Food Quality and Preference 119 (2024) 105235

Contents lists available at ScienceDirect

Food Quality and Preference

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

The effect of viscosity on flavour, mouthfeel and koku enhancement by tastants and yeast extracts in beef broths

Rutger Brouwer [a,*], Tessa Bouwkamp [a], Elke Scholten [b], Ciaran G. Forde [c], Markus Stieger [a,c]

[a] Food Quality and Design, Wageningen University & Research, The Netherlands
[b] Physics and Physical Chemistry of Foods, Wageningen University & Research, The Netherlands
[c] Sensory Science and Eating Behaviour, Wageningen University & Research, The Netherlands

ARTICLE INFO

Keywords:
Kokumi
Yeast extract
Taste enhancers
Koku enhancement
Temporal-Check-All-That-Apply
Cross-modal interactions

ABSTRACT

This study investigated the effect of viscosity on the dynamic sensory perception of savoury beef broths enriched with savoury enhancers to evaluate the effect of perceived thickness on the koku enhancement effect (*i.e.* thickness, flavour duration, and complexity). Beef broths were enriched with five combinations of tastants and taste enhancers [none (control); sodium chloride (NaCl); a combination of monosodium glutamate (MSG) and inosine monophosphate (IMP); yeast extract (Kokumax-100); a combination of yeast extract (Kokumax-100) with MSG and IMP]. Three levels of viscosity [low (η=0.72 mPa.s); medium (η=2.94 mPa.s); high (η=12.65 mPa.s)] were obtained by adding different concentrations of locust bean gum (0.00, 0.20, 0.40 w/w%) to beef broths. Temporal-Check-All-That-Apply (TCATA) profiling showed that yeast extract with MSG-IMP enhanced the intensity, richness, body, and duration of savoury sensations of low-viscous beef broths, demonstrating a koku enhancement effect. Increasing the viscosity of broths decreased the perception of taste (*i.e.* saltiness and savouriness) and flavour (*i.e.* beef flavour) for most broths, demonstrating a cross-modal suppression of taste and flavour by viscosity. Only broths with yeast extract (Kokumax-100) with MSG-IMP demonstrated stable flavour and taste enhancement across all broth viscosity levels. Koku enhancement by yeast extract (Kokumax-100) with MSG-IMP, MSG-IMP, and NaCl was observed for mouthfeel properties in broths with low and medium viscosity, but not in broths with high viscosity suggesting a suppression of koku enhancement at high broth viscosity. We conclude that (i) yeast extract (Kokumax-100) produces koku enhancement in liquid savoury broths when combined with taste enhancers monosodium glutamate (MSG) and inosine monophosphate (IMP), and (ii) the magnitude of the koku enhancement depends on the presence of taste enhancers and is attenuated at higher broth viscosity.

1. Introduction

Yeast extracts and kokumi compounds have been shown to affect the mouthfeel and flavour of foods. Kokumi compounds are typically di- or tripeptides such as γ-glutamyl-valyl-glycine and γ-glutamyl-cysteinyl-glycine that generate a rich, continuous, intense, and harmonious taste sensation (Nishimura & Kuroda, 2019). Kokumi compounds have no taste on their own but enhance umami, saltiness, sweetness, fattiness, continuity, mouthfulness, and thickness when added to foods (Ueda et al., 1990; Yamamoto & Inui-Yamamoto, 2023). In broths, the addition of kokumi compounds has been shown to enhance the perception of umami, beef flavour, mouthfulness, mouth-coating, thickness, and continuity (Dunkel et al., 2007; Hong et al., 2010; Miyaki et al., 2015; Tang et al., 2020), which is referred to as koku enhancement. The multidimensional enhancing properties of kokumi compounds make them promising ingredients to potentially reduce the fat, salt, and energy content of foods (Forde & Stieger, 2024). Kokumi compounds have been suggested as functional taste ingredients to support public health efforts to reduce the content of fat, salt, and to reduce energy density of foods (Forde & Stieger, 2024). The addition of kokumi compounds might compensate for the decline in mouthfeel, taste and flavour caused by fat, salt and energy reduction. Studies to date on kokumi compounds have been performed in low viscosity liquids or semi-solid foods (Li et al., 2022). These studies demonstrated that the addition of kokumi compounds enhances the perceived thickness (*i.e.* in mouth viscosity), continuity (duration of the sensation), and mouthfeel of savoury, umami

* Corresponding author.
E-mail address: rutger.brouwer@wur.nl (R. Brouwer).

https://doi.org/10.1016/j.foodqual.2024.105235
Received 14 April 2024; Received in revised form 27 May 2024; Accepted 27 May 2024
Available online 31 May 2024

solutions, broths, and soups (Shah et al., 2013; Ueda et al., 1990, 1994, 1997; Yang et al., 2017). The majority of studies investigating koku enhancement have been performed in liquid foods and the effect of adding kokumi compounds on koku enhancement in semi-solid and solid foods is underexplored. Miyamura et al. (2015) showed that kokumi compounds improved the thick flavour, aftertaste, and oiliness of fat-reduced peanut butter (Miyamura et al., 2015). Toelstede et al. (2009) isolated and identified kokumi compounds that enhance mouthfulness and complex taste continuity in Gouda cheese (Toelstede et al., 2009). One of the central components of koku enhancement is a stronger feeling of in-mouth thickness or viscosity, which has been linked to the feeling of richness and flavour complexity. This enhancement occurs without an associated increase in physical viscosity, suggesting it is perceptual in nature. It remains unclear how this perceptual enhancement occurs. Whereas the taste synergy between savoury taste-enhancing compounds is known, the complex interplay between the enhanced perceived thickness and changes in physical viscosity requires deeper exploration.

The enhanced continuity and complexity are temporal attributes that are best captured by dynamic sensory approaches. Tang et al. used Temporal-Check-All-That-Apply (TCATA) to study the effect of kokumi compounds on koku enhancement for a series of beef broths (Tang et al., 2020) and demonstrated that kokumi compounds enhanced the duration and intensity of savoury taste, flavour, mouthfeel, and aftertaste attributes.

Increasing the viscosity of liquid foods enhances perceived thickness and can suppress taste and flavour intensity through cross-modal texture-taste or texture-flavour interactions (Christensen, 1980; Cook et al., 2003; Deblais et al., 2021; Hollowood, 2002; Moskowitz & Arabie, 1970). Little is known about the interaction between physical changes in a food's viscosity and the perceptual effect of kokumi compounds on koku enhancement. The current study aimed to explore the effect of physical viscosity on the dynamic sensory perception of savoury beef broths enriched with savoury enhancers to evaluate the effect of perceived thickness on the koku enhancement effect (*i.e.* thickness, flavour duration, and complexity). Beef broths differing in viscosity and savoury enhancer composition were prepared, and the dynamic perception of taste, flavour, and mouthfeel was determined using the Temporal Check-All-That-Apply methodology.

2. Materials and methods

2.1. Preparation of base beef broth

Beef broths were prepared as previously described with minor modifications (Tang et al., 2020). In a large pan, 1540 g beef blade steak (AH Greenfields beef blade steak, Albert Heijn B.V., Netherlands), 317 g white onion (AH Gele uien, Albert Heijn B.V., Netherlands), 280 g white radish (Rettich, Groentehal de Goudreinet B.V., Netherlands), 233 g spring onion (AH Bosui, Albert Heijn B.V., Netherlands), and 75 g garlic (AH Knoflook, Albert Heijn B.V., Netherlands) were added to 7 L water and heated to boiling. The heat was then lowered, and the broth simmered for one hour. The broth was cooled to room temperature and strained through a double-layered cheesecloth to obtain the base beef broth. A fresh stock of base beef broth was prepared each morning of a test day. All ingredients used were food-grade. Sample preparation was executed in a food-safe environment and followed a safe for consumption protocol.

2.2. Preparation of beef broths differing in composition and viscosity

In total, 15 beef broths differing in composition and viscosity were prepared. The base beef broth (control) was enriched with different combinations of sodium chloride (NaCl, Salt extra fine, Jozo, Netherlands), monosodium glutamate (MSG, >99 % purity, Ajinomoto Foods Europe SAS, France), inosine monophosphate (IMP, International Flavour & Fragrances, Netherlands), and yeast extract (Kokumax-100, Kerry Ingredients & Flavours Ltd, Ireland) to obtain 5 different sample types (Table 1). The exact chemical composition of the yeast extract (Kokumax-100) is proprietary. However, Kokumax-100 is a yeast extract that is used as savoury and kokumi taste enhancer. Yeast extracts typically contain different kokumi di- and tripeptides such as γ-Glu-Leu, γ-Glu-Val, γ-Glu-Tyr and γ-Glu-Cys-Gly (Liu et al., 2015). Three levels of broth viscosity [low (η=0.72 mPa.s); medium (η=2.94 mPa.s); high (η=12.65 mPa.s)] were obtained by dissolving locust bean gum at different concentrations (0.0, 0.2, 0.4 w/w%) in the broth during boiling (Table 1). The viscosity of broths was determined using a rheometer (MCR 302 Rheometer, Anton Paar Benelux BVBA, Belgium) equipped with a DG26.7/Ti cup and a C-DG26.7/T200/Ti concentric cylinder. Flow curves were determined at shear rates ranging from 0.1 to 100 s^{-1} at a temperature of 55 °C. All broths displayed Newtonian flow behaviour.

2.3. Participants

Participants were recruited from the surroundings of the Wageningen University campus by posters, word of mouth, and online recruitment. All participants met the following inclusion criteria: aged between 18 and 30 years old, good general health (self-reported), non-vegetarian or non-vegan, no allergies, non-smoker (self-reported), and not pregnant. A panel of n = 42 participants (18 male, 24 female; age 24 ± 3 y; mean BMI 22.2 ± 2.5 kg/m^2) participated in the study. All participants

Table 1
Beef broths differing in viscosity and composition together with sample codes. The following abbreviations were used: LBG – locust bean gum, NaCl – sodium chloride, MSG – monosodium glutamate, IMP – inosine monophosphate and Kokumax-100 – yeast extract.

Viscosity	LBG (% w/w)	Composition	Concentration (% w/w)	Sample code
Low (0.72 mPa.s)	–	Base beef broth (control)	–	B
Low (0.72 mPa.s)	–	Base beef broth + NaCl	0.25 NaCl	NaCl
Low (0.72 mPa.s)	–	Base beef broth + MSG + IMP	0.8 MSG + 0.44 IMP	MI
Low (0.72 mPa.s)	–	Base beef broth + Kokumax-100	0.4 Kokumax-100	K
Low (0.72 mPa.s)	–	Base beef broth + Kokumax-100 + MSG + IMP	1.2 Kokumax-100 + 1.2 MSG + 0.67 IMP	KMI
Medium (2.94 mPa.s)	0.2	Base beef broth (control)	–	0.2B
Medium (2.94 mPa.s)	0.2	Base beef broth + NaCl	0.25 NaCl	0.2NaCl
Medium (2.94 mPa.s)	0.2	Base beef broth + MSG + IMP	0.8 MSG + 0.44 IMP	0.2MI
Medium (2.94 mPa.s)	0.2	Base beef broth + Kokumax-100	0.4 Kokumax-100	0.2 K
Medium (2.94 mPa.s)	0.2	Base beef broth + Kokumax-100 + MSG + IMP	1.2 Kokumax-100 + 1.2 MSG + 0.67 IMP	0.2KMI
High (12.65 mPa.s)	0.4	Base beef broth (control)	–	0.4B
High (12.65 mPa.s)	0.4	Base beef broth + NaCl	0.25 NaCl	0.4NaCl
High (12.65 mPa.s)	0.4	Base beef broth + MSG + IMP	0.8 MSG + 0.44 IMP	0.4MI
High (12.65 mPa.s)	0.4	Base beef broth + Kokumax-100	0.4 Kokumax-100	0.4 K
High (12.65 mPa.s)	0.4	Base beef broth + Kokumax-100 + MSG + IMP	1.2 Kokumax-100 + 1.2 MSG + 0.67 IMP	0.4KMI

Table 2
Sensory attributes and definitions used for TCATA evaluations.

Attribute	Definition
Taste	
Savouriness	The savoury taste intensity associated with monosodium glutamate.
Saltiness	The salty taste intensity associated with sodium chloride.
Sourness	The sour taste intensity associated with lemon/citric acid.
Flavour	
Beef flavour	The beef flavour intensity associated with cooked beef.
Spring onion flavour	The spring onion flavour intensity associated with freshly cut spring onion.
Mouthfeel	
Body thickness	The perception of volume, thickness, and viscosity of broth in the mouth.
Mouthcoating	The degree to which there is a leftover residue, a slick coating or film in the mouth that is difficult to clear.
Creaminess	The perception of a smooth texture, rather thick but which behaves like a fluid product when slightly pushing the tongue against the palate.

received an information brochure, joined an information session, and were given the opportunity to ask questions about the study. All participants signed an informed consent form. Participants were financially reimbursed for their participation.

2.4. Temporal-check-all-that-apply (TCATA)

Participants (n = 42) evaluated all samples using the Temporal-Check-All-That-Apply (TCATA) fading method in duplicate. The TCATA method used a pre-defined sensory attribute list (based on previous literature and pilot testing) including taste, flavour, and mouthfeel descriptors (Table 2). During the sample evaluation, participants pressed a start button in the TCATA software when they placed the broth in their mouth. Participants were instructed to swirl the broth in the mouth for 5 s before swallowing. Participants then continuously selected attributes that they perceived as applicable for 60 s on a screen. The selection of an attribute faded automatically after 8 s. Participants could reselect attributes during and after the fading period. Participants could not actively deselect attributes. The fading option eased the task burden of participants since they only had to focus on selecting attributes as they were perceived, and not on deselecting (Ares et al., 2016). The presentation order of the attributes was randomized for every participant, but the order was kept constant for each participant within a session.

2.5. Experimental approach

Participants attended five 60-minute sessions over a period of three weeks. The first session was a familiarisation session, the following four sessions were used for TCATA data collection.

In the familiarisation session, a brief presentation of the entire study was given to the participants. In this session, the TCATA procedure was explained to the participants, and they were introduced to the software. The attribute list (Table 2) was shared with participants to familiarise them with the attributes and definitions. Following that, participants tasted the base broth (control), NaCl broth, and KMI broth to familiarise themselves with the samples that potentially have the greatest differences in terms of mouthfeel, taste, and flavour. The consumption protocol was introduced (swirl samples in the mouth for 5 s) and practised. Finally, participants had the opportunity to ask questions and fill out a questionnaire about their demographic data and availability.

Participants were instructed not to eat, drink, smoke, brush their teeth, or wear perfume two hours before the four data collection sessions. During data collection sessions, participants first received a warm-up sample (beef broth with NaCl) to briefly reintroduce the test protocol, attributes, and definitions. Participants received 7 or 8 beef broth samples *per* session. Broths were presented monadically in brown glass vials following a completely randomised design. Three-digit codes were randomly assigned to each sample, with different codes across replicates. The broths were placed in a water bath to ensure a constant serving temperature of 55 °C. Participants were instructed to cleanse their palate with water and a cracker between samples. All samples were assessed by the participants (n = 42) in duplicate.

2.6. Data analyses

The TCATA results are frequency data for every citation *per* participant *per* attribute over time (one rating *per* second). The sum of citations was divided by the total number of participants to obtain the average citation proportion at each timepoint for each attribute. The average citation proportions were plotted against the consumption time to construct TCATA curves using the ggplot2 package (Meyners & Castura, 2018; Wickham et al., 2024). Two types of TCATA curves were used to visualize the data: (a) TCATA curves displaying one attribute for all samples at one viscosity level and (b) TCATA curves showing one attribute for one sample at three viscosity levels. The first type of TCATA curve allows for comparison of the broths. Highlighted bold lines in the TCATA curves represent significant differences, determined using Fisher's exact test, in the citation proportion between a broth compared to the control broth at that given moment in time (Castura et al., 2016; Meyners et al., 2016). Significant differences between all broths were determined by Fisher's pairwise comparison test using the rstatix package. The second type of TCATA curves allows for comparison of the low-viscous broths with the medium- and high-viscous broths. Highlighted bold lines represent significant differences in the citation proportion between the medium- or high-viscous broth compared with the low-viscous broth. The following parameters were extracted from the TCATA curves for every attribute of every sample: the citation maximum (C_{max}) is the maximum citation proportion of the TCATA curve, the time of maximum citation (T_{max}) is the timepoint at which the maximum citation proportion of the TCATA curve is reached, the area under the curve (AUC) is the cumulative area under the TCATA curve, the citation proportion end (C_{end}) is the citation proportion at the final timepoint of the TCATA evaluation, and the half time ($T_{0.5}$) is the time period that it takes for the maximum citation proportion to decline to half of its value (Castura et al., 2016; Visalli & Galmarini, 2024). For C_{max} and C_{end}, significant differences between broths were determined using Fisher's pairwise comparison test. For AUC, significant differences between broths were determined by a linear mixed model using the lme4 package (Bates & Maechler, 2023; Kassambara, 2023; McMahon et al., 2017). For T_{max} and $T_{0.5}$, no statistical data analysis was performed since these parameters were extracted from average citation proportion curves and have no raw data points, so only absolute differences were extracted and interpreted. All statistical data analyses were performed at a significance level of $p \leq 0.05$ using R software (R Core Team. (2023), 2023).

3. Results

The TCATA curves of all samples are provided in the supplementary materials (**Figure S1**) and the parameters extracted from the TCATA

Table 3
Summary of TCATA parameters for taste attributes extracted from TCATA curves (n = 42, duplicate) for beef broths varying in composition and viscosity. Different lower case letters indicate significant differences between samples in the same row ($p < 0.05$). The curve parameters C_{max}, AUC, C_{end}, T_{max}, and $T_{0.5}$ correspond to the maximum citation proportion, the area under the curve, the citation proportion at the end of the curve, the time to reach the maximum citation proportion, and the time after which maximum citation proportion declined to half of its value, respectively.

		Low viscosity					Medium viscosity					High viscosity				
		Base	NaCl	MI	K	KMI	0.2Base	0.2NaCl	0.2MI	0.2 K	0.2KMI	0.4Base	0.4NaCl	0.4MI	0.4 K	0.4KMI
Savouriness	C_{max}	0.33^{a}	0.60^{cdef}	0.72^{ef}	0.61^{cdef}	0.67^{def}	0.38^{ab}	0.56^{cde}	0.68^{def}	0.59^{cde}	0.74^{f}	0.33^{a}	0.54^{bcd}	0.64^{def}	0.46^{abc}	0.74^{f}
	AUC	10.9^{ab}	19.1^{cd}	27.4^{f}	20.3^{cde}	25.8^{def}	10.5^{ab}	17.6^{bc}	26.4^{ef}	19.7^{cde}	28.0^{f}	9.9^{a}	15.7^{abc}	23.2^{def}	15.5^{abc}	25.2^{def}
	C_{end}	0.07^{a}	0.10^{ab}	0.26^{cd}	0.17^{bde}	0.32^{c}	0.05^{a}	0.10^{ab}	0.24^{cd}	0.18^{bde}	0.26^{cd}	0.05^{a}	0.12^{abef}	0.22^{ce}	0.06^{af}	0.22^{ce}
	T_{max} (s)	15	20	14	14	12	14	16	20	17	14	19	19	11	17	16
	$T_{0.5}$ (s)	11	15	20	25	20	9	15	33	17	23	6	18	23	17	29
Saltiness	C_{max}	0.20^{ab}	0.41^{de}	0.59^{fg}	0.39^{cde}	0.69^{g}	0.15^{a}	0.39^{de}	0.51^{ef}	0.30^{bcd}	0.61^{fg}	0.12^{a}	0.35^{cd}	0.52^{ef}	0.24^{abc}	0.58^{fg}
	AUC	4.0^{ab}	11.7^{bcd}	19.6^{e}	10.1^{bc}	21.4^{e}	3.0^{a}	10.3^{bc}	16.4^{cde}	8.3^{ab}	21.8^{e}	2.3^{a}	7.0^{ab}	16.7^{de}	5.0^{ab}	17.2^{de}
	C_{end}	0^{a}	0.01^{a}	0.14^{c}	0.02^{a}	0.17^{c}	0.01^{a}	0.04^{ab}	0.11^{bc}	0.01^{a}	0.17^{c}	0.01^{a}	0.02^{a}	0.11^{bc}	0^{a}	0.14^{c}
	T_{max} (s)	14	17	13	11	11	12	17	17	17	14	17	16	12	12	14
	$T_{0.5}$ (s)	9	19	25	20	23	12	14	14	11	30	6	7	23	14	20
Sourness	C_{max}	0.30^{bcde}	0.21^{abc}	0.23^{abcd}	0.45^{e}	0.37^{de}	0.32^{bcde}	0.20^{ab}	0.22^{abc}	0.37^{de}	0.33^{bcde}	0.30^{bcde}	0.14^{a}	0.30^{bcde}	0.33^{bcde}	0.35^{cde}
	AUC	8.1^{abc}	5.1^{ab}	5.8^{abc}	11.3^{c}	11.2^{c}	8.5^{abc}	4.9^{ab}	6.5^{abc}	9.4^{abc}	8.4^{abc}	7.9^{abc}	3.8^{a}	7.6^{abc}	10.7^{bc}	9.6^{abc}
	C_{end}	0.04^{ab}	0.02^{ab}	0.01^{b}	0.02^{ab}	0.09^{a}	0.05^{ab}	0.02^{ab}	0.01^{b}	0.01^{b}	0.02^{ab}	0.04^{ab}	0.02^{ab}	0.02^{ab}	0.05^{ab}	0.07^{ab}
	T_{max} (s)	13	18	16	14	18	12	21	14	12	12	14	18	13	19	18
	$T_{0.5}$ (s)	16	14	10	12	19	14	7	18	19	15	17	17	18	19	14

Table 4
Summary of TCATA parameters for flavour attributes extracted from TCATA curves (n = 42, duplicate) for beef broths varying in composition and viscosity. Different lower case letters indicate significant differences between samples in the same row ($p < 0.05$). The curve parameters C_{max}, AUC, C_{end}, T_{max}, and $T_{0.5}$ correspond to the maximum citation proportion, the area under the curve, the citation proportion at the end of the curve, the time to reach the maximum citation proportion, and the time after which maximum citation proportion declined to half of its value, respectively.

		Low viscosity					Medium viscosity					High viscosity				
		Base	NaCl	MI	K	KMI	0.2Base	0.2NaCl	0.2MI	0.2 K	0.2KMI	0.4Base	0.4NaCl	0.4MI	0.4 K	0.4KMI
Beef flavour	C_{max}	0.39^{ab}	0.60^{cdef}	0.67^{defg}	0.59^{cde}	0.74^{fg}	0.35^{a}	0.52^{bcd}	0.76^{g}	0.55^{bcde}	0.76^{g}	0.29^{a}	0.44^{abc}	0.58^{cde}	0.52^{bcd}	0.70^{efg}
	AUC	8.9^{ab}	16.9^{cde}	20.4^{def}	20.4^{def}	24.8^{f}	8.0^{ab}	14.8^{abc}	22.9^{ef}	15.0^{bcd}	26.4^{f}	6.5^{a}	12.8^{abc}	18.7^{cdef}	15.1^{bcd}	24.5^{f}
	C_{end}	0.04^{a}	0.01^{a}	0.12^{bcde}	0.12^{bcde}	0.16^{def}	0.02^{a}	0.06^{ac}	0.12^{bcde}	0.04^{a}	0.24^{f}	0.01^{a}	0.07^{abd}	0.12^{bcde}	0.07^{abd}	0.19^{ef}
	T_{max} (s)	12	16	14	15	15	15	17	15	12	15	12	12	14	14	16
	$T_{0.5}$ (s)	11	15	20	25	20	9	15	33	17	23	6	18	23	17	29
Spring onion flavour	C_{max}	0.38^{abc}	0.44^{bc}	0.49^{c}	0.43^{bc}	0.48^{bc}	0.42^{bc}	0.37^{abc}	0.50^{c}	0.39^{abc}	0.44^{bc}	0.26^{a}	0.41^{bc}	0.46^{bc}	0.33^{ab}	0.38^{abc}
	AUC	9.9^{ab}	12.7^{b}	13.9^{b}	11.2^{ab}	12.3^{b}	10.1^{ab}	11.2^{ab}	12.5^{b}	10.0^{ab}	10.5^{ab}	4.9^{a}	9.2^{ab}	10.9^{ab}	8.9^{ab}	10.6^{ab}
	C_{end}	0.01^{ab}	0.06^{b}	0.05^{ab}	0.04^{ab}	0.01^{ab}	0.04^{ab}	0.02^{ab}	0.07^{b}	0.05^{ab}	0.02^{ab}	0^{a}	0.02^{ab}	0.07^{b}	0.01^{ab}	0.06^{b}
	T_{max} (s)	17	16	14	11	13	17	20	14	14	12	14	15	13	14	14
	$T_{0.5}$ (s)	12	16	17	8	17	12	17	17	16	16	12	13	16	17	12

Table 5
Summary of TCATA parameters for mouthfeel attributes extracted from TCATA curves (n = 42, duplicate) for beef broths varying in composition and viscosity. Different lower case letters indicate significant differences between samples in the same row ($p < 0.05$). The curve parameters C_{max}, AUC, C_{end}, T_{max}, and $T_{0.5}$ correspond to the maximum citation proportion, the area under the curve, the citation proportion at the end of the curve, the time to reach the maximum citation proportion, and the time after which maximum citation proportion declined to half of its value, respectively.

		Low viscosity					Medium viscosity					High viscosity				
		Base	NaCl	MI	K	KMI	0.2Base	0.2NaCl	0.2MI	0.2 K	0.2KMI	0.4Base	0.4NaCl	0.4MI	0.4 K	0.4KMI
Body thickness	C_{max}	0.16^{a}	0.31^{bc}	0.31^{bc}	0.23^{ab}	0.31^{bc}	0.27^{abc}	0.37^{bcde}	0.35^{bcd}	0.29^{bc}	0.39^{cde}	0.51^{def}	0.58^{f}	0.60^{f}	0.52^{ef}	0.58^{f}
	AUC	2.4^{a}	6.1^{ab}	5.3^{ab}	4.6^{ab}	6.6^{ab}	5.1^{ab}	7.7^{bcd}	7.5^{bc}	5.4^{ab}	7.6^{bc}	11.04^{cde}	14.0^{e}	13.7^{e}	12.1^{de}	12.3^{e}
	C_{end}	0^{a}	0.01^{a}	0^{a}	0.01^{a}	0.02^{a}	0.01^{a}	0^{a}	0^{a}	0^{a}	0.04^{a}	0.04^{a}	0.05^{a}	0.02^{a}	0.01^{a}	0.04^{a}
	T_{max} (s)	14	16	14	11	14	13	14	15	15	13	15	13	13	14	15
	$T_{0.5}$ (s)	7	8	10	11	10	11	8	12	10	11	10	15	12	14	9
Mouth-coating	C_{max}	0.20^{a}	0.27^{ab}	0.33^{abc}	0.29^{ab}	0.36^{bcd}	0.30^{abc}	0.38^{bcd}	0.41^{bcd}	0.38^{bcd}	0.32^{abc}	0.50^{de}	0.58^{e}	0.46^{cde}	0.59^{e}	0.52^{de}
	AUC	6.6^{a}	10.0^{ab}	12.6^{b}	10.0^{ab}	11.0^{ab}	9.9^{ab}	12.2^{ab}	15.3^{bc}	11.4^{ab}	12.6^{b}	19.8^{cd}	22.1^{d}	19.3^{cd}	20.9^{cd}	19.7^{cd}
	C_{end}	0.05^{a}	0.11^{abc}	0.14^{bcd}	0.11^{abc}	0.17^{bcd}	0.05^{a}	0.09^{ab}	0.22^{d}	0.11^{abc}	0.13^{abcd}	0.21^{cd}	0.21^{cd}	0.21^{cd}	0.18^{bcd}	0.22^{d}
	T_{max} (s)	18	22	20	28	20	20	24	23	18	24	17	27	16	17	17
	$T_{0.5}$ (s)	33	38	39	21	17	21	21	33	23	35	33	27	40	33	33
Creaminess	C_{max}	0.16^{a}	0.26^{abc}	0.30^{bcde}	0.17^{ab}	0.28^{abcd}	0.23^{abc}	0.43^{defg}	0.35^{cdef}	0.24^{abc}	0.28^{abcd}	0.50^{fg}	0.57^{g}	0.53^{g}	0.50^{fg}	0.44^{efg}
	AUC	3.1^{a}	6.2^{ab}	4.9^{ab}	3.4^{a}	5.8^{ab}	5.3^{ab}	9.0^{bc}	7.4^{abc}	5.2^{ab}	6.7^{ab}	11.4^{cd}	13.5^{d}	13.7^{d}	14.2^{d}	11.5^{cd}
	C_{end}	0^{a}	0.02^{a}	0.02^{a}	0^{a}	0^{a}	0^{a}	0.01^{a}	0.01^{a}	0.01^{a}	0^{a}	0^{a}	0.04^{a}	0^{a}	0.05^{a}	0.02^{a}
	T_{max} (s)	14	17	12	9	11	14	13	14	13	13	16	10	11	12	10
	$T_{0.5}$ (s)	12	6	9	17	17	11	11	11	12	20	11	16	16	18	21

curves (C_{max}, AUC, C_{end}, T_{max}, $T_{0.5}$) are summarised in Tables 3, 4, and 5, for taste, flavour, and mouthfeel attributes, respectively. **Section 3.1** describes the effects of combinations of taste enhancers on the taste, flavour, and mouthfeel of broths. **Section 3.2** focuses on the temporality (*e.g.* aftertaste, continuity, and roundness) of taste, flavour, and mouthfeel of broths differing in composition. **Section 3.3** describes the effect of viscosity on the taste, flavour, and mouthfeel of the broths.

3.1. Effect of taste enhancers on taste, flavour, and mouthfeel of broths

The addition of salt (NaCl), Kokumax-100 (K), MSG-IMP (MI), and Kokumax-100 with MSG-IMP (KMI) to low, medium, and high viscous base beef broths significantly increased C_{max}, AUC, and C_{end} for most taste and flavour attributes (Tables 3 and 4). This was especially the case for KMI and MI broths, which showed considerably higher enhancements of savouriness, saltiness, and beef flavour than the NaCl and K broths. The enhancement of sourness and spring onion flavour by NaCl, MI, K, and KMI was relatively small compared to the enhancement of other taste and flavour attributes and was not consistently significant. The addition of KMI to low viscous broths increased C_{end} of savouriness, C_{max}, AUC, and C_{end} of saltiness, and C_{max}, AUC, and C_{end} of beef flavour compared to the base broth. The addition of MI to low viscous broths increased C_{max} and AUC of savouriness compared to the base broth. At medium viscosity, the enhancement was attenuated, but KMI displayed the largest significant enhancements of taste and flavour attributes compared to the other broths (NaCl, MI, and K). KMI at medium viscosity increased C_{max}, AUC, and C_{end} of savouriness, saltiness, and beef flavour compared to the base broth. MI at medium viscosity showed a similar enhancement of these attributes, but the enhancement was less pronounced than for KMI. The enhancement of taste and flavour by KMI and MI was also observed in the high viscous broths, though attenuated compared to the low viscosity broth (Tables 3 and 4). KMI at high viscosity increased C_{max}, AUC, and C_{end} of savouriness, saltiness, and beef flavour compared to the base broth. In the case of MI, C_{end} of savouriness increased compared to base broth. Overall, compared to the other taste enhancers, the addition of KMI to the base broth had the largest enhancement effect on taste and flavour attributes at all viscosities. These results confirm the koku enhancement by monosodium glutamate and inosine monophosphate in combination with the yeast extract Kokumax-100 (KMI). The largest enhancements in C_{end} were found in the KMI broth, indicating longer-lasting taste and flavour sensations.

Regarding mouthfeel, the addition of NaCl, K, MI, and KMI enhanced the mouthfeel properties of low and medium viscous broths but did not affect the mouthfeel of the high viscous broths. MI and KMI broths showed the largest enhancement of mouthfeel properties, in line with the results for taste and flavour enhancement. For low viscous broths, KMI increased C_{max} of body thickness and C_{max} and C_{end} of mouth-coating compared to the base broth. MI at low viscosity increased C_{max} of body thickness, AUC of mouth-coating, and C_{max} of creaminess compared to the base broth, whereas these enhancements were not seen for KMI. At medium broth viscosity, the addition of KMI did not show a significant enhancement of mouthfeel properties. Only MI and NaCl broths displayed significant enhancement of mouthfeel at medium broth viscosity, increasing C_{end} of mouth-coating, whereas NaCl increased C_{max} of creaminess. These results confirm that MSG-IMP in combination with the yeast extract also shows the koku enhancement for mouthfeel for low and medium viscosities. The koku enhancement of mouthfeel by KMI was not observed in high viscous broths, in contrast to the results for taste and flavour attributes.

3.2. Effect of taste enhancers on temporality of taste, flavour, and mouthfeel of broths

The different taste enhancing compounds did not only affect the C_{max}, AUC, and C_{end} but also affected the temporality of taste, flavour, and mouthfeel, quantified as the time to reach maximum citation proportion (T_{max}; build-up of sensation) and the time to halve maximum citation proportion ($T_{0.5,}$ lingering of sensation). $T_{0.5}$ increased for most attributes for the NaCl, MI, K, and KMI broths compared to the base broth, demonstrating a slower decay of taste, flavour, and mouthfeel attributes after C_{max} was reached (prolongation of taste, flavour, and mouthfeel perception). This prolongation effect was observed for all viscosities. T_{max} of taste, flavour, and mouthfeel attributes differed by up to 10 s between broths within attributes (Tables 3, 4 and 5). However, T_{max} did not show systematic variations with the addition of the various taste enhancers. This suggests that the taste enhancers prolonged the lingering of taste, flavour, and mouthfeel attributes without considerably influencing the dynamic build-up of these attributes.

The TCATA curves for the taste and flavour attributes of all broths at all viscosities are depicted in Fig. 1**.** The strongest enhancements of the temporal profiles of savouriness, saltiness, and beef flavour were found for the MI and KMI broths, with consistent enhancement of the temporal profile of taste and flavour attributes for over 90 % of the timespan at all viscosities (Fig. 1**A – F, 1 J – L**). The TCATA curves show that KMI and MI strongly increased the continuity of the taste and flavour profiles at all viscosities.

The TCATA curves for the mouthfeel attributes of all broths are depicted in Fig. 2**.** Also in this case, especially MI and KMI strongly

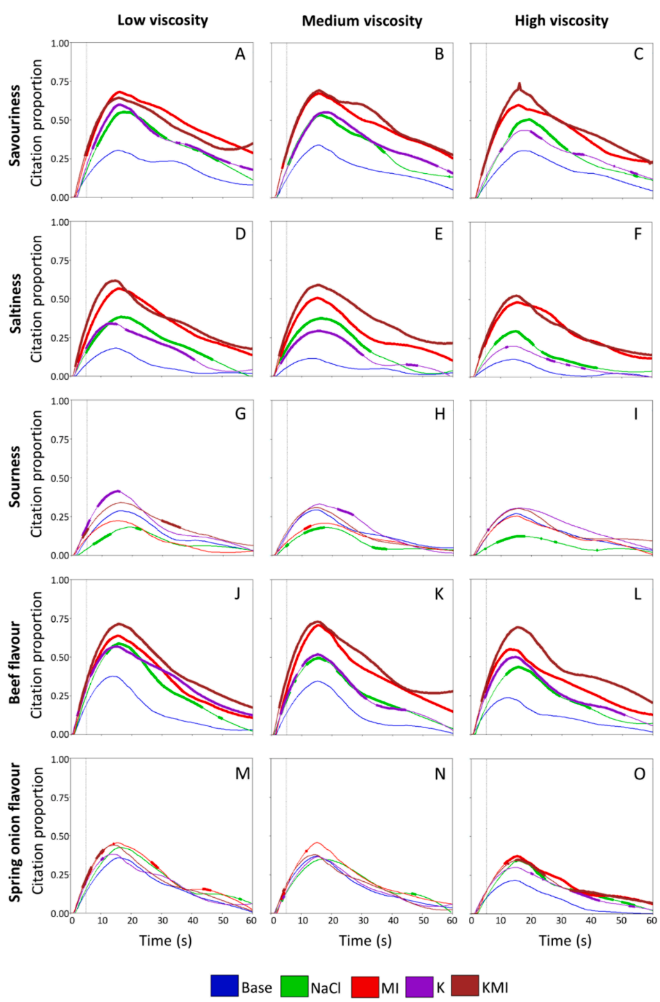

Fig. 1. TCATA profiles (n = 42, duplicate) of taste and flavour attributes of 15 beef broths at low, medium, and high viscosity showing beef flavour (A,B,C), savouriness (D,E,F), saltiness (G,H,I), spring onion flavour (J,K,L), and sourness (M,N,O). Thick lines indicate significant differences in citation proportion of an attribute when comparing the sample to the base broth using Fisher's exact test ($p \leq 0.05$). The vertical lines indicate the swallowing moment.

enhanced the temporal profiles of body thickness and mouth-coating. At low viscosity, MI and KMI significantly enhanced body thickness and mouth-coating for 60 % of the total timespan (Fig. 2**A, 2D**) and creaminess for 20 % of the total timespan (Fig. 2**G**) compared to the base broth. In medium viscosity broths, only KMI showed enhanced body thickness and mouth coating (Fig. 2**B, 2E**) compared to the base broth. No significant enhancements of mouthfeel attributes by the addition of taste enhancers were observed in high viscosity broths (Fig. 2**C, 2F, 2I**). To summarize, MI and KMI had similar effects on the enhancement of mouthfeel in low and medium viscous broths. As the influence of taste enhancers and yeast extracts (Kokumax-100) on mouthfeel was considerably reduced or negligible at high viscosity, we can conclude that viscosity of broths reduces the potential of taste enhancers and kokumi compounds to enhance mouthfeel while enhancement of taste and flavour is maintained (**section 3.3**).

3.3. *Influence of viscosity on temporal taste, flavour and mouthfeel perception of broths*

Increasing broth viscosity decreased taste and flavour perception of the base, NaCl, K, and MI broths. In contrast, for the KMI broths, increasing the viscosities from 0.72 to 2.94 mPa.s or from 0.72 to 12.65 mPa.s yielded no or only small reductions in taste and flavour perceptions. The KMI broth had the lowest reduction in beef flavour and savouriness, which demonstrates that the koku enhancement is still present in high viscous broths. The increase in viscosity enhanced the mouthfeel properties (body thickness, mouth-coating, and creaminess) of all broths: the base, NaCl, K, MI, and KMI broths. However, when increasing the viscosities from 0.72 to 2.94 mPa.s and from 0.72 to 12.65 mPa.s the KMI broth showed the smallest enhancements and some reductions for mouth-coating and creaminess.

The low viscous KMI broth also displayed large mouthfeel enhancement (Table 5 and Fig. 2). When the broth viscosity was increased, the mouthfeel enhancement of KMI decreased as mouthfeel profiles became similar across broths. These differences in mouthfeel enhancement due to broth viscosity show that the physical properties of the broths dominated the enhancement effects. The potential of taste enhancers and yeast extracts to enhance mouthfeel decreases with increasing broth viscosity. It is remarkable that enhancement of taste and flavour by taste enhancers and yeast extracts is less affected by viscosity, since taste and flavour enhancement was observed at all viscosity levels.

In contrast to the changes in C_{max}, AUC, and C_{end} of taste, flavour, and mouthfeel attributes, increasing viscosity did not systematically affect the temporality (*i.e.* T_{max} and $T_{0.5}$) of taste, flavour, and mouthfeel in the broths. This shows that the aftertaste and continuity can be affected by both kokumi compounds and viscosity, but the direction of the effect depends largely on the matrix and the enhancers.

4. Discussion

The current study explored the effect of viscosity on the dynamic sensory perception of beef broths enriched with taste enhancers, including a yeast extract (Kokumax-100). Low-, medium-, and high-viscous broths enriched with sodium chloride, MSG-IMP, Kokumax-100, and Kokumax-100 with MSG-IMP displayed significantly more intense and richer savoury, salty, and beef flavour profiles compared to the base beef broth. The broth with the combination of Kokumax-100 and MSG-IMP had the largest koku enhancement in terms of flavour intensity, complexity, and duration. The koku flavour enhancement was retained across viscosity levels, though mouthfeel effects were attenuated at higher viscosity. Our findings demonstrate that the combination of kokumi compounds from Kokumax-100 with MSG-IMP had the strongest koku enhancement and produced the most intense, rich, and long-lasting taste, flavour, and mouthfeel profile.

Kokumax-100 is a yeast extract that is used as savoury and kokumi

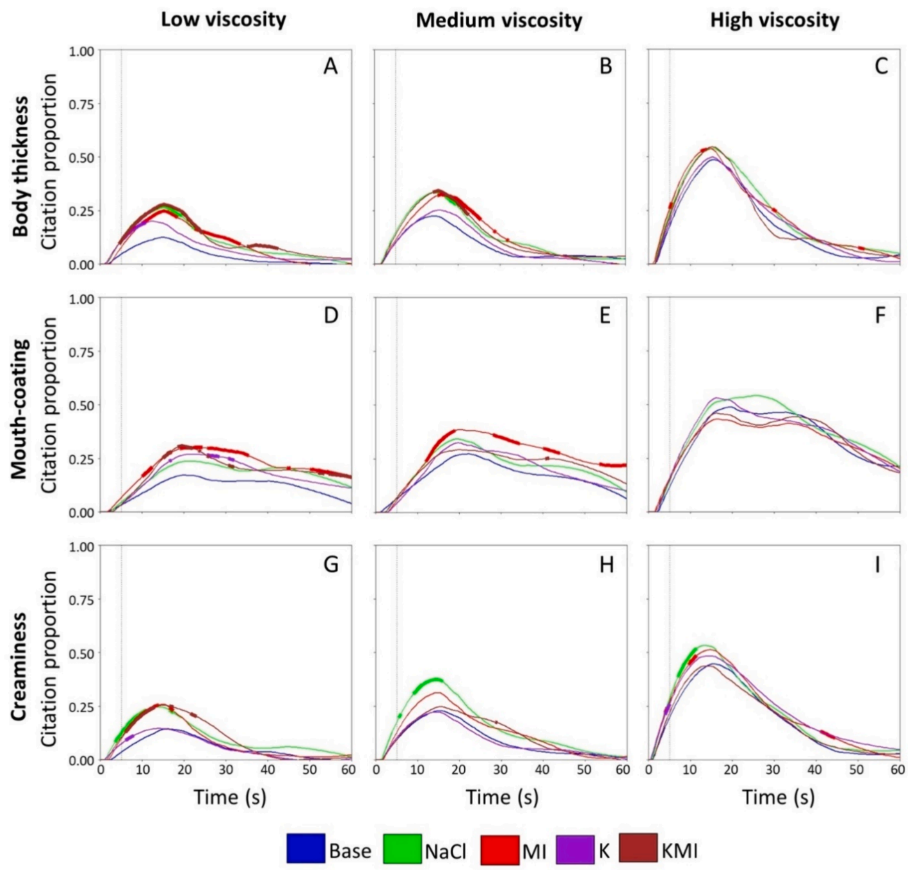

Fig. 2. TCATA profiles (n = 42, duplicate) of mouthfeel attributes of 15 beef broths at low, medium, and high viscosity showing body thickness (A,B,C), mouth-coating (D,E,F), and creaminess (G,H,I). Thick lines indicate significant differences in citation proportion when comparing the sample to the base broth using Fisher's exact test ($p \leq 0.05$). The vertical lines indicate the swallowing moment.

taste enhancer. Yeast extracts typically contain different kokumi di- and tripeptides (Liu et al., 2015). The kokumi compounds in the yeast extract had a smaller effect on the sensory profiles of beef broths when served alone, as opposed to when combined with MSG and IMP. Literature has shown that kokumi compounds do not influence taste or flavour perception when they are present in a matrix without any other taste compounds (Kuroda & Miyamura, 2015; Ueda et al., 1990). The largest flavour enhancement was indeed found for the Kokumax-100 with MSG-IMP. This is in line with previous research that investigated the synergistic effects of kokumi compounds and savoury taste enhancers. These studies have shown that the overall flavour intensity of beef broths increased when kokumi compounds were combined with savoury taste enhancers (Hong et al., 2012; Jung et al., 2010; Tang et al., 2020). At low viscosity, the addition of different taste enhancers did not lead to a physical change in viscosity, yet broths with NaCl, MSG-IMP, and Kokumax-100 with MSG-IMP enhanced the perception of perceived body thickness, mouth-coating, and creaminess. The combination of savoury enhancing compounds, such as MSG and IMP, are known for enhancing the continuity, mouthfulness, impact, and thickness of food products, creating a richer sensory experience with little additional calories (Yamaguchi & Kimizuka, 1979).

With increasing viscosity of the broths, a decrease in taste and flavour for most broths was observed. In the medium viscous broths, the reduction of taste and flavour was considerably smaller than in the high viscous broths, and this can be explained by the lower concentration of locust bean gum (LBG). At low locust bean gum concentrations, intermolecular entanglements are not formed (González-Tomás et al., 2004), so the diffusion of flavour and taste molecules is not much affected. Similarly, González-Tomás et al. (2004) found no changes in perceived aroma intensity in solutions with a low concentration of locust bean gum. In the more viscous broths, the flavour, taste, and mouthfeel profile were reduced in intensity. This is in line with previous studies that observed a decrease in flavour intensity when substantially increasing the viscosity (Cook et al., 2003; Delwiche, 2004; Ferry et al., 2006; Hollowood, 2002; Malone et al., 2003). One explanation is a reduction in the diffusion coefficient of the flavour molecules within the matrix due to more entanglements of the locust bean gum, which has also been shown to provide a lower release of aroma in other studies (de Roos, 2006; Lubbers, 2006). The slower diffusion leads to a lower number of interactions between the tastants and the sensors on the tongue. Another explanation could be physical or chemical interactions between the thickening agent and aroma compounds, which lead to a lower release and perception of aroma. In addition, the decreased fluidity of the higher viscous broths may lead to a reduced spreading of the broth through the mouth and, subsequently, a reduction in the contact area between the broth and the tongue. These situations would lead to a reduction in stimulated taste papillae and, consequently, decrease taste perception (Malone et al., 2003). The flavour of the broth with Kokumax-100 with MSG and IMP was only slightly attenuated by the increase in viscosity.

Increasing broth viscosity led to an increase in perceived body thickness, mouth-coating, and creaminess for all broths. Such an increase in different mouthfeel attributes is in line with previous research. For example, an increase in thickness as a result of an increase in viscosity was also observed for semi-solid and fluid foods (Stanley & Taylor, 1993), an increase in creaminess for oil-in-water emulsions and soups (Akhtar et al., 2005; Daget & Joerg, 1991), and an increase in mouth-coating for emulsions (Camacho et al., 2015) Textural differences between the base broth and the broths with taste enhancers diminished at the high viscosity level. This suggests that the physical increase in viscosity suppressed the perceptual koku mouthfeel enhancement that was observed at lower viscosity. The reduction of koku enhancement at higher viscosities could be explained by Weber's law. Weber's law states that the minimal change in stimulus intensity necessary to perceive a notable difference is a constant fraction of the original stimulus intensity (Fechner & Adler, 1966). The concentration of the yeast extract (Kokumax-100) was kept constant across broths differing in viscosity, whereas the change in physical viscosity caused by addition of locust bean gum led to an increase in thickness. This implies that the stimulus intensity (thickness) of the high viscous broths was larger than the stimulus intensity of the low viscous broths. Consequently, in order to perceive an enhancement in mouthfeel properties by Kokumax-100 with MSG and IMP in high viscous broths, the minimal mouthfeel enhancement needs to be proportionally larger and equivalent to the perceptual effect of the increased thickness. Consequently, the high viscous broths might display mouthfeel enhancement by Kokumax-100 with MSG-IMP when the concentration of these compounds is proportionally increased. Notably, the koku enhancement of taste and flavour attributes was maintained at higher viscosity, while the koku enhancement of mouthfeel properties was reduced. The magnitude of koku enhancement was thus higher for taste and flavour attributes than for mouthfeel attributes (*i.e.* body thickness, mouth-coating, and creaminess). These findings highlight an inhibition rather than a synergy between the physical and perceptual *thickness* of the broths. This also presents a future challenge of applying koku enhancement in semi-solid and solid food systems through the addition of kokumi compounds.

Koku enhancement is also associated with an increase in the duration of savoury sensations, which contributes to an overall perception of greater 'richness'. The addition of Kokumax-100 with MSG-IMP to the broth samples also influenced the lingering of flavour perception in the current trial, with an increased duration of savouriness, saltiness, sourness, beef flavour, body thickness, and mouth-coating of broths containing Kokumax-100 with MSG-IMP. This is in line with previous studies that found that kokumi peptides have the potential to enhance lingering (Dunkel et al., 2007; Toelstede et al., 2009).

The implication of these findings is that low-calorie flavour enhancers, such as MSG-IMP and kokumi tri-peptides from yeast extracts, can be added to recreate the richness associated with higher-calorie broths to sustain the perception of richness and savoury intensity. This shows promise for a variety of food categories and research areas. More knowledge of kokumi compounds could help to improve the quality of low-caloric soups, broths, and drinks, making them more appealing to consumers, and to extend and apply koku enhancement to solid, savoury foods. New food product categories, such as meat, dairy, and snack alternatives, struggle to replicate the savoury taste, richness, and mouthfeel of the foods they strive to mimic. Understanding how to dose different taste enhancers, such as kokumi compounds, in these new more solid-like product categories could significantly improve the overall quality of the products. However, transferring the koku enhancement by kokumi compounds from liquids to solid foods requires additional research, as demonstrated by the current study.

5. Conclusions

We conclude that (i) the yeast extract Kokumax-100 in combination with monosodium glutamate and inosine monophosphate showed koku enhancement in liquid savoury broths, and (ii) the magnitude of the koku enhancement depends on the presence of other taste enhancers and is attenuated with increasing broth viscosity. While koku enhancement of taste and flavour attributes by Kokumax-100 with monosodium glutamate and inosine monophosphate was maintained at high broth viscosity, the koku enhancement of mouthfeel properties was reduced considerably by the increased broth viscosity. Using a combination of different compounds shows promising effects for applications and enhancement of taste, flavour, and mouthfeel properties in low-caloric, low viscous foods, and potentially also in solid matrices or new food applications.

Ethical statement

Participants joined a familiarization session and received an information brochure about the study. They were given the time and opportunity to ask questions. They were fully aware of what participation to the current study meant. Participants all gave an affirmative reply and signed an informed consent form before they enrolled the study. The informed consent stated:

- I have read the information brochure. I was able to ask all my questions. My questions have been answered sufficiently. I have had enough time to decide whether or not to participate.
- I understand that participation is voluntary. I also know that I may decide at any time to not participate or to stop participating in the study. Without stating any reason.
- I know that for study monitoring purposes some individuals could have access to all my data. Those people are listed in this information brochure. I consent to that access by these persons.
- I give consent to collect and use my personal data for the purposes described in the information brochure.
- I consent to my data being stored at the research location for another 15 years after publication of this study.
- I want to participate in this study.

Finally, all the consumed products were safe for consumption.

CRediT authorship contribution statement

Rutger Brouwer: Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Tessa Bouwkamp:** Methodology, Investigation, Conceptualization. **Elke Scholten:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Ciaran G. Forde:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Markus Stieger:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: C. G. Forde has received reimbursement for speaking at conferences sponsored by companies selling nutritional products and serves on the scientific advisory council for Kerry Taste and Nutrition, and is part of an academic consortium that has received research funding from Abbott Nutrition, Nestec, and Danone. The other authors have no conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgements

We like to thank Kerry Taste and Nutrition and International Flavors and Fragrances for donating the Kokumax-100 and the inosine monophosphate, respectively. We thank Nova Heesakkers for her help with the data collection and Claudia Tang for her feedback on the broth preparation. This research was funded and performed within the framework of the public-private partnership project "Improving sensory quality of meat analogues" funded by TKI (Topsector Agri & Food, Netherlands, grant number LWV20.78). Partners of the project are Symrise AG, Germany; Nissin Foods Holding, Japan; Starfield, China;

AAK, Sweden; Vivera, Netherlands; and GoodMills Innovation, Germany.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2024.105235.

References

Akhtar, M., Stenzel, J., Murray, B. S., & Dickinson, E. (2005). Factors affecting the perception of creaminess of oil-in-water emulsions. *Food Hydrocolloids, 19*(3), 521–526. https://doi.org/10.1016/j.foodhyd.2004.10.017

Ares, G., Castura, J. C., Antúnez, L., Vidal, L., Giménez, A., Coste, B., Picallo, A., Beresford, M. K., Chheang, S. L., & Jaeger, S. R. (2016). Comparison of two TCATA variants for dynamic sensory characterization of food products. *Food Quality and Preference, 54*, 160–172. https://doi.org/10.1016/j.foodqual.2016.07.006

Bates, D., Maechler, M., Bolker [aut, B., cre, Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., simulate. formula), P. N. K. (shared copyright on, & Tanaka, E. (2023). *lme4: Linear Mixed-Effects Models using 'Eigen' and S4* (1.1-35.1) [Computer software]. https://cran.r-project.org/web/packages/lme4/index.html.

Camacho, S., Liu, K., Linden, A., Stieger, M., & van de Velde, F. (2015). Formation, Clearance and Mouthfeel Perception of Oral Coatings Formed by Emulsion-Filled Gels. *Journal of Texture Studies, 46*, 399–410. https://doi.org/10.1111/jtxs.12140

Castura, J. C., Antúnez, L., Giménez, A., & Ares, G. (2016). Temporal Check-All-That-Apply (TCATA): A novel dynamic method for characterizing products. *Food Quality and Preference, 47*, 79–90. https://doi.org/10.1016/j.foodqual.2015.06.017

Christensen, C. M. (1980). Effects of solution viscosity on perceived saltiness and sweetness. *Perception & Psychophysics, 28*(4), 347–353. https://doi.org/10.3758/BF03204394

Cook, D. J., Hollowood, T. A., Linforth, R. S. T., & Taylor, A. J. (2003). Oral shear stress predicts flavour perception in viscous solutions. *Chemical Senses, 28*(1), 11–23. https://doi.org/10.1093/chemse/28.1.11

Daget, N., & Joerg, M. (1991). Creamy perception Ii. In model soups. *Journal of Texture Studies, 22*(2), 169–189. https://doi.org/10.1111/j.1745-4603.1991.tb00012.x

de Roos, K. B. (2006). 11—Modelling aroma interactions in food matrices. In A. Voilley, & P. Etiévant (Eds.), *Flavour in Food* (pp. 229–259). Woodhead Publishing. https://doi.org/10.1533/9781845691400.2.229.

Deblais, A., Hollander, E. D., Boucon, C., Blok, A. E., Veltkamp, B., Voudouris, P., Versluis, P., Kim, H.-J., Mellema, M., Stieger, M., Bonn, D., & Velikov, K. P. (2021). Predicting thickness perception of liquid food products from their non-Newtonian rheology. *Nature Communications, 12*(1), 6328. https://doi.org/10.1038/s41467-021-26687-w

Delwiche, J. (2004). The impact of perceptual interactions on perceived flavor. *Food Quality and Preference, 15*(2), 137–146. https://doi.org/10.1016/S0950-3293(03)00041-7

Dunkel, A., Köster, J., & Hofmann, T. (2007). Molecular and sensory characterization of γ-glutamyl peptides as key contributors to the kokumi taste of edible beans (Phaseolus vulgaris L.). *Journal of Agricultural and Food Chemistry, 55*(16), 6712–6719. https://doi.org/10.1021/jf071276u

Fechner, G. T., & Adler, H. E. (1966). *Elements of Psychophysics*. Rinehart and Winston: Holt.

Ferry, A.-L., Hort, J., Mitchell, J. R., Cook, D. J., Lagarrigue, S., & Valles Pamies, B. (2006). Viscosity and flavour perception: Why is starch different from hydrocolloids? *Food Hydrocolloids, 20*(6), 855–862. https://doi.org/10.1016/j.foodhyd.2005.08.008

Forde, C., & Stieger, M. (2024). Perceptual and Nutritional Impact of Kokumi Compounds. In M. Kuroda (Ed.), *Kokumi Substance as an Enhancer of Koku: Biochemistry, Physiology, and Food Science* (pp. 229–242). Springer Nature. https://doi.org/10.1007/978-981-99-8303-2_13.

González-Tomás, L., Carbonell, I., & Costell, E. (2004). Influence of type, concentration and flow behaviour of hydrocolloid solutions on aroma perception. *European Food Research and Technology, 218*(3), 248–252. https://doi.org/10.1007/s00217-003-0852-7

Hollowood, T. A. (2002). The effect of viscosity on the perception of flavour. *Chemical Senses, 27*(7), 583–591. https://doi.org/10.1093/chemse/27.7.583

Hong, J.-H., Kwon, K.-Y., & Kim, K.-O. (2012). Sensory characteristics and consumer acceptability of beef stock containing the glutathione-xylose maillard reaction product and/or monosodium glutamate. *Journal of Food Science, 77*(6), S233–S239. https://doi.org/10.1111/j.1750-3841.2012.02724.x

Hong, J. H., Jung, D. W., Kim, Y. S., Lee, S. M., & Kim, K. O. (2010). Impacts of glutathione maillard reaction products on sensory characteristics and consumer acceptability of beef soup. *Journal of Food Science, 75*(8), S427–S434. https://doi.org/10.1111/j.1750-3841.2010.01783.x

Jung, D. W., Hong, J. H., & Kim, K. O. (2010). Sensory characteristics and consumer acceptability of beef soup with added glutathione and/or MSG. *Journal of Food Science, 75*(1), S36–S42. https://doi.org/10.1111/j.1750-3841.2009.01411.x

Kassambara, A. (2023). *rstatix: Pipe-Friendly Framework for Basic Statistical Tests* (0.7.2) [Computer software]. https://cran.r-project.org/web/packages/rstatix/index.html.

Kuroda, M., & Miyamura, N. (2015). Mechanism of the perception of "kokumi" substances and the sensory characteristics of the "kokumi" peptide, γ-Glu-Val-Gly. *Flavour, 4*(1), 11. https://doi.org/10.1186/2044-7248-4-11

Li, Q., Zhang, L., & Lametsch, R. (2022). Current progress in kokumi-active peptides, evaluation and preparation methods: A review. *Critical Reviews in Food Science and Nutrition, 62*(5), 1230–1241. https://doi.org/10.1080/10408398.2020.1837726

Liu, J., Song, H., Liu, Y., Li, P., Yao, J., & Xiong, J. (2015). Discovery of kokumi peptide from yeast extract by LC-Q-TOF-MS/MS and sensomics approach. *Journal of the Science of Food and Agriculture, 95*(15), 3183–3194. https://doi.org/10.1002/jsfa.7058

Lubbers, S. (2006). Texture–aroma interactions. In *Flavour in Food* (pp. 327–344). Elsevier. https://doi.org/10.1533/9781845691400.3.327.

Malone, M. E., Appelqvist, I. A. M., & Norton, I. T. (2003). Oral behaviour of food hydrocolloids and emulsions. Part 2. Taste and aroma release. *Food Hydrocolloids, 17*(6), 775–784. https://doi.org/10.1016/S0268-005X(03)00098-5

McMahon, K. M., Culver, C., Castura, J. C., & Ross, C. F. (2017). Perception of carbonation in sparkling wines using descriptive analysis (DA) and temporal check-all-that-apply (TCATA). *Food Quality and Preference, 59*, 14–26. https://doi.org/10.1016/J.FOODQUAL.2017.01.017

Meyners, M., & Castura, J. C. (2018). The analysis of temporal check-all-that-apply (TCATA) data. *Food Quality and Preference, 67*, 67–76. https://doi.org/10.1016/j.foodqual.2017.02.003

Meyners, M., Jaeger, S. R., & Ares, G. (2016). On the analysis of rate-all-that-apply (RATA) data. *Food Quality and Preference, 49*, 1–10. https://doi.org/10.1016/j.foodqual.2015.11.003

Miyaki, T., Kawasaki, H., Kuroda, M., Miyamura, N., & Kouda, T. (2015). Effect of a kokumi peptide, γ-glutamyl-valyl-glycine, on the sensory characteristics of chicken consommé. *Flavour, 4*(1), 17. https://doi.org/10.1186/2044-7248-4-17

Miyamura, N., Jo, S., Kuroda, M., & Kouda, T. (2015). Flavour improvement of reduced-fat peanut butter by addition of a kokumi peptide, γ-glutamyl-valyl-glycine. *Flavour, 4*(1), 16. https://doi.org/10.1186/2044-7248-4-16

Moskowitz, H. R., & Arabie, P. (1970). Taste intensity as a function of stimulus concentration and solvent viscosity. *Journal of Texture Studies, 1*(4), 502–510. https://doi.org/10.1111/j.1745-4603.1970.tb00748.x

Nishimura, T., & Kuroda, M. (Eds.). (2019). *Koku in Food Science and Physiology: Recent Research on a Key Concept in Palatability*. Springer. https://doi.org/10.1007/978-981-13-8453-0.

R Core Team. (2023). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. https://www.R-project.org/.

Shah, A. K. M. A., Ogasawara, M., Kurihara, H., & Takahashi, K. (2013). Effect of drying on creatine/creatinine ratios and subsequent taste of herring (clupea pallasii) fillet. *Food Science and Technology Research, 19*, 691–696. https://doi.org/10.3136/fstr.19.691

Stanley, N. L., & Taylor, L. J. (1993). Rheological basis of oral characteristics of fluid and semi-solid foods: A review. *Acta Psychologica, 84*(1), 79–92. https://doi.org/10.1016/0001-6918(93)90074-2

Tang, C. S., Tan, V. W. K., Teo, P. S., & Forde, C. G. (2020). Savoury and kokumi enhancement increases perceived calories and expectations of fullness in equicaloric beef broths. *Food Quality and Preference, 83*. https://doi.org/10.1016/j.foodqual.2020.103897

Toelstede, S., Dunkel, A., & Hofmann, T. (2009). A series of kokumi peptides impart the long-lasting mouthfulness of matured gouda cheese. *Journal of Agricultural and Food Chemistry, 1440–1448*. https://doi.org/10.1021/jf803376d

Ueda, Y., Sakaguchi, M., Hirayama, K., Miyajima, R., & Kimizuka, A. (1990). Characteristic flavor constituents in water extract of garlic. *Agricultural and Biological Chemistry, 54*(1), 163–169. https://doi.org/10.1080/00021369.1990.10869909

Ueda, Y., Tsubuku, T., & Miyajima, R. (1994). Composition of sulfur-containing components in onion and their flavor characters. *Bioscience, Biotechnology, and Biochemistry, 58*(1), 108–110. https://doi.org/10.1271/bbb.58.108

Ueda, Y., Yonemitsu, M., Tsubuku, T., Sakaguchi, M., & Miyajima, R. (1997). Flavor characteristics of glutathione in raw and cooked foodstuffs. *Bioscience, Biotechnology, and Biochemistry, 61*(12), 1977–1980. https://doi.org/10.1271/bbb.61.1977

Visalli, M., & Galmarini, M. V. (2024). Multi-attribute temporal descriptive methods in sensory analysis applied in food science: A systematic scoping review. *Comprehensive Reviews in Food Science and Food Safety, 23*(1), e13294.

Wickham, H., Chang, W., Henry, L., Pedersen, T. L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D., Brand, T. van den, Posit, & PBC. (2024). *ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics* (3.5.0) [Computer software]. https://cran.r-project.org/web/packages/ggplot2/index.html.

Yamaguchi, S., & Kimizuka, A. (1979). Psychometric studies on the taste of monosodium glutamate. *Glutamic Acid: Advances in Biochemsitry and Physiology*, 35–54.

Yamamoto, T., & Inui-Yamamoto, C. (2023). The flavor-enhancing action of glutamate and its mechanism involving the notion of kokumi. *Npj Science of Food, 7*(1). https://doi.org/10.1038/s41538-023-00178-2

Yang, J., Sun-Waterhouse, D., Cui, C., Dong, K., & Wang, W. (2017). Synthesis and sensory characteristics of kokumi γ-[Glu]n-phe in the presence of glutamine and phenylalanine: Glutaminase from bacillus amyloliquefaciens or aspergillus oryzae as the catalyst. *Journal of Agricultural and Food Chemistry, 65*(39), 8696–8703. https://doi.org/10.1021/acs.jafc.7b03419