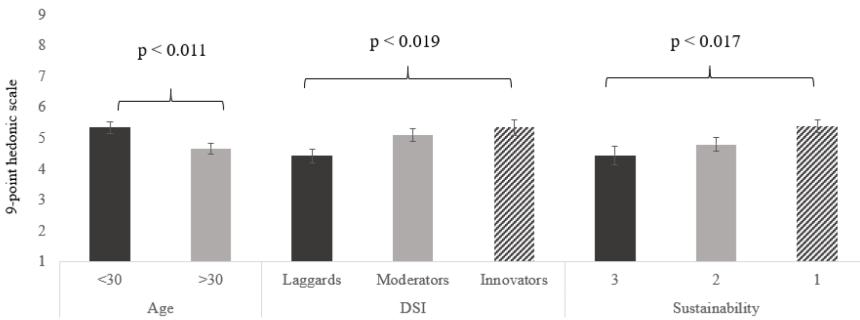


Figure 14. The overall liking (+SEM) of age, domain-specific innovativeness (DSI) and sustainability (SUS) attitude groups for sample PB100. Age groups were below 30 years old (*n*=95) and above 30 years old (*n*=101), DSI groups were Laggards (*n*=51), Moderators (*n*=78), and Innovators (*n*=68) and sustainability groups were 1–3 (1: *n*=42, 2: *n*=67, 3: *n*=88), where group 1 is the highest level of agreement and group 3 the lowest level of agreement to the statement "sustainability is an important factor when making food choices".

5.3.2 Relative importance of different texture properties on overall liking (Studies I and IV)

In Study I, penalty-lift analyzes based on the mouthfeel liking and aggregated TDS data in five different time periods (0–25s) showed that thickness and creaminess (5–15s) are associated positively with mouthfeel liking in five commercial PB yogurts (**Figure 15**). On the other hand, thinness (6–10s) is associated negatively with mouthfeel liking.

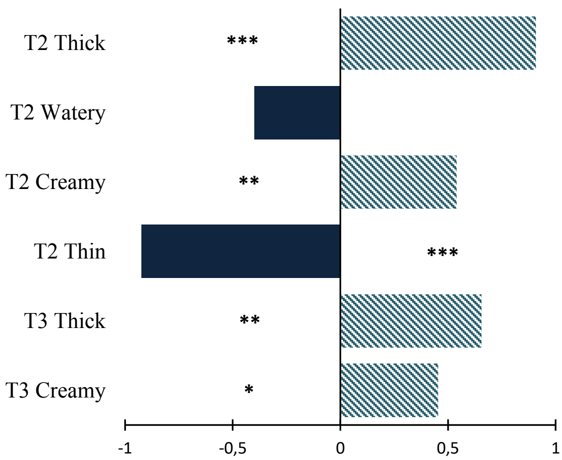


Figure 15. Penalty-lift analysis of 5 commercial plant-based products in 5 different time intervals T1=1–5 s, T2=6–10 s, T3=11–15 s, T4=16–20 s, and T5=21–25 s. Dark blue bars indicate the significant positive drivers of mouthfeel liking and striped bars indicate the significant negative drivers of liking. Stars indicate significant mean drops (**p*<0.05, ***p*<0.01, ****p*<0.001), *n*=87. The figure does not present all the time intervals because the analysis was only performed if the sample size (attribute selection among the panel) was greater than 20%.

In Study IV, the relationship between the visual texture and mouthfeel attributes and the overall liking among PB yogurts was studied and visualized by PLS regression (**Figure 16**). Texture and mouthfeel sensations used in the PLS regression figure represent the intensities (scale 0–3) for each attribute. The first factor of the PLS regression model explained 52% of the variation of the overall liking, and 70% of the variation of the texture properties within the 6 samples analyzed. The second factor explained 15% and 18%, respectively. Altogether, the PLS regression model explained 67% of the variation of the overall liking and 88% of the variation of the texture properties using the two first PCs i.e., the variation of the samples is explained more specifically by the texture properties, according to the two components.

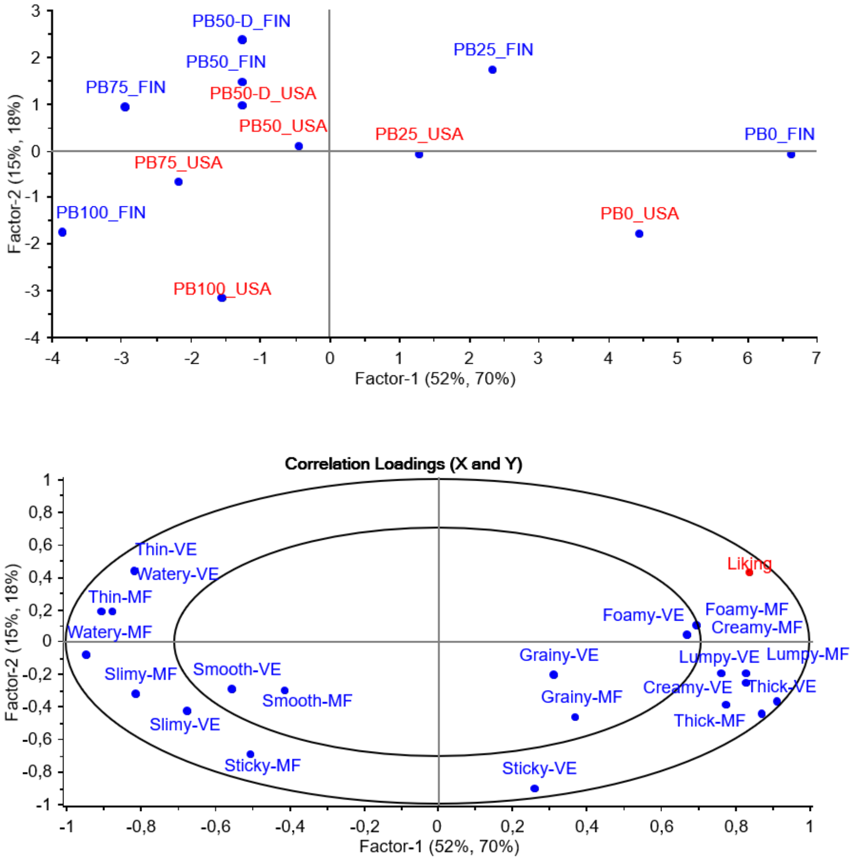


Figure 16. PLS regression bi-plots for scores (a) and for loadings (b) of texture and overall liking for six plant-based yogurts. The abbreviations of the samples are in accordance with Table 11.

The overall liking was predicted by texture attributes for PB data (pooled results from all the samples labeled as PB yogurt) using linear regression analysis (**Table 24**). The results of the models' estimation show that when overall liking goes up by one point creamy by mouthfeel intensity increases 0.39 and 0.42 in the US and in Finland, respectively. In addition, when the overall liking goes down by one point, for example, slimy intensity increases by 0.61 and 0.49

in the US and in Finland, respectively. Furthermore, the estimated models explained 16–33% of the overall liking in the US and 11–22% in Finland.

Table 24. The linear regression of the samples labeled as plant-based yogurts. Visual experience (VE) and mouthfeel (MF) characteristics were selected as independent factors and overall liking as the dependent factor for the model in the US (*n*=101) and in Finland (*n*=96) separately.

USA, *n*=101	***B***	**SE**	**R^2**
Constant	5.10	0.22	
Creamy (MF)	0.39	0.07	0.16
Slimy (MF)	-0.61	0.09	0.24
Smooth (MF)	0.41	0.08	0.29
Watery (MF)	-0.40	0.08	0.33

FIN, *n*=96	***B***	**SE**	**R^2**
Constant	6.55	0.16	
Watery (MF)	-0.47	0.09	0.11
Slimy (MF)	-0.49	0.10	0.19
Creamy (MF)	0.42	0.11	0.22

6 DISCUSSION

The dynamic mouthfeel profiles present valuable scientific information for future research on PB yogurts because no such dataset has been available in Finland or elsewhere. Specifically, the industry will benefit from the published temporal dynamic mouthfeel profiles and drivers of liking when developing PB yogurts. The extensive previous literature demonstrates the relationship between physicochemical and mouthfeel properties in conventional dairy yogurts. However, more research is required on the mouthfeel perception and rheology of various PB yogurts with different ingredients to develop PB yogurts that achieve consumer acceptance successfully.

Selected factors influencing mouthfeel perception are studied. The results provide information on whether there are ways to influence the mouthfeel perception in PB yogurts by adding flavors. By examining the role of product information on the mouthfeel, we will understand if there are different expectations for PB and dairy yogurts. Furthermore, the cross-cultural differences in mouthfeel are discussed. The role of appearance and mouthfeel in texture perception are also analyzed. Finally, the acceptance of PB yogurts and the importance of texture properties, i.e., which texture characteristics are drivers of liking and which are drivers of disliking will be discussed.

6.1 Mouthfeel and texture characterization

The results demonstrate how descriptors used to characterize dairy yogurts are also relevant for characterizing non-dairy yogurts, these include thick and creamy. As in previous experiments with semi-solid products, the descriptors used to characterize the dynamic mouthfeel profile in this thesis (Study I) were related to either viscosity and bulk properties (thick, thin, or watery) or more complex mouthfeel sensations (foamy) and surface properties (sticky and creamy) (Devezeaux de Lavergne 2015a; de Wijk et al., 2003; Nguyen et al., 2017). It has been previously reported that bulk-dominated texture features are detected relatively quickly in semi-solid foods. In Study I, the attribute thickness was the first dominant attribute during mastication for all the products, excluding one of the PB yogurts (P1). The same has been shown previously with dairy yogurts (Chen & Stokes, 2012; Devezeaux de Lavergne 2015). The dynamic mouthfeel perception highlights, however, that a reduction in viscosity occurs over time and is relevant to oral processing (Engelen et al., 2003). Although only two dairy samples were included in the study as reference samples, it was seen that the decrease in viscosity is more significant in PB yogurts compared to dairy yogurts. Dairy yogurts remained higher in the dominance of creamy until the end of mastication, while thinness and wateriness dominated in the PB products, which could result from the fracture properties and lack of relevant enzymes in the mouth to hydrolyze the protein (Devezeaux de Lavergne 2015b) in PB yogurts.

The PB yogurts exhibited a wide range of viscoelastic properties due to the various hydrocolloids. The added thickeners include potato, corn and tapioca starch, pectin, xanthan, and locust bean gum. In addition, starch and cell-wall polysaccharides are present in different amounts depending on the oat ingredient used, which also contribute to the viscosities in PB gels (Brückner-Gühmann, Banovic, et al., 2019; Ercili-Cura et al., 2015; Jeske et al., 2018). The results revealed some structural differences between PB and dairy yogurts. For example, a significantly faster structure recovery was found in PB yogurts than in dairy yogurts. That is, PB products showed visible yet significantly smaller hysteresis loop areas than dairy yogurts, probably due to the difference in the gelling agents and their interactions. It has been demonstrated with polysaccharide gels that the gel-like behavior is related to molecular and physical interactions and thus the network structure formation (Bozzi et al., 1996).

Moreover, not all the PB yogurts showed similar structure recovery. We hypothesize that the counterclockwise loop of sample P2 could be explained by the higher amount of remaining beta-glucan in the sample, which supports the thickening behavior. A similar pattern has been demonstrated with solutions containing amylodextrin and beta-glucan (Carriere & Inglett, 1999). Further studies should investigate the influence of remaining beta-glucan in the hysteresis loop. This study suggests that PB and dairy yogurts with a similar mouthfeel profile may have different viscoelastic properties.

Creaminess is a complex attribute, and according to Lawless & Heymann (2010), it is made up of several combined qualities like smoothness, slipperiness, mouthcoating, viscosity, and dairy aroma. Interestingly, two of the PB yogurts were also perceived as creamy according to the TDS results. Previous studies conducted with dairy or PB gels showed that increased viscosity (Akhtar et al., 2005; Janhøj et al., 2006), high total solid content (Brückner-Gühmann, Banovic, et al., 2019), added starch (Eliasson, 2004; Morell et al., 2015; Sjöö & Nilsson, 2017) or alternative structural components like starch particles, protein aggregates and hydrocolloids play a role in perceived creaminess. Our results also suggest that pectin might play a role in the thick and creamy mouthfeel.

There are fundamental differences in the quality of fat between PB and dairy yogurts. As in dairy yogurts, the milk fat crystals melting in the mouth may contribute to the creamy mouthfeel, while in PB yogurts the canola and rapeseed oils are in liquid form. According to our previous findings, oil content does not significantly affect creaminess in PB yogurts, which is not the case in dairy yogurts as demonstrated by several studies (Arancibia et al., 2015; Kokini, 1987; Mosca et al., 2012; Tomaschunas et al., 2012).

This study emphasizes the importance of rheological large deformation tests and their ability to explain essential mouthfeel sensations in PB yogurts. In our research, rheological parameters showed the strongest connections with thickness and creaminess of all the physicochemical parameters. This was seen mainly in large deformation tests in PB yogurts. Pearson correlations also support this; all the mouthfeel sensations are correlated with both steady shear rates (SS10 and SS50) and apparent viscosity either positively (thick and creamy) or negatively (thin and watery). Thick and creamy mouthfeel sensations were positively correlated with steady shear rates and apparent viscosity. The PLS regression demonstrates that thickness and creaminess are strongly associated, consistent with prior studies indicating that creaminess results from a thick mouthfeel (Akhtar et al., 2005; Dickinson, 2018). Studies I and II show that instrumental and sensory methods should not be considered substitutive but rather complementary methods when developing PB yogurts cost-effectively and in a timely manner. Notably, instrumental data is valuable to have when changing the raw material from one to another and scaling from pilot scale to production.

6.2 The role of selected factors on the mouthfeel perception

6.2.1 Product information and mouthfeel

Descriptive information, like product information, has a more significant role in unfamiliar new products compared to familiar food products (Piqueras-Fiszman & Spence, 2015; Shankar et al., 2009; Tuorila et al., 1998; Vidal et al., 2013). For example, the product's name has been shown to affect the liking ratings of foods (Guinard et al., 2001; Hubbard et al., 2016; Liu et al., 2017; Pliner & Pelchat, 1991; Torres-Moreno et al., 2012). Nevertheless, there are fewer studies on the impact of product information on sensory responses like perceived texture properties.

The results indicate that product information does not play a role when the intensity of texture properties is evaluated, implying that there are no differences in the expectations for mouthfeel between plant- and dairy-based yogurts. However, when the appropriateness of the thickness was evaluated by the just about right scale, a difference was found between the plant- and dairy-based labeled samples (PB50), yet only among the US consumers. The PB50 sample (50:50 labeled as PB) was evaluated as closer to the "just about right" than the PB50-D sample (50:50 labeled as Dairy). The results are in line with Adise et al. (2015). They investigated consumers' willingness to try animal and vegan versions of foods (chocolate milk, macaroni, cheese, chicken tenders, or meatballs) that were told to be vegan substitutes for animal products or actual animal products. They found that respondents liked foods more if told they were vegan. Our results acknowledged this with JAR results as well as overall liking: highlighting that consumers might be more tolerant and forgiving toward PB products compared to conventional products, which is not so surprising after all.

6.2.2 Visual experience and mouthfeel

In Study IV, the same texture properties were evaluated by visual experience (VE) and by mouthfeel (MF). We applied a subtraction of the texture properties technique (MF-VE) to calculate the difference and thus to 1) identify which texture descriptors are emphasized visually and which by mouthfeel and 2) to understand if there is variation between the samples. It should be noted that the mouthfeel perception also includes the visual aspect due to order bias in the evaluation (Lawless & Heymann, 2010). There are visible trends in the results: the perceived creamy is highlighted by mouthfeel, apart from sample PB0. Thickness, in contrast, is highlighted by the VE for all the samples, apart from PB50. There are, however, variations between the samples in the attributes thin, watery, and sticky. The difference between MF and VE was small for the attributes smooth, lumpy, grainy, and foamy, showing that such attributes are equally highlighted visually and by mouthfeel regardless of the sample. Moreover, Study

IV demonstrated differences in the meaning of descriptors in English and Finnish. The grainy and sticky attributes were evaluated differently by VE and MF in the US and Finland. For example, in Finland, grainy was evaluated higher by VE than MF (VE>MF), whereas in the US, it was the other way around (VE<MF). This could be due to a subtle difference in the meaning of these attributes in English and Finnish. According to Lawless et al. (1997), who studied texture attributes in English and Finnish, another possible translation for grainy could have been "jyväinen".

Since texture is a multidimensional sensory property (Szczesniak, 2002), it is interesting to determine whether some descriptors are more related to visual perception rather than tactile sensation. We conclude that the studied texture properties are perceived by both VE and MF but it is noteworthy that emphasis can differ, depending on the sample. The results define the difference between the thickness perception to be more visual, whereas creamy combines visual and mouthfeel properties. The results follow Santagiuliana et al. (2019), who studied the role of visual and oral sensory cues on sensory perception and the liking of novel, heterogeneous foods; they concluded that both visual and oral sensory cues impact texture and flavor perception in a new type of cheese (Santagiuliana et al., 2019).

6.2.3 Aroma and mouthfeel

We hypothesized that added vanilla aroma could enhance the sweetness and thus also the perceived thickness. However, the added aromas did not impact the studied mouthfeel properties. Nevertheless, five separate results demonstrate a potential interaction between vanilla aroma and thickness perception, although these are insignificant, implying that more research is needed to further study the impact of aromas on mouthfeel perception. First, vanilla samples scored slightly higher in thickness and stickiness, compared to lemon flavored and unflavored samples. Second, in vanilla samples, the perceived melting sensation occurred slower than in lemon and unflavored samples. Third, TDS results indicate that sweetness and thickness were selected around the same time period in the vanilla sample, which supports the potential interaction of sweetness and thickness perception. Four, a positive Pearson correlation between sweetness and mouthfeel properties also promotes the possible connection between these two sensory modalities. Finally, it was previously suggested that yogurts flavored with a mixture of aromas were perceived as smoother and thinner than those with only one added aroma compound (Saint-Eve et al., 2004). A similar trend is seen in our volatile profiles and TDS results, as the vanilla sample had fewer volatiles present, and the vanilla samples were not perceived as thick as the lemon samples without the nose clip.

With insignificant interaction between vanilla and thickness perception, our results do not align with the study by de Wijk et al. (2003) who showed that vanilla aromas enhanced thickness, creaminess, and fattiness in vanilla custards (de Wijk et al., 2003). Furthermore, Kora et al. (2003) demonstrated how fruity aroma decreased thickness in low-fat stirred yogurts. However, our results are consistent with a study by Tournier et al. (2009). They explored aroma or taste interactions with texture in custard desserts, with varying viscosities, sucrose level, and aroma nature. They did not find aroma or taste interactions with texture (Tournier et al., 2009). Our results also indicate that the impact of aroma–taste–texture interactions depend on the aroma used, which was also concluded by Gierczynski et al., (2011).

6.2.4 Cross-cultural differences and mouthfeel

The main difference between Finnish and English languages was found in the descriptor creamy. The connotation of the term "kermainen" (Engl. creamy) might refer more to cream-like, that is, cream used in coffee, whereas "creamy" in English might refer more to pudding-like food e.g. crème brule. Thus, in Finnish, the term represents something liquid that tastes like cream, whereas in English, creamy represents a more dimensional e.g., semisolid food structure. This is seen in the results as the Finns consistently rated all samples as less creamy. Another explanation heard many times from the panelists attending the preliminary panel in the US was that "we are not used to such a creamy yogurt in the US." Scientists have found that creaminess perception functions as a combination of smoothness, viscosity, fatty mouthfeel, and cream flavor (Frøst & Janhøj, 2007). Another complex descriptor was slimy, with Finnish consumers rating it as higher than US consumers for the sample PB100. The explanation could also lie in the nuanced differences between the term in the two languages. Both languages refer to a resistance to tongue movement; however, in Finnish, "limainen" (Engl. slimy) might have a more negative connotation than the English version.

6.3 Consumer perception of plant-based yogurts among consumers in Finland and the US

6.3.1 Consumer acceptance of plant-based yogurts

Studies I and IV showed that dairy yogurt was more liked than PB yogurt. In Study I, the yogurts were evaluated blinded, and in Study IV with product information. Interestingly, in Study I, one PB and dairy yogurt were equally liked by mouthfeel, whereas the dairy yogurt was more liked by overall liking, highlighting that other factors, like appearance and flavor properties, had a more significant role in overall liking in PB yogurts. In addition, it has been demonstrated earlier by Grasso et al. (2020) and Gupta et al. (2022) that PB (soy) and dairy yogurts scored equally high in texture and overall acceptability when evaluated blinded.

We found clear support that dairy-like characteristics in PB yogurts increased the liking scores among all consumers. Among the PB labeled samples, the yogurt with the lowest PB content was the most liked. Our results with PB yogurts follow previous results with other types of food products: the more a vegan food shares the sensory property with the more familiar animal-based food, the more acceptable it might be found (Hoek et al., 2011; Lea & Worsley, 2001; Piqueras-Fiszman & Spence, 2015; Tuorila et al., 1994).

Interestingly, sample PB25 (25% PB yogurt) labeled as PB yogurt was equally liked with the 100% dairy yogurt labeled as dairy yogurt. Moreover, the pooled results from both countries demonstrate that PB50 had higher liking scores than PB50-D. These findings reveal that consumers appreciate yogurts labeled as PB yogurts more than yogurts labeled as dairy yogurts. One explanation is that consumers are more forgiving of sensory properties of PB than conventional dairy foods. The results by Adise et al. (2015) support the finding that participants liked foods more if told they were vegan. Although consumers included in our study did not consume PB yogurts regularly, they were all willing to try PB yogurts: such consumers might be more approving of PB foods compared to conventional foods than consumers who are not interested in consuming PB yogurts (Adise et al., 2015).

Furthermore, it is noteworthy that samples PB100 and PB75 had the highest standard deviations among the liking scores, indicating that a group of consumers value PB yogurts with little or no dairy-like characteristics. When the liking results were compared between demographic groups, consumption frequencies, and attitude scales and questions, we found that consumers less than 30 years old liked the 100% PB yogurt more than older consumers. Michel et al. (2021) studied consumers' attitudes toward meat, pea, and algae burgers. They also discovered that age emerged as a significant predictor of the attitude toward pea burgers. Younger age was associated with higher taste, healthiness, and environmental friendliness ratings for the pea burger (Michelet al., 2021). This can be attributed to young people being interested in trying new foods and thus being more likely to consume meat alternatives (Hoek et al., 2011; Siegrist et al., 2018; Slade, 2018).

Moreover, consumers' attitudes explained part of the acceptance of the 100% PB yogurt. The DSI scale and agreement on sustainability played a role in the overall acceptance of 100% PB yogurt. A significant difference between the Laggards and the Innovators was found in the overall liking of the sample PB100. This is consistent with results from Study I on commercial PB yogurts, where the Innovator group showed a greater liking for the PB products than the Laggards. This is supported by Huotilainen et al. (2006), who found that, in general, innovative consumers are more likely to try and use new products than less innovative consumers (Huotilainen et al., 2006). It is important to note that as the younger generations of consumers appear, the consumer group who values sustainability is expected to grow. Therefore, the acceptability of PB yogurt with such sensory characteristics is also expected to grow.

Although consumers in Finland rated the overall liking of each sample consistently slightly higher than consumers in the US, there were no significant differences between the consumers in both countries in any of the samples. We hypothesized that Finns would like the PB yogurts more than consumers in the US, as we believe Finns are more familiar with oat products. However, the consumers in the study represented very similar consumer groups in both countries, according to the demographics and the measured attitudes, which could explain the result.

6.3.2 The relative importance of different texture properties

The results of Study I suggest that mouthfeel attributes, thickness, and creaminess are not just connected with dairy yogurts but also with PB yogurts. The same has been demonstrated with dairy yogurts by Bayarri et al. (2010) and by Brückner-Gühmann et al. (2019). They demonstrated that the sensory attribute creamy increases the overall liking of the PB products, while other attributes – sour, chalky, and floury – decrease the overall liking (Bayarri et al., 2010; Brückner-Gühmann, Banovic, et al., 2019). Furthermore, the penalty-lift analyzes in Study I indicate that wateriness was the driver of disliking for PB yogurts, whereas thickness and creaminess throughout mastication were selected as drivers of liking.

The previous literature shows that if the sensory quality of the food is not what is expected, a decrease in liking might occur (Piqueras-Fiszman & Spence, 2015; Zellner et al., 2004). With the calculation of MF minus VE, we aimed to understand if the attribute was more highlighted by the VE or by MF. Interestingly, for sample PB100, the positive attributes decreased and negative attributes increased from sight to mouth. This could be explained by the expectation set by the VE of PB100 on overall liking, which is not fulfilled by the MF (Burgess, 2016; Santagiuliana et al., 2019; Schifferstein & Verlegh, 1996). Further investigation is required to precisely understand the role of VE and MF characteristics on overall liking.

Study IV demonstrates that samples with the lowest PB content (PB0, PB25) were evaluated closest to the just-about-right level in visual and mouthfeel thickness. The Pearson correlations and linear regression indicate that VE on its own does not play as essential a role as the mouthfeel attributes. However, it should be noted that VE may and likely does influence the mouthfeel because of the order bias in the procedure, i.e., all the panelists evaluated the samples first by VE and then by mouthfeel.

PLS regression demonstrated variation between US and Finnish consumers when all the texture attributes, samples, and overall liking were included in the model. The characteristics smooth and grainy were located inside the circle which could be due to the fact that these properties were evaluated equally low across all the samples. Clearly, negative properties such as slimy, thin, and watery are located closer to each other, and positive attributes thick, creamy, lumpy, and foamy closer to each other. Interestingly, stickiness by mouthfeel is located closer to other negative properties, and visual stickiness is closer to overall liking and other positive properties. The PLS and the linear regression show that exceptionally creamy is a positive driver and slimy and watery are negative drivers. The linear regression also shows that the texture properties explain the overall liking stronger in the US than in Finland. That is, taste and flavor properties may play a more significant role in the overall liking of yogurts labeled as PB yogurts in Finland than in the US. However, more research is needed to indicate this.

6.4 Methodological considerations

6.4.1 Sample selection

Studies I–II aimed to characterize the mouthfeel and physiochemical properties of commercial PB yogurts. Thus, we aimed to find PB yogurts that vary in their structure and texture properties. For the preliminary GDA, all available commercial oat-based yogurts from the Finnish supermarket were included in the study. One sample was left out, as its flavor profile in GDA was so distinctive. Five different samples were an adequate number to study further with consumers. In addition, two dairy yogurts, representing standard dairy yogurts in Finland, were selected as reference samples. In Study II, the presented relationships between the physicochemical parameters and mouthfeel are only valid within the studied PB and dairy yogurts. The results highlight that further investigation is necessary to demonstrate the impact of different macromolecules and hydrocolloids on the physicochemical and sensory properties in model PB yogurts.

The unflavored fermented oat-based yogurt base was obtained from Valio for Study III. The commercial yogurt base was selected to study the cross-modal interactions between added aroma and mouthfeel. The benefit of a non-commercial model sample would have been the advantage of understanding the factors impacting the structure and texture. However, in addition to the tedious process, the preparation would have produced less homogenous samples in their texture and flavor properties, which would have caused uncertainty in the results. Thus, commercial yogurt base was decided to be used.

The samples in Study IV represented typical PB and dairy yogurts in the Finnish market. According to the results of Study I–II, the Valio sample showed a similar sensory and instrumental profile compared to other oat-based yogurts we studied. The study focused on mouthfeel properties; thus, blueberry-flavored yogurts instead of non-flavored were selected to mask the differences in appearance and flavor. The color of both samples was blue, and the overall flavor profile consisted of blueberry flavor. The PB yogurt across all the studies (I–IV) has been the same with only a few moderations. Furthermore, according to the unpublished preliminary rheological measures conducted on both types of yogurts in Study IV, the flow curves of the samples showed a similar pattern as the PB and dairy yogurts in Study II. This indicates that the results of Study IV can be generalized to other similar and typical yogurts on the market. However, it should be noted that PB yogurts exhibit a wide range of viscoelastic properties, resulting from the fact that different hydrocolloids at different levels were incorporated into the samples at different levels. That is, very different structural profiles would cause a different result. However, previous research studying various PB yogurts such as soy, almond, and cashew indicated that the sensory profile can be very different compared to oat (Grasso et al., 2020; Gupta et al., 2022). Thus, the results can only be generalized to similar oat and dairy-like yogurts.

6.4.2 Sensory evaluation methods used in this study

When Study I was initiated in the fall of 2018, different methods were considered to understand the sensory profiles of PB yogurts. GDA documented by Lawless & Heymann (2010) was decided to be the best starting point to understand the sensory profile of Finnish commercial PB yogurts. The GDA was conducted as a preliminary study at Valio, R&D with a trained panelist. The preliminary lexicon was partly built through the literature on dairy yogurts (Nguyen et al. 2018), soybean and dairy custards (Engelen et al., 2003), vanilla custards (de Wijk et al., 2003), and different emulsion-filled gels (Devezeaux de Lavergne et al. 2015), as well as selected descriptors used at Valio R&D. In addition to the preliminary GDA, TDS with consumers was conducted to further understand the products' mouthfeel properties (Study I).

TDS is a reasonably new method, and there is much discussion about its features, such as the number of panelists and descriptors involved (Nguyen et al., 2017; Varela et al., 2018). A consensus has not been reached among researchers on the concept of dominance (Varela et al., 2018). In our studies (I and III), TDS was performed according to the definition of dominance attribute proposed by Pineau et al. (2009). There is also a debate regarding whether TDS should be conducted with a trained panel or consumers. Some researchers suggest TDS is better suited for consumers than trained panelists (Schlich, 2017; Varela et al., 2018). It should be noted, however, that most of the research done so far in TDS has been done with trained panels. In Study I, the panelists were semi-trained and in Study III, they were trained. In addition, part of the participants had experience on sensory evaluation from previous sensory studies at the department.

For Study III, GDA and TDS were conducted as supplementary methods with a trained panel. When the cross-modal interactions are studied, most studies have been conducted with static methods, and fewer have focused on dynamic sensory perception (Charles et al., 2017; Oliveira et al., 2021; Saint-Eve et al., 2006; Velázquez et al., 2020). However, time-dependent methods have been previously used to understand cross-modal interactions (Charles et al., 2017; Saint-Eve et al., 2006; Velázquez et al., 2020). Since sensory interactions arise due to the simultaneous perception of different stimuli (Noble, 1996), more attention should be paid to the dynamics of sensory perception. A review showed that temporal methods could provide accurate descriptions of aroma perception in dairy products (Gierczynski et al., 2011). TDS also revealed that some aromas could be perceived even when the nose clip was on, indicating that the nose clip did not block the nasal cavity entirely.

In the study IV, the overall-liking of the samples were studied with a 9-point hedonic scale and texture properties with RATA and JAR questions. RATA was chosen for its ability to provide a good alternative to the resource- and time-intensive descriptive sensory analysis for these types of samples (Varela & Ares 2014; Oppermann et al. 2022). For example, Oppermann et al. (2017) showed that RATA intensity resulted in similar overall configurations compared to GDA. However, it is important to note that RATA results should be interpreted with more caution and warrant a deeper investigation on how the RATA scales are understood and used by consumers, particularly when conducted in multiple language. This is discussed more in depth in the chapter 6.4.4.

6.4.3 Participants in sensory studies

In Study I, the respondents were volunteers from the greater Helsinki area who were able and willing to try spoonable PB and dairy snacks. Most participants (68%) were students or staff members from the Faculty of Agriculture and Forestry. Moreover, the participants were skewed toward the younger, of whom the majority were female (88%). Thus, care needs to be taken when applying the results to the whole population.

Participants were recruited from the local consumer databases of sensory evaluation laboratories in both countries for Study IV. The study was first conducted in Amherst, MA, US, and then in Turku, Finland. Recruitment occurred according to the predetermined quota for age, health status, and consumption of yogurts. Both studies were conducted during the high corona pandemic peak, which impacted the final panel size. The participants in both countries were also skewed toward young students, most of whom were female. As a result, the food neophobia scores were, on average, relatively low. Food neophobia usually decreases from childhood to adulthood (Tuorila et al., 1998, 2001). Furthermore, both locations in the US and Finland were urban areas and panelists represented university staff and students. The results could have been different if the consumers came from less urban areas.

6.4.4 Culture and language

Cross-cultural research is becoming increasingly relevant in consumer and sensory science, motivated by the need to move from local to global perspectives (Meiselman, 2013) and the research not being as tedious and expensive as it used to be (Slater & Yani-de-Soriano, 2010). However, cross-cultural research poses several limitations to the validity and generalizability of the findings. Many of the challenges are reviewed by Ares (2018). These include sampling procedures, conceptual and linguistic equivalence, data collection procedures, and cultural differences in response style. It has been previously demonstrated that highly trained panels in different countries can provide comparable results using standardized lexicons (Drake et al., 2005; Murray et al., 2001). However, since the aim of Study IV was to understand the differences, particularly in hedonic responses, we used consumer panels.

Another challenge could be the use of scales due to cultural differences in response style and interpretation of scale anchors. Thus, we decided to use choice-based methods like CATA as much as possible. The challenge, however, in CATA questions is that it requires accurate translations of the descriptors to assure identical meaning in both cultures and languages. This should be noted when cross-cultural studies are conducted in countries with multiple cultural backgrounds and ethnicities like the US. Ares et al. (2018) reviewed differences in response style among cultural or ethnic groups within the same country. For example, studies conducted in the United States have shown that white non-Hispanic people are less likely to show extreme response style than white Hispanics (Marín et al., 1992). In this study, 53% of the US consumers were Caucasian, 39% Asian, and only 4% Hispanic or Latino, and 4% of the consumers did not disclose their ethnicity or identified as "other". The variation within the US results could be due to the distribution within the ethnicities, however this was not studied in the thesis.

Finnish derives from the Finno-Ugric and English from Indo-European languages and thus have very few commonly derived words in everyday language. Although the two cultures have some strong parallels in dietary habits (e.g., moderate to high intake of dairy products), there are some differences between the countries. For example, Finland, among other Northern countries like Scotland and Canada, have a long tradition of using oat in various foods (Webster & Wood, 2011). In Finland, the food use of oat is rapidly increasing (Natural Resources Institute Finland, 2019), whereas, in the US, it is not as widely consumed. Lawless et al. (1997) studied Finnish and English texture terms among consumers and food professionals. They concluded that the categorization for the texture terms was generally similar for the two knowledge groups and the two language groups. However, some of the differences are attributed to nuance or differences in shades of meaning and connotation. One example is that Finnish has three specific words for the English term "thick." In retrospect, perhaps a better translation for thick would have been "jähmeä" instead of "paksu," as it better describes the resistance to flow rather than dimensional thickness. However, since it was evident that the studied samples were yogurts, it was also evident that the thickness in the mouth would refer to resistance to flow even though the term in Finnish was "paksu" instead of "jähmeä."

7 CONCLUSIONS

This thesis has examined the texture perception and acceptance of plant-based (PB) yogurts. The first aim of this thesis was to characterize the mouthfeel and physicochemical properties of plant-based yogurts. This characterization of commercial Finnish PB yogurts was established for the first time. The dynamic mouthfeel profiles varied considerably depending on the PB sample. Our first hypothesis was that PB and dairy yogurts have a similar mouthfeel profile. The results did not confirm this hypothesis. At the same time, we discovered that the typical attributes used to describe dairy yogurts were also relevant for describing PB yogurts. Our second hypothesis was that the PB and dairy yogurts had different structures. The results confirmed the second hypothesis and indicated that PB and dairy yogurts with a similar mouthfeel profile might have very different viscoelastic properties. Given this, the importance of rheological large deformation tests and their ability to explain essential mouthfeel sensations should be considered when developing PB yogurts.

The second aim of the thesis was to determine the selected factors on texture and mouthfeel perception, including added aroma, product information, visual experience, and cross-cultural differences. There are challenges to overcoming the negatively associated mouthfeel properties in PB yogurts. We hypothesized that enhanced sweetness perception by the added aroma enhances perceived thickness. The aromas affected the sweetness perception; however, the mouthfeel properties were not enhanced or suppressed by the aromas alone or by the enhanced sweetness sensation, rejecting this third hypothesis. The results showed that mouthfeel is not easily modified by added aromas. Further research on aroma–texture relationships could focus on other characteristics like creamy, smooth, slimy, and watery.

We also aimed to determine the impact of product information, visual experience, and cross-cultural differences on mouthfeel perception. These factors were studied in the final study. First, product information that included the name of the yogurt (dairy vs. PB) did not affect the intensity of mouthfeel perception, stressing that the expectations for mouthfeel properties were similar for PB and dairy yogurts among consumers. Second, the role of visual experience on mouthfeel was studied. This thesis proposes that consumer perception of texture is affected differently by visual experience and mouthfeel, depending on sample and texture characteristics. For example, the perception of thickness is emphasized by visual experience in PB yogurts. This underlines that care needs to be taken when giving instructions on evaluating the texture of a yogurt sample. Third, the role of cross-cultural differences on mouthfeel was studied. The results indicate that the interpretation of mouthfeel can vary depending on the culture and language. The most significant difference was found in the descriptor creamy, potentially due to the differences in languages and the PB yogurt market between the US and Finland. The term creamy is also a complex attribute and may cause differences in the interpretation of the term between the panels. Such multi-layered attributes should be used with care in cross-cultural studies.

The third aim of the thesis was to examine the consumer acceptance of plant-based yogurts among Finnish and US consumers. The results showed no major differences in overall liking of PB yogurts between the consumers in Southwestern Finland and Massachusetts, suggesting that consumers in Finland and the US may like yogurts similarly. Consumers' demographics or attitudes did not explain the results. This could be a result of similar consumer groups in both countries. We hypothesized that Finnish consumers would be more familiar with oat-based products than US consumers and that familiarity would have a positive impact on the acceptability of plant-based yogurts. Even though more Finnish consumers had tried PB yogurts, it was not associated with a greater liking of oat yogurts. The results indicate that prior experience with oat-based yogurts and oat foods does not necessarily impact the liking of the studied samples, rejecting our initial hypothesis. This suggests that expectations could be driven by experience with conventional products rather than with a novel PB food.

Finally, we aimed to define the relative importance of different texture properties. We hypothesized that creaminess would be a driver of liking within PB yogurts. That was confirmed in both consumer studies (I and IV). Particularly, the mouthfeel property creaminess was a driver of liking, and wateriness and sliminess were drivers of disliking in both countries in Study IV. The results also suggest that consumers in the US value texture properties over other attributes more than Finns. More research is required to show this.

We suggested that as we increase dairy content in PB yogurt it would increase the liking due to increasing expected sensory properties. As expected, yogurts with a higher proportion of dairy were more liked compared to samples with a lower proportion of dairy. The results are precise: on a 9-point hedonic scale, there is a 2-point difference in overall liking between PB and dairy yogurts, underlining that there is still work to be done if a similar acceptance for PB yogurts as dairy yogurts is wanted. However, mimicking dairy-like mouthfeel in PB yogurt is possibly still tricky to achieve primarily due to the different macromolecules that form their structures. A possibility to develop blended samples would help the green transition to be faster and more efficient.

Two views often dominate the conversations about plant-based foods. The first is that PB foods should mimic their animal counterparts. The second is that new PB categories should be developed next to the well-established conventional food categories. Our results emphasize that the ideas are not mutually exclusive. Although yogurts with a higher proportion of dairy were more liked than samples with a lower proportion of dairy, there is a growing segment of young consumers who accept PB yogurts that are different from typical dairy yogurts. To support the transition to more sustainable diets, a deep understanding of product perception and the consumer traits that determine acceptance or rejection is required. Moreover, culturally relevant implications should be understood to meet consumer expectations in different countries. While more research on sensory perception and consumer acceptance of various PB foods is required in academia and industry, also authorities should focus on new ways of implementing PB foods to be more accessible to a wider audience.

The power of sensory perception in the motivation of consumers toward sustainable food behavior is fascinating. So far, the human senses are the best instruments for the overall sensory evaluation of food to understand complex food experiences. The sensory properties of products should be good enough for consumers. In order for newly introduced products to succeed on the market in the longer term, sensory food science offers various opportunities for food product development and business.

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