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A mouthfeel wheel based on physiological mechanisms for the sensory evaluation of beer and alcohol-free beer

Mouthfeel is a multimodal sensory experience and an important component of overall flavour perception, yet it remains less clearly defined than taste and aroma. This study aimed to develop and sensory-validate a practical mouthfeel wheel for beer, with particular focus on alcoholic and non-alcoholic beers. Existing mouthfeel frameworks, including the Meilgaard Beer Flavour Wheel, Langstaff's beer mouthfeel framework, and Gawel's wine mouthfeel wheel, were reviewed to refine terminology and guide the development of a comprehensive physiology-based mouthfeel wheel. A simplified version was created for sensory validation and comparison with existing frameworks. The simplified Wolinska-Kennard Mouthfeel Wheel organises beer mouthfeel attributes into four main categories: Irritation, Sensation, Movement, and Texture. It was compared with the Meilgaard and Langstaff frameworks during sensory evaluation sessions using alcoholic and non-alcoholic beer samples. Panellists assessed the frameworks for clarity, layout, logic, structure, and descriptor use. Statistical analysis showed that all four main categories significantly discriminated between the alcoholic and non-alcoholic beer samples while maintaining acceptable panel agreement. Compared with the Meilgaard and Langstaff frameworks, the simplified Wolinska-Kennard Mouthfeel Wheel provided broader perceptual coverage and more consistent descriptor use.
These findings suggest that the simplified Wolinska-Kennard Mouthfeel Wheel offers a clear and practical tool for beer mouthfeel evaluation, while the comprehensive framework provides a flexible model for future adaptation to different beer styles, applications, and consumer-oriented evaluations.

Descriptors: Mouthfeel, beer, non-alcoholic beer, sensory lexicon

1 Introduction

Mouthfeel is described as a complex and multidimensional sensory experience that involves a range of sensations beyond mechanical properties [1–11]. Despite its significance, mouthfeel is often disregarded and overlooked, especially when compared to the extensive study and wide research dedicated to taste and aroma [4, 5, 12, 13]. The definition of mouthfeel is ambiguous and open to interpretation, often used interchangeably with texture. However, mouthfeel is far more complex. While texture describes the mechanical and structural properties of food (such as firmness, crunchiness, or viscosity), it is only one aspect of the broader mouthfeel experience [2, 4, 5, 13–15]. Mouthfeel is also frequently used interchangeably with other multidimensional terms such as "body" and "palate fullness". Although the scope of these attributes overlaps with the overall mouthfeel experience, they are not strict synonyms and are often used inconsistently [5, 6, 16–23].

Body refers to descriptors such as fullness, smoothness, richness, viscosity, consistency, and compactness of a product's texture and overall flavour perception [6, 18, 23, 24], whereas palate fullness can be seen as one aspect of body, more specifically qualities related to viscosity, density, including the perceived weight and resistance of flow [6, 18, 20, 21].

Mouthfeel recognition arises from the integration of signals from two main sensory pathways: the oral somatosensory and oral chemosensory systems. The oral somatosensory system detects physical sensations, using mechanoreceptors and proprioceptors. It conveys information about texture (e.g. creamy, smooth), pressure (e.g. firmness), and the physical movement and breakdown of food in the mouth [15, 25–27]. The oral chemosensory system, primarily transmitted by the trigeminal nerve (the main neural pathway),

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processes chemical irritants. This results in specific sensations such as cooling, warming, and burning [3, 28, 29].

Instrumental methods provide objective data regarding the physical properties that contribute to mouthfeel, among which are rheological measurements, soft tribology and advanced tools such as electric tongues. While rheology measures features like viscosity and thickness [30–32], soft tribology studies friction and lubrication between surfaces representing tongue and palate [2, 5, 30, 32–34].

Advanced tools, such as Electronic Tongues (ETs) [35, 36] and Quartz Crystal Microbalance (QCM) sensors [37, 38] have been used to measure certain taste signals and mouthfeel attributes in beverages, such as bitterness, astringency, and body. Additionally, a recent study by Melenie Koehler et al. (2024) shows that AFM (Atomic Force Microscopy) can be used to investigate food texture and mouthfeel at the microscopic and molecular levels, providing detailed maps of surface topography and mechanical properties at the nanometre scale [39].

However, these instrumental tools are limited, as they cannot fully capture the entire mouthfeel experience [4]. Consequently, sensory panels remain the most trusted and commonly used approach, as they provide valuable human perception data, though they require more time, training, and resources [40]. To standardise sensory terminology for clear communication among professionals, sensory wheels are used. A sensory wheel is a structured framework that categorises sensory attributes to ensure and support consistent evaluation of food and beverages.

In this study, a new mouthfeel wheel, referred to as the Wolinska-Kennard Wheel, was developed for beer and alcohol-free beer and evaluated against existing frameworks, including Meilgaard Beer Flavour Wheel, Langstaff's beer mouthfeel framework and Gawel's wine mouthfeel wheel, using a trained panel. The aim is to support brewers and beverage producers in describing mouthfeel more clearly and developing more balanced and appealing products. This is especially important in the challenging non- and low-alcohol segments, where mouthfeel is often compromised but plays a key role in consumer acceptance [5, 18].

2 Methods

2.1 Conceptual development of the Wolinska-Kennard Wheel

The development of the Wolinska-Kennard Wheel is based on the most recent research findings that are summarised in a comprehensive review [41] and the critical assessment of the three state-of-the-art mouthfeel wheel frameworks: 1) the Meilgaard Beer Flavour Wheel [42], 2) the Langstaff's beer mouthfeel framework [43], 3) the Gawel's wine mouthfeel wheel [6]. In addition, Schmelzle's Beer Aroma Wheel [45] was reviewed during the development process. Although it is primarily intended for the evaluation of beer aroma and flavour rather than mouthfeel, it includes a limited number of mouthfeel-related descriptors (e.g. mouthfeel, body, foam, texture, viscosity, and astringency). These descriptors were considered during the conceptual development of the comprehensive mouthfeel wheel.

Based on this research, a comprehensive mouthfeel wheel was first developed (Fig. 1A), incorporating a broad range of attributes, including psychological (consumer-oriented) attributes. Then, a simplified version of the wheel was created (Fig. 1B) for the sensory evolution in this study. The reduction aimed to improve usability, reduce panel fatigue and evaluation time, minimise confusion caused by highly similar or overlapping descriptors, account for language differences in an internationally applicable tool, especially when communicating with consumers, and facilitate direct comparison with the Meilgaard and Langstaff frameworks.

Additionally, the descriptor selection was refined during regular tasting sessions involving a range of beer styles (including lager, stout, ale, IPA, and wheat beer, alcoholic and non-alcoholic counterparts), allowing the descriptors to be reviewed and adjusted based on panel feedback. Furthermore, some descriptors were excluded in the simplified wheel because they were not considered relevant to the study, while remaining part of the comprehensive framework. For example, e.g. "slimy" and "ropy" are commonly associated with microbiological spoilage rather than the mouthfeel characteristics evaluated in the present study [44].

The simplified wheel (Fig. 1B) should therefore be viewed as an application-specific version of the comprehensive framework and can be adapted for different evaluation objectives, beer styles, and product categories by selecting descriptors from the comprehensive wheel.

It consists of four physiologically based categories: Sensation, Irritation, Movement, and Texture. Sensation and Irritation represent trigeminal (chemesthetic) perceptions but distinguish between generally non-aversive sensations (e.g. cooling, warming, drying) and sensations perceived as irritating or aversive (e.g. burning, puckering, and numbing). Movement describes the behaviour of the beverage within the oral cavity, including its flow, coating, and persistence, where Texture describes the physical characteristics of the beer perceived in the mouth, such as smoothness and creaminess. Together, these four categories provide a structured physiological framework for beer mouthfeel evaluation.

The following sections describe the rationale behind the selection and organisation of the descriptors included in the proposed mouthfeel framework.

2.1.1 The Beer Flavour Wheel by Meilgaard et al. (1979)

The beer flavour terminology proposed by Meilgaard et al. (1979) has two sections: one for odour and one for taste, which includes a specific section for mouthfeel (Class 13), featuring descriptors like alkaline, mouth-coating, metallic, astringent, powdery, carbonation, warming, and a separate section for fullness (Class 14), which contains only one sub-section, body. Although fullness and body are closely related to mouthfeel, they are presented as distinct categories [42]. Furthermore, in this framework, both mouthfeel and fullness are placed under the broader heading of "taste" and

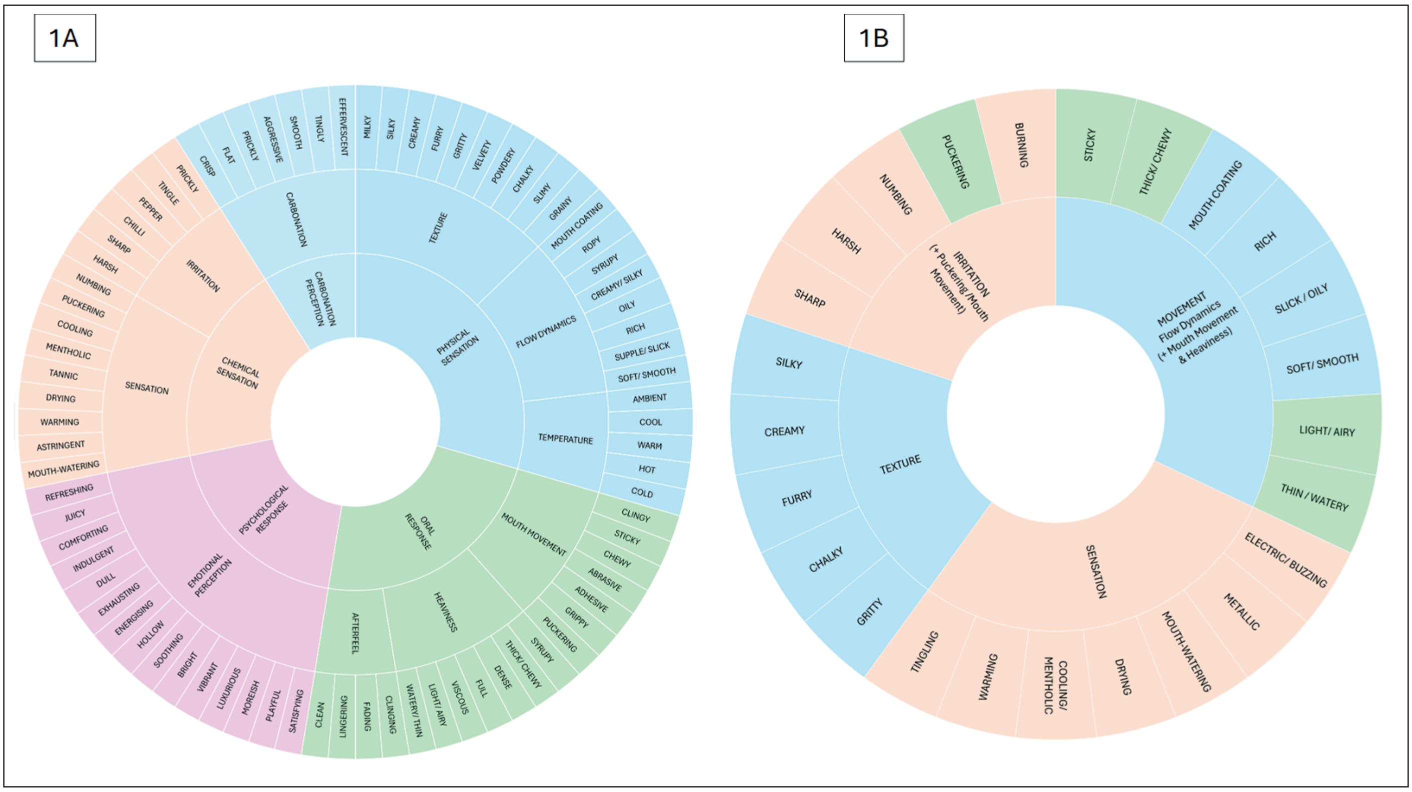

Fig. 1 **(A) Proposed Comprehensive Mouthfeel Wheel for alcoholic and non-alcoholic beers. The colour scheme represents the main aspects of mouthfeel perception. Chemical Sensation (Irritation and Sensation) reflects trigeminal (chemesthetic) perception. Physical Sensation (Texture, Flow Dynamics, and Temperature) represents tactile and mechanoreceptive perception. Oral Response (Mouth Movement, Heaviness, and Afterfeel) reflects oral processing, movement, and the persistence of mouthfeel during and after consumption. Psychological Response (Emotional Perception) represents emotional or hedonic responses. Carbonation Perception is presented separately because carbonation is a key driver of beer mouthfeel, producing both trigeminal and tactile sensations**
(B) Simplified Mouthfeel Wheel used in the validation study. The reduced mouthfeel wheel was derived from the comprehensive framework. The colour scheme illustrates the relationship between the two wheels by indicating the categories from which the descriptors were selected

"odor", which can be argued to be incorrect based on research conducted after 1979. Mouthfeel sensations arise predominantly through tactile and chemesthetic mechanisms rather than taste or smell [46].

In the Wolinska-Kennard Wheel, several components from Meilgaard's work were refined and integrated or excluded:

Integrated and Refined Attributes:

- Metallic sensation was retained but reclassified under Oral Chemosensory (Sensation), as it combines retro-olfactory perception with other chemosensory components, including taste and trigeminal sensations that contribute to metallic flavour perception (metal, metal ions, rust) [47]
- Warming sensations were maintained under Oral Chemosensory (Sensation) to capture heat-related trigeminal responses linked, for example, to ethanol [48]
- Mouth-coating, powdery, and drying sensations were reorganised under Texture, Movement, where they correspond to tactile and proprioceptive experiences such as sticky, silky, chalky, furry, and dry.
- Carbonation (described as flat or gassy) was not retained as a separate section. Instead, its perceptual effects (tingling, sharp, numbing) were included in Sensation category reflecting the fact that similar sensations may arise from different sources (e.g. hop compounds, CO_2) [49]. This approach simplifies the process and prevents panellists from differentiating not only between sensations but also their sources, which can be difficult. However, the carbonation category was included in the comprehensive wheel (Fig. 1A) as part of the broader mouthfeel framework.

Excluded:

- Terms like "body" and "palate fullness" were excluded in the Wolinska-Kennard Mouthfeel Wheel due to their ambiguity and broader meaning (not specific enough).
- However, "body" remains an important descriptor in the overall sensory evaluation of beer and should be considered complementary to the proposed mouthfeel wheel.
- The broad descriptor *astringent/*astringency was excluded as it combines many overlapping sensations, including drying, puckering, roughness, chalky, tightening, harsh, mouth-drying, tea-like [50].
- *Alkaline - the term was not included in* Wolinska-Kennard Mouthfeel Wheel*, as it refers to taste perception rather than mouthfeel.*

2.1.2 The Langstaff beer mouthfeel framework (1991)

Langstaff reorganised the mouthfeel-related classes into three sensory groups: Carbonation (sting, bubble size, foam volume, and total carbon dioxide), Fullness (density and viscosity), and Aftertaste (oily mouthfeel, astringency, and stickiness) [43]. While this represented progress as a mouthfeel sensory approach, it remains limited, as it does not account for a broader range of sensations, such as warming, cooling, drying, among others, which are essential to capture the complexity of mouthfeel fully. Wolinska-Kennard Wheel adapts these concepts to better align with physiological perception.

Integrated and Refined Attributes:

- Carbonation – Langstaff's framework introduces new terms such as foam and bubble size, which were not mentioned in the previous framework. Both have a significant influence on mouthfeel, but within the Wolinska-Kennard Wheel, the focus is placed on the sensory perception or textural quality these features create, rather than on their physical characteristics alone. For example, foam would be described as creamy or silky (Texture). Hence, as previously mentioned, carbonation was not included as a separate section in the Wolinska-Kennard Wheel.
- Oily and Sticky – both terms were incorporated under Movement as slick/oily and sticky.

Excluded:

- Astringency and fullness were removed due to their complex and ambiguous meaning and to prevent overlap with more precisely defined tactile attributes.
- The Aftertaste section was excluded to maintain focus on sensations occurring during oral manipulation rather than post-swallow flavour persistence.

2.1.3 The Red Wine Mouthfeel Wheel by Gawel et al. (2000)

The mouthfeel framework created by Gawel et al. (2000) for red wine provides a detailed and comprehensive spectrum of mouthfeel attributes [6]. Although the framework was originally designed for the wine industry, it served as both an inspiration and a source of valuable descriptive terminology in this study.

This mouthfeel wheel for red wine is divided into four main categories: Feel, Astringency, Acidity and Flavour. The Feel category includes tactile and thermal sensations such as Temperature/Heat (warm, hot, chilli, pepper), Texture and Weight (watery, thin, full, viscous, creamy, syrupy), Chemical or Carbonation Effects (metallic, steely, sour, acidic), and Surface Smoothness (suede, silk, chamois, satin, soft, supple). The Astringency category encompasses sensations linked to drying or tightening in the mouth, including Drying (dry, parching, numbing, rich, puckery), Adhesive (sticky, clingy, mouth-coating), and Particulate or Surface Texture (chalky, grainy, powdery, gritty, dusty). Acidity (metallic, steely, sour, soapy) and Flavour (lift, activity, concentration) are limited to a small number of attributes. Although detailed, several of these terms are either too specific to wine or too numerous for efficient evaluation. Elements from Gawel's framework were selectively adapted into the Wolinska-Kennard Wheel.

Integrated and Refined Attributes:

- Core tactile descriptors like creamy, silky, powdery, chalky were retained under Texture.
- Astringent-related terms such as drying, puckering, numbing, and harsh were included under Sensation and Irritation Category.
- Warming was integrated within Sensation Category to reflect its trigeminal origin.
- Texture and Weight were reframed as movement-related attributes (e.g. thick, chewy, rich, smooth) in Movement, linking them to proprioceptive feedback during oral processing.

Excluded:

- The Acidity and Flavour sections were omitted, as they refer to taste and overall flavour perception rather than tactile or trigeminal sensations.
- Surface Smoothness – the whole category, including descriptors like suede, chamois, and satin, was excluded to improve clarity and relevance for beer evaluation.
- Feel – this descriptor was initially considered for inclusion in the Wolinska-Kennard Wheel; however, the structure was later revised to focus on a physiological perspective.
- Temperature was not included as an attribute, since it depends on serving conditions, but is presented in the comprehensive Mouthfeel wheel.
- Astringency – the term was excluded, and the category was broken down into specific sensations distributed across relevant subcategories in the Wolinska-Kennard Wheel to reduce overlap and clarify sensory meaning.

As a direct result of these comparative observations, literature research and comprehensive feedback from the panel, the structure of the Wolinska-Kennard Wheel was revised to align with physiological mechanisms rather than relying solely on sensory sensations or traditional categories. This approach provides a more systematic foundation for classifying attributes and organises beer mouthfeel attributes from a physiological perspective into four categories: irritation and sensation, linked to the oral chemosensory (chemesthetic) system, and movement and texture, linked to the oral somatosensory system (Fig. 1, Table S1).

Furthermore, several factors which were included in the comprehensive wheel and are known to influence mouthfeel were intentionally excluded from the simplified version of the Wolinska-Kennard Wheel as they are dependent on external conditions, individual differences or not directly relevant to beer. These factors are:

- Pressure - while pressure is a tactile modality (sensations detected by mechanoreceptors) in the perception of semi-solid and solid foods, it is not independently perceived in the context of beer [2, 15]. However, pressure-related experiences that apply to beer are already included within other categories of this framework, e.g. Movement, Texture.

Table 1 Main categories and subcategories of the Meilgaard, Langstaff, and Wolinska-Kennard Wheel used to assess a commercially available German-style wheat beer and its non-alcoholic counterparts

Framework used for evaluation	Main mouthfeel categories Intensity test (1-9) ATTRIBUTES	Mouthfeel sub-categories Check-all-that-apply (CATA) DESCRIPTORS
The Beer Flavour Wheel by Meilgaard et al. (1979)	• Mouthfeel	• Alkaline, • Mouth-coating, • Metallic, • Astringent, • Powdery, • Carbonation, • Warming
	• Fullness	• Body
The Langstaff beer mouthfeel framework (1991)	• Carbonation	• Sting • Bubble size • Foam volume • Total carbon dioxide
	• Fullness	• Density • Viscosity
	• Aftertaste	• Oily mouthfeel • Astringency • Stickiness
Wolinska-Kennard Mouthfeel Wheel (KWK)	• Sensation	• Movement • Texture • Tingling • Warming • Cooling/ Menthol • Mouthwatering • Metallic • Electric/Buzzing
	• Irritation	• Burning • Drying • Puckering • Numbing • Harsh • Sharp
	• Movement	• Thin/Watery • Light/ Airy • Soft/ Smooth • Slick/Oily • Rich • Mouthcoating • Thick/Chewy • Sticky
	• Texture	• Silky • Creamy • Furry • Chalky • Gritty

- Saliva - has an important influence on mouthfeel perception. The lubrication provided by saliva plays a crucial role in mouthfeel by maintaining the stability of the salivary film and stimulating mechanoreceptors [51]. However, it is a highly individual aspect that cannot be easily predicted [52, 53]. Hence, it was not included, as it depends on individual physiology.
- Serving temperature - affects trigeminal sensitivity and texture perception [25, 54]. However, it was not included as a specific attribute, since it mainly depends on serving conditions, which should be selected according to the specific beer style. The authors recommend reporting the temperature of the samples as part of a sensory evaluation.
- Emotional and psychological associations were also excluded to maintain the focus on technical mouthfeel evaluation and to facilitate comparison with existing beer mouthfeel frameworks. However, they have been retained in the comprehensive framework for potential use in future consumer-oriented evaluations.

The Wolinska-Kennard Mouthfeel Wheel organises beer mouthfeel into four physiologically based main categories: Texture, Movement, Irritation, and Sensation, with clear descriptors under each to support comprehensive but panel-friendly evaluation (Fig. 1).

2.1.4 Sensory panel training and descriptor refinement

Before the formal sensory evaluation, the proposed mouthfeel descriptors were developed and refined through regular tasting sessions conducted with the BarthHaas UK Internal Sensory Panel (participants from different departments). Between 12 and 17 panellists participated in these sessions over several months. A range of beer styles, including lager, ale, stout, IPA, and wheat beer, was evaluated to assess the relevance, clarity, and applicability of the proposed descriptors.

To improve panellists' understanding and consistency in descriptor use, a series of reference standards was incorporated into the training. All reference materials were presented at three dilution levels (undiluted, 50:50 with water, and water only) to demonstrate changes in mouthfeel intensity. Sugar syrup was used to demonstrate differences in viscosity and mouthfeel flow. Oat drink was used to illustrate creamy, silky, milky, and smooth textures, as well as differences in flow characteristics. Carbonated water was used to demonstrate tingling, prickly, sparkling sensations, while hop extracts were used to familiarise panellists with drying, puckering, numbing, harsh, sharp, tannic, and warming sensations. Additionally, commercially available peppermint syrup was used as a reference standard to demonstrate cooling and menthol-like sensations.

Following each session, the descriptors and their definitions were discussed to identify ambiguous, overlapping, or redundant terms and to refine their wording.

Feedback from these training sessions contributed to the development of the simplified and final wheel used in the study.

2.2 Sensory evaluation methodology

The Meilgaard wheel and Langstaff's framework were evaluated alongside the simplified Wolinska-Kennard Wheel during sensory sessions. Each framework was used to assess a commercially available German-style wheat beer (5.3% vol.) and its non-alcoholic counterpart (<0.5% vol.). Both beverages were brewed under the Bavarian Purity Law; however, there is no official information from the producer on how the beers were manufactured. Both were purchased from a local retail shop. This selection allowed panellists to compare the three tools regarding the term clarity, layout, logic, overall structure, and their ability to capture differences between samples.

2.2.1 Selected sensory frameworks

Given the limited research on beer-specific mouthfeel evaluation, the Beer Flavour Wheel by Meilgaard et al. (1979) and the Langstaff et al. (1991) beer mouthfeel model were selected for comparison with the Wolinska-Kennard Wheel, as both are directly applicable to beer.

This allowed panellists to compare the three frameworks in terms of term clarity, layout, logic, overall structure, and their ability to capture differences between samples.

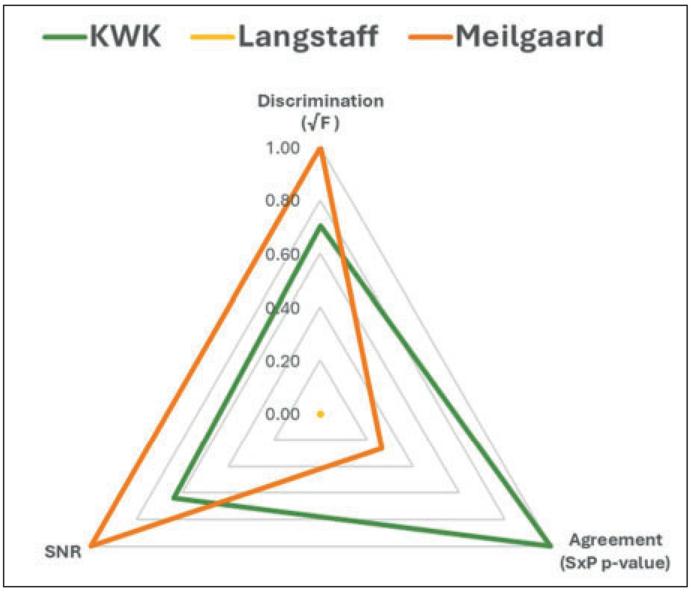

Fig. 2 Radar plot summarising the performance of the three frameworks across three metrics: discrimination strength (mean √F), signal-to-noise ratio (SNR), and panel agreement (mean sample × panellist p-value). Values were normalised using min–max scaling to allow comparison of metrics with different units

The Meilgaard framework included two sections: a specific section for mouthfeel (Class 13), which features descriptors like alkaline, mouth-coating, metallic, astringent, powdery, carbonation, warming and a separate section for fullness (Class 14), which contained only one sub-section - body [42]. The Langstaff framework reorganised the mouthfeel-related classes (Class 13: Mouthfeel and Class 14: Fullness) into three sensory groups: Carbonation (sting, bubble size, foam volume, and total carbon dioxide), Fullness (density and viscosity), and Aftertaste (oily mouthfeel, astringency, and stickiness) [43]. This framework is an adaptation of the mouthfeel-only section of Meilgaard's Beer Flavour Wheel.

2.2.2 Panellist setup and instructions

All evaluations were conducted in a controlled sensory room with neutral lighting and minimal external odours. Panellists completed the assessments using digital tests on a tablet or mobile device via the Compusense platform. Prior to testing, panellists were briefed on the evaluation procedure, including an explanation of each mouthfeel attribute and category.

2.2.3 Sample preparation and serving procedure

Beer samples (alcoholic and non-alcoholic German-style wheat beer) were prepared and served in the sensory area. Beers were stored refrigerated (~4–6 °C) and exposed to room temperature for 30 minutes before serving to reach the recommended wheat-beer temperature (10–12 °C). Bottles were gently inverted twice before serving to evenly mix any sediment. Fifty millilitres of each sample were poured into blue sensory cups, labelled with three-digit random codes, to mask visual cues, and covered with plastic lids. Samples were poured no more than 15 minutes before serving. Panellists were presented with the two beer samples to evaluate based on one mouthfeel framework at a time.

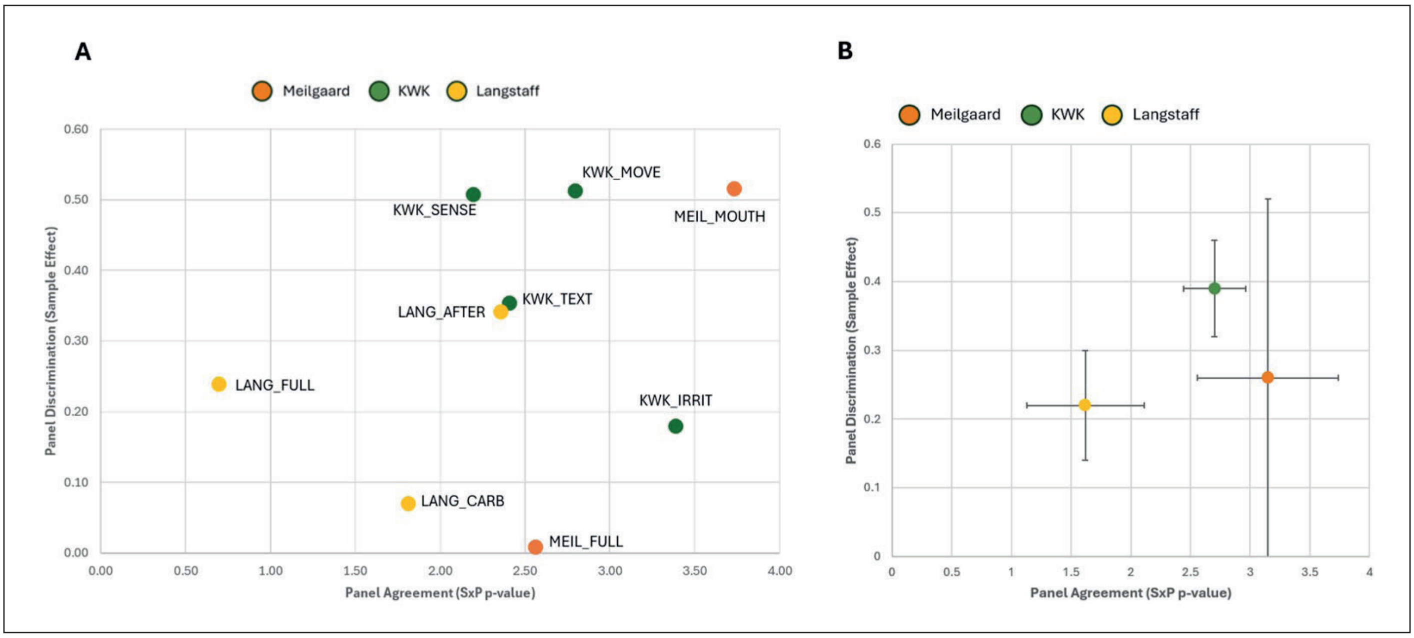

Fig. 3 **(A) Discrimination–agreement plot for individual attributes for the three frameworks. Attributes located in the upper-right region exhibit strong discrimination and high panel agreement**
(B) Average Discrimination–agreement comparing the three frameworks. Discrimination strength is represented by √F effect sizes from mixed-framework analyses, while panel agreement is represented by sample × panellist interaction p-values. KWK = Wolinska-Kennard; LANG = Langstaff; MEIL = Meilgaard

2.2.4 Evaluation protocol

For each sample, panellists followed a standardised mouthfeel evaluation procedure. After removing the lid from the sample cup, the panellists were asked to take a sip, move the beer around the mouth, and swallow the sample. Panellists repeated this tasting process two additional times (three in total). For each sample, participants were asked to rate the intensity of each main mouthfeel category using a 1–9 scale and, additionally, to select mouthfeel attributes, also called sub-categories (Check-All-That-Apply; CATA), only if applicable (Table 1). Panellists were encouraged to cleanse their palates with water and plain crackers before proceeding to the next sample.

At the end of each session, panellists were encouraged to provide feedback on the test and mouthfeel attributes, including any they found unclear, difficult to use, or missing. Their feedback was incorporated into a comprehensive summary and comparison of the three mouthfeel frameworks (Table S2, Supplementary Material).

2.3 Data collection and statistical analysis

Two samples (alcoholic and non-alcoholic German-style wheat beer) were evaluated using the three sensory frameworks (Meilgaard Beer Flavour Wheel, Langstaff's beer mouthfeel framework, Wolinska-Kennard Wheel) across three sessions. Most panellists took part in all sessions, although the panel composition varied slightly. This was considered in the statistical analysis. In total, 26 responses were collected per sample.

Data were collected digitally, using Compusense Cloud (Compusense Inc., Canada). Each framework was set up so that main categories were rated for intensity on a 1 - 9 scale, while sub-categories were recorded as attributes using a check-all-that-apply (CATA) method.

Differences in descriptor performance among frameworks were evaluated using multivariate analyses based on performance metrics derived from mixed linear frameworks (LMM). Four indicators were extracted for each attribute: discrimination strength (√F), signal-to-noise ratio (SNR), panel agreement (sample × panellist interaction p-value), and residual variance. LMMs were used to assess product differences while accounting for variation between panellists [40, 55].

All variables were standardised before analysis. Principal component analysis (PCA) was performed using the correlation matrix to reduce data complexity and explore relationships among attributes. Results were visualised using the first two principal components.

Framework centroids were calculated as the average PCA coordinates of attributes within each framework. The distance between each attribute and its framework centroid was then calculated to assess how spread out the attributes were in multivariate space, following the concept of permutational analysis of multivariate dispersion (PERMDISP) [56]. Statistical analyses were carried out using XLSTAT (Addinsoft, France).

3 Results

3.1 Performance of individual attributes

Linear mixed-model (LMM) analysis was conducted for each attribute to assess the ability of the frameworks to discriminate between

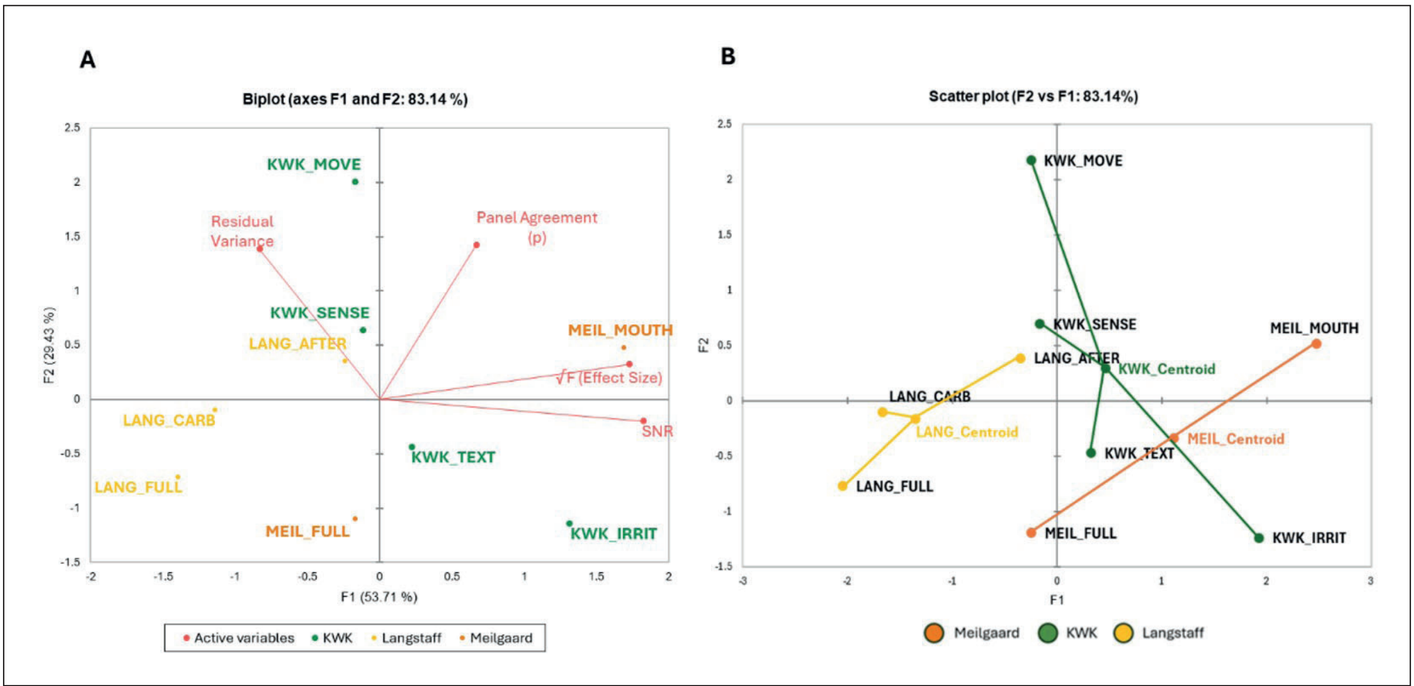

Fig. 4 **(A) Principal component analysis of attribute performance metrics. Attributes are plotted based on PCA scores derived from discrimination strength (√F), signal-to-noise ratio (SNR), panel agreement (sample × panellist interaction p-value), and residual variance. Vector orientation indicates the contribution of each metric to the PCA axes, with attributes located in the direction of a vector exhibiting higher values for that metric. The first two components explained 83.14% of the variance in attribute performance**
(B) Principal component analysis (PCA) of attribute performance metrics with visualisation of multivariate dispersion. Each point represents an attribute, while triangles indicate the centroid of each framework. Line segments show the Euclidean distance between attributes and their framework centroid, corresponding to the distance-to-centroid values used in the PERMDISP test. Attributes positioned farther from the centroid indicate greater dispersion within the framework's performance space. KWK = Wolinska-Kennard; LANG = Langstaff; MEIL = Meilgaard

alcohol and non-alcohol samples. Discrimination strength, the panellist's ability to clearly distinguish attributes among the samples, was expressed as the square root of the F-statistic (√F), with higher values indicating stronger discrimination between samples (Tables S3 and S4, Supplementary Material).

None of the frameworks showed significant discrimination between the samples as an overall mouthfeel profile. However, differences were observed at the category level.

All four Wolinska-Kennard attributes significantly ($p < 0.05$) discriminated the samples: Texture ($p = 0.0016$), Sensation ($p = 0.0065$), Movement ($p = 0.0339$), and Irritation ($p = 0.0210$). The corresponding √F values ranged from 2.20 to 3.39) indicating moderate-to-strong discrimination. The strongest discrimination within Wolinska-Kennard was observed for Irritation (√F = 3.39) and Movement (√F = 2.79).

In the Langstaff framework, only Fullness significantly differentiated the samples ($p = 0.023$), whereas Carbonation ($p = 0.077$) and Afterfeel ($p = 0.490$) did not.

In comparison, in the Meilgaard framework, both attributes significantly discriminated the samples. Mouthfeel ($p=0.0005$), showed the strongest discrimination in the study (√F = 3.73), while Fullness ($p=0.0134$) also significantly differentiated the samples (√F = 2.56)

3.2 Discrimination strength, signal-to-noise ratio, and panel agreement

Discrimination strength, signal-to-noise ratio (SNR), and panel agreement were compared across the three frameworks, with high panel agreement indicating greater consistency among panellists and lower variability in scoring. SNR was calculated as the ratio of the product F-statistic to residual variance, with higher values indicating stronger sensory signals relative to measurement noise.

The Meilgaard framework showed the highest mean SNR (8.80), followed by the Wolinska-Kennard Wheel (6.42), while the Langstaff framework showed a much lower value (2.37), Table S4, Supplementary Material. Residual variance was similar across frameworks, although slightly lower for Meilgaard attributes, suggesting slightly better repeatability.

Panel agreement was assessed using the sample × panellist interaction term from the mixed models. Non-significant interaction terms indicated consistent perception of sample differences among panellists. Most attributes showed acceptable panel agreement, with the exception of Meilgaard Fullness ($p = 0.009$), which indicated inconsistent interpretation. Overall, the Wolinska-Kennard Wheel showed the highest average panel agreement.

These results were visualised in a radar plot (Fig. 2) based on the three summary measures: average discrimination (√F), average agreement (sample × panellist p-value), and signal-to-noise ratio (SNR). Because these values were measured on different scales, values were normalised using min-max scaling before visualisation.

3.3 Discrimination and panel agreement of individual attributes

Attribute performance was further examined using a discrimination–agreement plot (Fig. 3A) that plots discrimination strength (√ F) against panel agreement (sample × panellist p-value). This allowed the simultaneous evaluation of attribute sensitivity and panel consistency.

Attributes in the upper-right region of the plot exhibit both strong discrimination and high panel agreement. In this analysis, one of Meilgaard's framework descriptors showed the strongest discrimination (Mouthfeel, MEIL_MOUTH) with equally strong agreement, while the other (Fullness, MEIL_FULL) showed almost no discrimination and lower agreement, suggesting variation in panel interpretation. The Wolinska-Kennard attributes, particularly Irritation (KWK_IRRIT) and Movement (KWK_MOVE), also showed strong discrimination with consistent panel agreement. In contrast, Langstaff attributes generally showed weaker discrimination across samples.

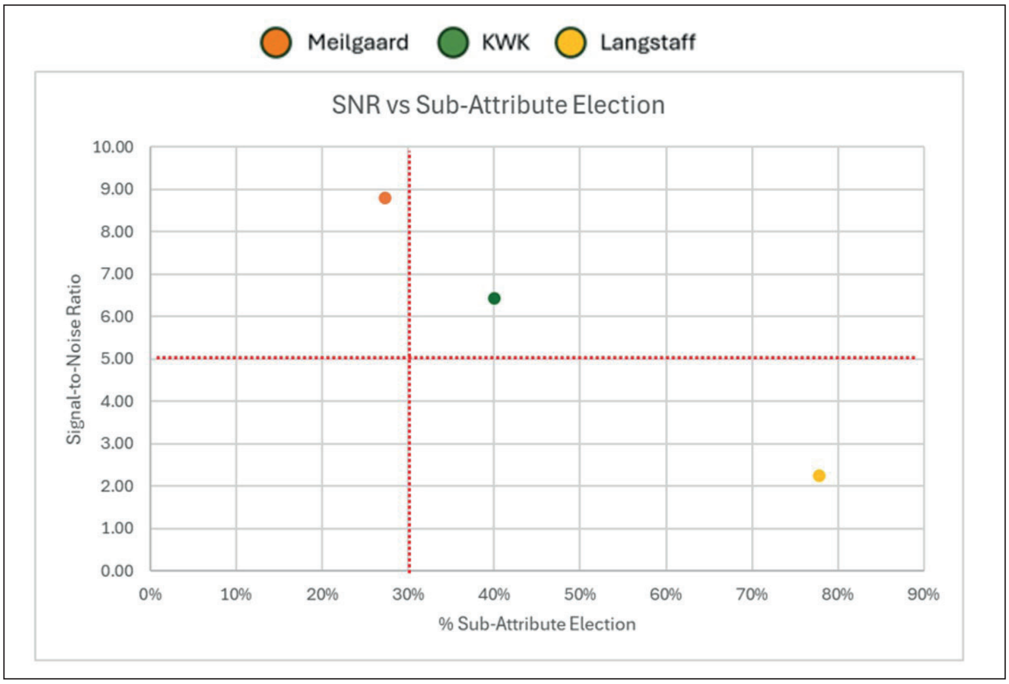

Fig. 5 Relationship between descriptor citation frequency in the CATA evaluation and discrimination strength in descriptive analysis. The x-axis represents the percentage of attributes within each framework selected by more than 30% of panellists, while the y-axis represents the average signal-to-noise ratio (SNR) derived from the mixed-framework descriptive analysis. Red dashed lines indicate interpretive thresholds for perceptual salience (30% attribute selection) and strong discrimination (SNR = 5). KWK = Wolinska-Kennard; LANG = Langstaff; MEIL = Meilgaard

The overall degree of Discrimination and Agreement of the frameworks was further evaluated (Fig. 3B) by calculating centroids and using average standard error bars. Meilgaard showed the greatest average discrimination, but also a higher degree of panellist disagreement, whereas the Wolinska-Kennard Wheel showed stronger average agreement across attributes.

3.4 Multivariate analysis and visualisation of framework performance (PCA and PERMDISP)

To further compare attribute performance across frameworks, principal component analysis (PCA) was applied to attribute metrics from the mixed-framework analyses, including discrimination strength (√F), signal-to-noise ratio (SNR), panel agreement (sample × panellist p-value), and residual variance (Fig. 4A). To assess descriptor dispersion, framework centroids were calculated in PCA space, and the Euclidean distance of each attribute from its centroid was visualised (Fig. 4B).

The first two principal components explained 83.14% of the total variance (F1 = 53.71%, F2 = 29.43%). Their eigenvalues were 2.148 and 1.177, while all remaining factors had values below 1.

The first principal component (F1) was mainly associated with discrimination strength and SNR, as shown by the alignment of the √F and SNR vectors along the positive F1 axis. Meilgaard Mouthfeel (MEIL_MOUTH), Wolinska-Kennard Irritation (KWK_IRRIT), and Wolinska-Kennard Texture (KWK_TEXT) were positioned positively along this axis.

The second principal component (F2) was driven by panel agreement and residual variance, with both having positive loadings on F2 but opposite loadings on F1. Wolinska-Kennard Movement (KWK_MOVE) and Wolinska-Kennard Sensation (KWK_SENSE) aligned more closely with panel agreement, and Wolinska-Kennard Texture (KWK_TEXT) occupied an intermediate position.

Langstaff attributes clustered mainly in regions associated with lower discrimination strength, particularly Langstaff Carbonation (LANG_CARB) and Langstaff Fullness (LANG_FULL), suggesting weaker sample differentiation. Meilgaard attributes were strongly associated with the discrimination axis, mainly due to the high performance of the Mouthfeel attribute (MEIL_MOUTH).

The dispersion pattern (Fig. 4B) showed that Wolinska-Kennard descriptors occupied a broader region of the PCA performance space. Langstaff descriptors were tightly clustered, while Meilgaard framework showed intermediate dispersion.

3.5 CATA citation frequency and discrimination-strength

CATA responses were used to assess how well each framework captured perceived sensory differences between alcoholic and non-alcoholic German-style wheat beer samples at the level of individual sub-category terms. In contrast to the previous analysis, which focused on the main categories, the CATA evaluated the frequency of specific descriptors selected by panellists (Fig. 5).

Differences were observed across the three frameworks in the proportion of frequently selected descriptors. In the Wolinska-Kennard Wheel, 40% of descriptors were selected by more than 25% of panellists. In the Langstaff framework, this value was 78%, while the Meilgaard framework showed the lowest proportion (27%).

In this study, descriptors selected by more than about 25% of panellists were considered perceptually crucial. To complement the CATA results, descriptor performance was also evaluated using signal-to-noise ratios (SNR), calculated as the ratio of the sample F-statistic to residual variance. Descriptors with SNR values above about five were considered to show strong discrimination relative to measurement noise.

4 Discussion

4.1 Interpretation of individual attributes

The Wolinska-Kennard Wheel showed significant discrimination across all four main categories: Texture, Sensation, Movement and Irritation. This suggests that the physiologically based structure captured several different aspects of beer mouthfeel rather than relying on one broad descriptor. The high panel agreement also indicates that panellists used these categories consistently.

In comparison, the Meilgaard framework showed strong discrimination, mainly driven by the broad Mouthfeel attribute. This may be because the term captures the overall mouthfeel experience rather than separating it into more specific sensory dimensions. However, the lower agreement observed for Fullness suggests that broad descriptors may be interpreted differently by panellists.

In contrast, the Langstaff framework showed weaker discrimination. This may be related to the broad and overlapping nature of its categories, such as Carbonation, Fullness and Afterfeel. For example, Carbonation can generate several different sensations, including tingling, sharpness and numbing, which may make it difficult to evaluate as a single attribute. In addition, Afterfeel is not a specific mouthfeel attribute but rather describes how long a sensation remains after swallowing. It can refer to different types of sensations, which may make it difficult to interpret consistently as a single category.

4.2 Interpretation of framework discrimination strength, signal-to-noise ratio, and panel agreement

The Meilgaard framework had the highest discrimination strength and SNR, indicating the strongest sample differentiation relative to measurement error, although panel agreement was slightly lower because of variability in Fullness ratings. The Langstaff framework showed the weakest performance across all three measures, with all normalised values reduced to zero. In contrast, the Wolinska-Kennard Wheel showed the highest panel agreement and moderately strong discrimination. Although its SNR was lower than that of the Meilgaard framework, its attributes produced more consistent responses across panellists.

4.3 Discrimination and panel agreement of individual attributes

Overall, this analysis indicates that several Wolinska-Kennard attributes, particularly Irritation and Movement, combined moderate-to-strong discrimination with high panel agreement. This suggests that these categories were not only able to differentiate between the samples, but were also interpreted consistently by panellists. The Meilgaard Mouthfeel attribute showed the strongest discrimination, which suggests that this broad category was effective at capturing overall differences between the samples. However, Meilgaard Fullness showed lower agreement, indicating that panellists may have interpreted this attribute less consistently. In contrast, the weaker discrimination observed for several Langstaff attributes suggests that broader or less clearly defined categories may be more difficult for panellists to apply consistently.

4.4 Interpretation of multivariate analysis and visualisation of framework performance (PCA and PERMDISP)

The lack of significant PERMDISP differences may be related to the small number of attributes within each framework. However, the PCA visualisation suggests that Wolinska-Kennard descriptors captured multiple performance dimensions, whereas the other frameworks occupied more limited regions of the performance space.

Together, the PCA and dispersion analyses suggest that the Wolinska-Kennard Wheel provides a more diverse set of sensory descriptors, capturing both discrimination strength and panel agreement. In contrast, Langstaff descriptors were associated with lower discrimination, while the Meilgaard framework's strong discrimination was driven by one dominant attribute.

The stronger discrimination was likely due not only to a small number of attributes, but also to the broad Mouthfeel attribute capturing the full range of mouthfeel-related properties. On the other hand, the Langstaff framework showed low discrimination despite including fewer categories than the Wolinska-Kennard Wheel. This suggests that the weaker performance was not only related to the number of attributes, but also to their broad and less clearly defined nature. For example, Carbonation may include several different sensations that can arise from different drivers, making it difficult to evaluate as a single attribute. Afterfeel reflects sensations that remain after swallowing rather than the immediate mouthfeel experience, which may limit its usefulness for direct mouthfeel assessment. Fullness, as also observed in the Meilgaard framework, is a broad descriptor and may have been difficult for panellists to interpret consistently.

4.4.1 Interpretation of CATA citation frequency and discrimination strength

Although Langstaff showed the highest selection frequency, its descriptors showed weaker discrimination in the descriptive analysis.

This may indicate that several Langstaff terms represent broad sensory constructs and may have been used to capture multiple sensations at once, consistent with descriptor dumping.

In contrast, the Wolinska-Kennard framework includes more specific trigeminal and textural descriptors, resulting in a lower citation frequency but more targeted use. These findings agree with the descriptive analysis, where several Wolinska-Kennard descriptors showed strong discrimination. The Meilgaard framework showed low citation rates, suggesting that only a small number of descriptors captured the main sensory differences between samples.

4.5 Limitations and future work

This study was limited to two German-style wheat beer samples, one alcoholic and one non-alcoholic, and therefore further validation is needed across a broader range of beer styles. Future studies should include additional alcoholic and non-alcoholic beers, repeated sensory sessions, and potentially instrumental measurements to further assess the robustness of the Wolinska-Kennard Wheel.

The comprehensive framework may also be adapted for different beer styles, product categories, and evaluation objectives by selecting descriptors relevant to the specific application. However, its large number of descriptors may make panellist training more challenging, particularly during the initial stages, as some descriptors may overlap or be difficult to distinguish. Future studies should investigate the most effective training strategies and determine which descriptors are essential for specific applications.

5 Conclusions

The Wolinska-Kennard Mouthfeel Wheel was developed from a physiological perspective to reflect how mouthfeel is perceived through different sensory systems. A comprehensive mouthfeel wheel was first developed, covering a broad range of physical, oral, chemical, and psychological descriptors. From this, a simplified wheel was created for the sensory evaluation presented in this study. The simplified wheel was designed to improve usability, reduce panel fatigue and evaluation time, and allow direct comparison with existing beer mouthfeel frameworks.

Compared with the Meilgaard and Langstaff frameworks, the simplified Wolinska-Kennard Wheel showed broader perceptual coverage and higher panel agreement while maintaining good strong discrimination between samples. All four main Wolinska-Kennard categories significantly discriminated between the samples and showed acceptable panel agreement, indicating that the categories were used consistently by the panellists. In addition, both the Wolinska-Kennard and Meilgaard frameworks produced stronger sensory signals relative to measurement error than the Langstaff framework. Although the Meilgaard framework showed the strongest overall discrimination, this appeared to be mainly driven by its broad Mouthfeel category rather than by a greater ability to distinguish individual mouthfeel characteristics. In contrast, the Langstaff framework showed lower discrimination, likely because its categories were less clearly defined.

Overall, these findings suggest that the final simplified Wolinska-Kennard Wheel (Fig. 2) provides a structured and informative approach to beer mouthfeel evaluation by combining specific descriptors with broad sensory coverage. The comprehensive wheel provides a wider descriptor framework that can be adapted for different beer styles, products, and evaluation objectives. It may also support future consumer-oriented studies by including psychological descriptors that were not evaluated in the present work.

Further validation across a wider range of beer styles, including both alcoholic and non-alcoholic beers, is needed to determine the most appropriate descriptor sets for different applications and to confirm the robustness of both the comprehensive and simplified versions of the Wolinska-Kennard Wheel.

Declaration of interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Katarzyna Wolinska-Kennard reports a relationship with BarthHaas UK that includes employment. Christina Schönberger reports a relationship with BarthHaas GmbH & Co. KG that includes employment. Jocelyn Tillner reports a relationship with BarthHaas UK that includes employment. Mihaela Puiu reports a relationship with BetaTec Hop Products that includes employment. Jeff Dailey reports a relationship with John I. Haas, Inc., Yakima, USA, that includes employment. Adam Fenton reports a relationship with BarthHaas UK that includes employment.

Ethics statement

The sensory evaluation was conducted in accordance with ethical guidelines approved by the Social Research Ethics Committee (SREC) in University College Cork (approval number: Log 2025-385).

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Author contributions

Katarzyna Wolinska-Kennard: Writing – original draft, Data curation, Formal analysis, Methodology, Visualization, Investigation. Christina Schönberger: Conceptualization, Supervision, Writing – review and editing. Jocelyn Tillner: Project administration, Writing – review and editing. Mihaela Puiu: Formal analysis; Software. Jeff Dailey: Formal analysis; Software; Visualisation. Adam Fenton: Funding acquisition; Resources. Aylin W. Sahin: Conceptualization, Supervision, Writing – review and editing

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Supplementary material

Table S1 A structured classification of attributes and descriptors, systematically organised into main categories and sub-categories from a physiological perspective, to reflect the underlying mechanisms of mouthfeel perception.v

System	Main mouthfeel categories ATTRIBUTES	Mouthfeel sub-categories DESCRIPTORS	Description
Oral chemosensory (Chemesthesis)	Sensation	Tingling	Light, fizzy sensation
		Warming	Heat sensation
		Cooling / Menthol	Refreshing, cold-like sensation
		Mouthwatering	An increase in salivation, juicy, refreshing
		Metallic	Metallic flavour perception (metal, metal ions, rust)
		Electric / Buzzing	Electric-like sensation
		Drying	A mouth-dehydrating sensation
	Irritation	Burning	Hot, sometimes painful sensation
		Puckering	Tightening sensation, typically felt on the inner cheeks, gums, or lips.
		Numbing	A dulling or desensitising sensation
		Harsh	Rough, aggressive, blunt, and lingering
		Sharp	Pointed, stinging, cutting
Oral somatosensory (Proprioceptive system)	Movement	Thin / Watery	Light, fast-moving, and low in resistance; may feel slightly watery or dilute.
		Light / Airy	Light, fast-moving, refreshing
		Soft / Smooth	Silky, smooth
		Slick / Oily	Smooth and slightly oily; more substantial than slippery
		Rich	Thick, heavy, slow to move; high resistance
		Mouthcoating	Clings or spreads across surfaces during movement
		Thick / Chewy	Dense, syrup-like, slow-moving; feels like it needs working in the mouth
		Sticky	Resists movement and may feel gluey or lingering
Oral somatosensory (Tactile system)	Texture	Silky	Soft, smooth, glides without weight or grain. Lighter and smoother than creamy
		Creamy	Thick, smooth, and soft, rich or dairy-like
		Furry	Soft, fine coating sensation on oral surfaces
		Chalky	Dry, dusty, or powdery, flour-like
		Gritty	Tactile sensation of fine particles
	Pressure	While pressure is a relevant tactile modality in the perception of semi-solid and solid foods, it is not independently perceived in the context of beer. Instead, pressure-related experiences (such as force, impact, or structural firmness) are already reflected within other categories of this framework, particularly within Texture and Movement & Resistance. For this reason, Pressure is not included as a standalone perceptual category in the beer mouthfeel model	
	Temperature	Temperature influences mouthfeel perception, but it is not included as an attribute in the wheel itself, as it reflects serving conditions rather than a sensory quality	

Table S2 Supplementary Materials: Pan ellist feedback on the Langstaff, Meilgaard, and Wolinska-Kennard frameworks during sensory evaluation

FRAMEWORK	COMMENTS FROM THE PANEL
Meilgaard et al. (1979)	A bit too concise, doesn't fully characterise.
	Mouthfeel wheel is not comprehensive.
	Lack of description in sub-categories makes it difficult to answer in the right way.
	Fullness - missing attribute, sometimes between watery and thick. Easy to follow procedure but the term astringent can be to generic
	Fullness - there are not enough attributes, but not sure what to choose
	The term “characterless” feels too generic and may benefit from a clearer definition.
	The attribute “drying” is missing and could be important to include.
Langstaff et al. (1991)	The carbonation and fullness categories are somewhat unclear and appear too broad.
	The carbonation category may need additional options to better describe how it feels.
	I struggle with the carbonation category; it's unclear whether they refer to appearance or mouthfeel. If they are meant to describe mouthfeel, I would appreciate a wider range of options.
	While carbonation has a significant influence on mouthfeel, I would prefer to focus on the sensation it delivers rather than the driver itself.
	Viscosity and density are quite generic attributes; in fact, they are physical properties of the liquid that can be measured analytically.
Wolinsk-Kennard Mouthfeel Wheel (KWK)	Very descriptive - easier to follow
	I like how the “movement” category is rated low for thick liquids and high for thin ones; it feels more intuitive.,
	The test is easy to follow, and the attributes are clearly categorised.
	Well structure test
	A good, clear system

Table S3 Supplementary Material: Results from linear mixed-model analysis of attributes within three sensory frameworks

Framework	Attribute	Product F	√F	Residual Variance	SNR	Sample Pr>F
Wolinska-Kennard	Texture	5.792	2.41	1.040	5.57	**0.0016**
Wolinska-Kennard	Sensation	4.823	2.20	1.240	3.89	**0.0065**
Wolinska-Kennard	Movement	7.806	2.79	1.724	4.53	**0.0339**
Wolinska-Kennard	Irritation	11.470	3.39	0.981	11.69	**0.0210**
Langstaff	Fullness	0.483	0.69	1.140	0.42	**0.0 229**
Langstaff	Carbonation	3.286	1.81	1.530	2.15	0.0767
Langstaff	Afterfeel	5.548	2.36	1.339	4.14	0.4903
Meilgaard	Fullness	6.561	2.56	1.210	5.42	**0.0134**
Meilgaard	Mouthfeel	13.922	3.73	1.143	12.18	**0.0005**

Values in bold are statistically significant at $p < 0.05$. Higher √F values indicate stronger discrimination between samples.

Table S4 Supplementary Material: Summary results from linear mixed-model analysis of attributes within three sensory frameworks

Framework	Attributes	Significant	% Significant ($p<0.05$)	Avg $\sqrt{F}$	Avg SNR
Wolinska-Kennard	4	4	100%	2.734	6.42
Langstaff	3	1	33.30%	1.621	2.37
Meilgaard	2	2	100%	3.146	8.8