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The taste of diversity: Sensory characteristics in diverse wheat aimed for food production under climate change

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ABSTRACT

To ensure production sustainability and food security under climate change, it is essential to improve the resilience and nutritional quality of staple crops by transferring suitable traits from diverse sources, while maintaining sensory attributes preferred by consumers to support acceptance and adoption. Therefore, the present study evaluated sensory characteristics using 13 traits, in a diverse wheat genotype ($n = 49$) belonging to 17 genetic groups, by Quantitative Descriptive Analysis, a trained panel, and using wholegrain porridge as a model. The results revealed significant genotypic differences ($p < 0.001$) for all 13 sensory traits. Rye-introgressed lines (e.g., 1RS.1BL+2BS.2RL, 2R/2B, 1R+6R) and old cultivars exhibited higher intensity for odour descriptors (graham flour, rye flour, corn, cooked rice), firmer texture, and distinct grey/beige colour. Ancient wheat species, such as einkorn, spelt, and *Triticum timopheevi* showed a milder aroma and flavour profile and higher sweetness than the rest of the evaluated wheat groups. *T. carthlicum* and landraces were characterised by bitterness, umami, and a gritty mouthfeel. Strong positive correlations were observed among odour traits ($r = 0.68–0.91$), while texture grittiness correlated with bitterness ($r = 0.67$). Sweetness showed moderate to strong negative correlations with odour and flavour traits ($r = -0.42$ to -0.75). Multivariate analysis explained 63.3% of the total variance, and clustering grouped the genotypes into three distinct sensory intensity classes. These findings highlight that sensory attributes may pose opportunities and challenges when genes for resilience and nutrition are transferred from diverse wheat genotypes to adapted wheat and novel food products are developed from these materials.

1. Introduction

Wheat (*Triticum* spp.) is one of the most important staple crops in the world, providing a significant share of calories, proteins, and essential micronutrients for human populations (Shewry and Hey, 2015). Modern wheat breeding has predominantly prioritised agronomic performance, such as high yield, disease resistance, and grain uniformity, to ensure food security and economic returns for farmers (Johansson et al., 2023). However, achieving food security under climate change increasingly requires a shift toward sustainable breeding approaches that enhance environmental resilience and nutritional adequacy. This includes leveraging genetically diverse plant materials such as landraces, ancient species, and introgression lines to improve stress tolerance, micronutrient content, and adaptability to future agroecosystems (Benitez-Alfonso et al. 2023; Johansson et al. 2024). To be successful in the long term, sustainable wheat breeding must meet consumer expectations for sensory quality, which influences food choices, dietary patterns, and food waste reduction (Johansson et al. 2020; Starr et al. 2015; Wendin et al. 2020). This requires breeders to avoid selecting genotypes that compromise desirable sensory traits, while farmers, producers, and

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food system actors can harness the knowledge of unique sensory profiles to develop niche products that support local economies, promote biodiversity, and contribute to more sustainable and diversified food systems. Beyond agronomic performance, sensory quality contributes directly to reducing food waste and promoting healthy eating habits, both of which are core elements of a sustainable food system. Leveraging diverse wheat lines for improved taste and texture can increase wholegrain consumption, which aligns with planetary health and sustainability goals (Barry-Ryan et al. 2020; Maschio et al. 2023). At the same time, understanding the nutritional composition of wheat and its impact on human health remains a crucial aspect of breeding programs aimed at developing widely accepted and nutritionally enhanced varieties.

Wheat is a valuable source of protein, iron (Fe), zinc (Zn), and other phytochemicals, but it also has the potential to accumulate undesirable elements such as cadmium (Cd) (Iqbal et al. 2022; Rai et al. 2019; Shewry and Hey 2015). Recent efforts in biofortification and sustainable breeding have led to the identification of wheat genotypes with high Fe and Zn contents, low Cd accumulation, and acceptable protein content (Lan et al. 2024a; Tiwari et al. 2016; Wiebe et al. 2010). These traits are critical for addressing micronutrient deficiencies, especially in regions where wheat is a dietary staple (Bansode and Kumar 2015). Yet, to be widely accepted and successful in the market, such nutritionally enhanced genotypes must also meet consumer expectations for sensory quality, like odour, taste, appearance, texture, and flavour

Consumer preferences are strongly influenced by sensory characteristics (Imtiyaz et al. 2021). Sensory attributes such as flavour and texture are consistently cited as the most important factors in food choice, including for wheat-based products like bread and porridge (Wendin et al. 2020). The COVID-19 pandemic, which left many individuals with impaired taste and smell abilities, further highlighted the central role of sensory perception in food satisfaction, quality of life and culture (Lechner et al. 2023; Moraschini et al. 2022). Sensory experiences are shaped not only by intrinsic product characteristics but also by external factors such as age, health status, environment, and cultural habits (Jeong and Lee 2021; Rai et al. 2023). As such, understanding the sensory variability in wheat genotypes is vital for product development and could also be interesting for breeding programs aiming to deliver wheat varieties that are both nutritious and desirable to consumers.

Although sensory traits are crucial for consumer acceptance, comprehensive studies examining these attributes across the wide genetic diversity of wheat are still limited (Castellari et al. 2023; Jensen et al. 2010; Starr et al. 2013, 2015; Vindras-Fouillet et al. 2021). A wide array of wheat germplasm exists, including ancient species (einkorn, emmer, spelt), landraces, and modern cultivars, which exhibit substantial genetic and phenotypic diversity (Gadaleta et al. 2023; Velu et al. 2019). Of particular interest are introgression lines, developed through traditional breeding by incorporating rye (*Secale cereale*) chromosomal segments into wheat, which have been linked to enhanced disease resistance and environmental adaptability (Johansson et al. 2020, 2024; Merker and Lantai 1997; Merker and Rogalska 1984; Rahmatov et al. 2016b). To address the current lack of detailed sensory characterization across diverse wheat germplasm, analytical sensory evaluation methods, particularly Quantitative Descriptive Analysis (QDA), offer a robust framework to objectively assess the organoleptic attributes of wheat-based food products using human senses (Jönsson et al. 2025; Starr et al. 2013).

QDA relies on selected and trained panellists to analytically identify and quantify key sensory attributes, such as appearance, odour, taste, texture, and flavour, enabling repeatable and statistically analysable sensory profiles (Johansson 2021; Trigo et al. 2024). These profiles can support product differentiation, guide consumer-focused wheat breeding, and bridge the gap between nutritional quality and market appeal.

The sensory significance of genetic variation in wheat was highlighted by Starr et al. (2013), who evaluated 24 diverse wheat samples and observed significant differences in odour descriptors among species, landraces, and cultivars. Their study showed correlations between physical grain characteristics (e.g., colour, hardness) and specific aroma profiles, such as cocoa and malt. Starr et al. (2015) further demonstrated that aroma descriptors found in wheat porridge were largely retained in bread, confirming that porridge serves as a reliable medium for sensory screening in early-stage selection. Their findings also showed that milling fractions, such as bran and endosperm, contributed distinctly to aroma variation, emphasising the influence of genotype on both wholegrain and refined wheat products.

The present study aimed to evaluate sensory quality characteristics of a wide array of wheat genotypes (modern, old, ancient, landraces and introgression lines), representing genetic diversity in wheat which could be of use for future cultivation, especially under Nordic conditions, but also elsewhere. These genotypes were selected based on their agronomic performance, stress resilience, and nutritional characteristics (unpublished data), making them an important asset for future breeding of stress-tolerant/resistant, highly nutritious wheat genotypes. However, for their use in wheat improvement, an increased understanding of their variation in sensory properties is of major importance. We hypothesize that the variation in sensory properties of the wheat material utilized is as wide as its diversity, which contributes to the unique opportunities but also challenges in using it for breeding purposes.

2. Materials and method

2.1. Plant materials and sample preparation

A total of 49 wheat genotypes of diverse origins were selected for sensory evaluation based on previously identified traits of interest. These genotypes were analysed for key nutritional and agronomic elements (manuscript in preparation), and the results from these analyses guided the selection of materials for the present study. To reflect the genetic variation and facilitate comparative analyses, genotypes were classified into 17 genetically distinct categories. These categories represent a broad spectrum of wheat diversity, encompassing introgression lines, landraces of bread wheat, old cultivars (released before 1960), ancient species such as spelt, emmer, and einkorn, including *T. Timopheevii, T. Carthlicum*, and modern bread wheat cultivars (Table 1). All genotypes were cultivated under standard field management practices during the 2022/2023 growing season at the breeding station of Lantmännen in Bjertorp, Sweden (Latitude: 58°16′00″N; Longitude: 13°06′00″E) in order to minimise environmental variability and ensure that observed differences were primarily due to genetic variation rather than management practices. Following harvest, wheat samples were oven-dried at 40 °C for 24 h to reduce moisture content to below 14 % before threshing. The dried grains were milled into

Table 1
Genotypic groups and the corresponding number of genotypes represented in each group.

Number	Genotype Group	Genotype count
1	1BS.1RL	1
2	1R/1D	13
3	1R+6R	4
4	1RS.1BL+2BS.2RL	3
5	1RS.1DL	3
6	2R/2B	2
7	2R/2D	3
8	2RL	1
9	3R/3D	1
10	*T. Carthlicum*	1
11	Einkorn	1
12	Emmer	7
13	Landrace	1
14	Modern cultivar (MC)	2
15	Old cultivar (OC)	2
16	Spelt	3
17	T. *Timopheevi*	1

wholegrain flour using a KoMo Fidibus XL Grain Grinder (600 W, hopper volume: 1200 *g*, grinding capacity: 200 *g*/min, KoMo GmbH & Co. KG, Germany), producing finely ground wholegrain flour suitable for porridge preparation. Although some genotype groups included only one or a few genotypes, this indicates the relative rarity of certain wheat species and introgression lines. Nevertheless, their inclusion was important to capture the genetic and sensory diversity of wheat. To account for unequal group sizes and ensure reliable statistical comparisons, the experiment was designed as a randomized complete block design (RCBD) with three replications, so that each genotype was well represented.

2.2. Porridge sample preparation for sensory evaluation

Porridge samples were prepared according to the method described by Starr (2015), with one procedural modification. To prepare each batch, 640 g of ordinary tap water was measured and brought to a boiling point (100 °C) in a kettle to inactivate endogenous amylase enzymes in the flour. The boiling water was then poured into a large heatproof bowl, and 160 g of finely ground wholegrain flour was immediately whisked vigorously until a smooth, homogeneous slurry was achieved. The bowl was then covered with aluminium foil to prevent surface drying and placed in an oven (SelfCookingCenter®; Rational, Germany). The oven was pre-set to full steam mode (100 % humidity) at 130 °C, and the samples were cooked for 25 min. After cooking, the porridge was re-whisked to ensure uniform texture. The cooked mixture was then portioned using a teaspoon measure dipped in water into 30 ml food-safe plastic dressing cups with lids (FORMO, transparent, round, 30 ml capacity). Each cup was labelled with a randomised three-digit code to ensure blind evaluation. The sealed sample cups were held in a warming cabinet (CBT530H, Hot banquet trolley, ASCO, Turkey) at 40 °C for 1.5 h before serving to the sensory panel, allowing the samples to release their aroma and flavour attributes while remaining at a comfortable and suitable temperature for consumption.

2.3. Sensory evaluation

Sensory evaluation using QDA was conducted by a trained analytical panel at Kristianstad University. Ethical approval was granted by the University-wide Ethics Council of Kristianstad University (Dnr-U2025–2.1.12–299) before the start of the study. The evaluation procedure followed the ISO 6658:2017 and 13299:2016 standards (Swedish Institute for Standards, 2016; 2017) for sensory analysis. Eight trained panellists, recruited according to ISO standard 8586:2023 (Swedish Institute for Standards, 2023), participated in the assessments.

2.4. Panel training and attribute generation

Prior to the main evaluation, the panel (age 20–45) engaged in a structured training and attribute generation phase. A representative subset of porridge samples, selected to reflect the sensory extremes of the full test design, was used for this purpose. The panellists were also presented with some training references such as standard solutions representing the four basic tastes (umami, sour, sweet, and bitter) prepared according to ISO 3972:2011 (Swedish Institute for Standards, 2011) at dilution level D1, along with wholegrain wheat and rye flours subjected to different treatments (dry, wet, and boiled). Initially, panellists evaluated the training samples individually and generated their descriptive vocabulary. Following this, the panel convened to discuss, refine, and agree on a common set of sensory descriptors, including operational definitions (Table 2) and scale usage. In line with standard practices in the sensory laboratory, the data from the training sessions were not archived. During this period, panellists were trained to use a 110 mm unstructured line scale, anchored at 10 (‘a little’) and 90 (‘much’), in accordance with ISO 4121:2003 (Swedish Institute for Standards, 2003). This scale, integrated into the EyeQuestion software used by the laboratory for data collection, was applied to achieve consensus in intensity ratings across descriptors, thereby maintaining repeatability.

Table 2
Sensory descriptors with definitions for the odours, textures, and flavours found in wheat porridge.

Designation	Sensory attributes	Definition
Q1	O-Graham flour	wholegrain wheat flour mixed with cold water
Q2	O-Rye flour	wholegrain rye flour
Q3	O—Corn	uncooked popcorn kernels
Q4	O-Cooked rice	boiled jasmine rice
Q5	A-Gray	colour nuance
Q6	A-Beige	colour nuance
Q7	TM-Grittiness (sandy)	sandy feeling in the mouth
Q8	TM-Sturdiness/ Compact	tightly knit and less porous in the mouth, with minimal separation between components.
Q9	T-Umami	basic taste
Q10	T-Sweetness	basic taste
Q11	T-Bitterness	basic taste
Q12	F-Graham flour	wholegrain wheat flour
Q13	F-Rye flour	wholegrain rye flour

O: indicative of Odour/Aroma, A: indicative of Appearance, TM: indicative of Texture/Mouthfeel, T: indicative of Taste, F: indicative of Flavour

2.5. Evaluation procedure

The full set of 49 wheat genotypes was evaluated in triplicate, resulting in 147 coded porridge samples. Evaluations were conducted over nine days across three weeks, with six genotypes assessed each day to manage fatigue and ensure consistency. Each panellist evaluated all samples in triplicate, and samples were presented in a randomised order, with individual presentation sequences for each panellist to minimise bias from order effects. Sensory evaluations were conducted in a dedicated sensory laboratory that conformed to the ISO 8589:2010/A:2014 standards (Swedish Institute for Standards, 2014). The facility featured controlled lighting, temperature, and individual booths to minimise external distractions. Data collection was managed digitally using EyeQuestion software (v4.11.68, Logic8, Netherlands). Each sample was served as a 30 ml portion in a coded, food-safe, lidded container and tempered at 40 °C prior to serving. Panellists were allowed sufficient time to evaluate each sample fully before proceeding to the next. The evaluations were performed in one two-hour session per day for three consecutive days per evaluation week.

2.6. Data analysis

Analysis of variance (ANOVA) was performed to evaluate the effects of genotype on assessed sensory attributes. Variance components were estimated using a general linear model, with genotype treated as a fixed effect. Where significant differences were detected ($p < 0.05$), mean comparisons were conducted using Tukey’s Honest Significant Difference (HSD) test, implemented in the *agricolae* package in R (Mendiburu 2023).

Pearson correlation coefficients among traits were calculated and visualised using the *corrplot* package (Wei et al. 2021) to assess the strength and direction of inter-trait relationships. Combined multivariate analyses across all sensory attributes were conducted to explore patterns of variation and discrimination between genotypes. Principal Component Analysis (PCA) was performed to explore multivariate patterns and reduce data dimensionality, using the *factoextra* package (Kassambara and Mundt 2016) for computation and visualisation. Hierarchical clustering and interactive heatmap dendrograms were generated using the *heatmaply* package (Galili et al. 2018), based on

Ward's D2 linkage and Euclidean distance, to display patterns of genotype similarity based on sensory profiles.

To further explore group differentiation and trait contributions, Linear Discriminant Analysis (LDA) was conducted using the *MASS* package (Ripley et al. 2013), with graphical outputs produced using *ggplot2* (Wickham and Sievert 2009) and *ggrepel* (Slowikowski et al. 2021) for enhanced label clarity. All data were interpreted in the context of genotypic groupings for reporting and subsequent discussion.

3. Results

3.1. Genotypic impact on wheat sensory profiles

Analysis of variance (ANOVA) revealed highly significant genotypic effects ($p < 0.001$) for all 13 sensory attributes evaluated across wheat genotypes (Table 3). These attributes include odour, appearance, texture, colour, taste, and flavour. Among the odour descriptors, O-Graham flour (wet), O-Rye flour, O—Corn (raw), and O—Cooked rice (white) showed pronounced variations among genotypes ($p < 0.001$). The appearance traits, A-Gray and A-Beige also displayed strong genotypic differentiation. Significant differences were observed in texture-related traits, particularly TM-Grittiness (sandy) and TM-Sturdiness/Compactness, with TM-Sturdiness/Compactness exhibiting especially high mean squares, indicating greater discriminatory power. For taste-related traits, including T-Umami, T-Sweetness, and T-Bitterness, as well as flavour descriptors F-Graham flour and F-Rye flour, significant genotypic variation was also evident ($p < 0.001$). In contrast, block effects were not significant and residual mean squares were relatively low for all evaluated sensory traits across replicates.

The Tukey HSD test revealed substantial variation among wheat genotypes across all evaluated sensory dimensions, including appearance, mouthfeel/texture, taste, flavour, and aroma/odour (Fig. 1; Supplementary Table).

Aroma-related descriptors showed significant genotypic variation. For O-Graham flour (wet), the highest intensities were found in old cultivars and 2RL, followed by 1R+6R, while einkorn and landrace were among the lowest. O-Rye flour displayed a similar trend, with 1R+6R and old cultivars ranking highest, and einkorn and landrace at the lower end. In O—Corn (raw), old cultivars, 1R+6R, and emmer scored highest, whereas *T. Carthlicum* and *T. Timopheevi* recorded the lowest values. For the O—Cooked rice aroma, the highest scores were observed in old cultivars and 2R/2B, while einkorn, *T. Carthlicum*, and 3R/3D showed the lowest intensities. These findings indicate diverse aromatic profiles across genotypes, offering breeding opportunities to enhance aroma-related consumer appeal.

Notable differences were also observed in visual traits. For A-Gray, introgression lines such as 1R+6R and 1RS.1BL+2BS.2RL and modern cultivars exhibited the highest values, suggesting a more pronounced gray hue. Ancient wheats like spelt, 3R/3D, and emmer scored significantly lower, reflecting a lighter appearance. A similar pattern emerged for A-Beige, where 1RS.1BL+2BS.2RL, einkorn, and *T. Timopheevi* ranked highest, while spelt, 3R/3D, and emmer remained at the lower end.

The differences in mouthfeel were apparent. For TM-Grittiness (sandy), landraces, *T. Carthlicum*, and 1RS.1DL had the highest scores, indicating coarser textures. In contrast, spelt and einkorn suggested smoother mouthfeel. TM-Sturdiness/Compact scores were highest in modern cultivars, old cultivars and spelt, highlighting a firm, compact texture. *T. Carthlicum*, 1RS.1DL, and 2R/2D scored lower, suggesting a less sturdy consistency.

Taste profiles also varied among genotypes. S-Umami was highest in 2R/2D, landrace, and *T. Carthlicum*, and lowest in 1BS.1RL and 3R/3D For S-Sweetness, einkorn, T. *Timopheevi*, and landrace had the highest scores, while 1BS.1RL, 2RL, and 1R+6R were the least sweet. S-Bitterness was strongest in landrace, 1RS.1DL, and 1RS.1BL+2BS.2RL, whereas einkorn and 2RL were least bitter. These variations highlight taste differences that may influence consumer preferences.

Flavour descriptors further differentiated the genotypes. For F-Graham flour, high scores were recorded for old cultivars, 2RL, and *T. Carthlicum*, followed by introgression lines such as 1R+6R and 1RS.1DL. Ancient wheat species, such as emmer, spelt, and einkorn, also displayed notable graham-like flavours. In the F-Rye flour category, 1BS.1RL, 1R+6R, and modern cultivars ranked highest, while lower values were observed in landrace, *T. Timopheevi*, and einkorn. These data reveal the flavour richness of certain genotypes, which could be leveraged to develop more appealing wheat-based foods.

3.2. Sensory trait interrelationships

Pearson's correlation analysis revealed several significant relationships among the 13 sensory attributes (Fig. 2). Strong positive correlations were observed among the descriptive odour traits, including O-Graham flour, O-Rye flour, O—Corn, and O—Cooked rice, with coefficients ranging from 0.68 to 0.91 ($p < 0.001$). Similarly, strong associations were noted between F-Graham flour and O-Graham flour (wet), O-Rye flour, O—Corn (raw), with O—Cooked rice (white) (r = 0.54–0.86, $p < 0.001$). Taste attributes such as T-Sweetness showed significant negative correlations with odour/aroma traits, especially with O-Graham flour (wet) and O—Corn ($r = -0.61$ to -0.67, $p < 0.001$), and with T-Rye flour ($r = -0.75$, $p < 0.001$). Similarly, T-Umami and T-Bitterness were negatively correlated with texture compactness, O-Graham flour (wet), O-Rye flour, O—Corn (raw), O—Cooked rice (white), F-Graham flour and F-Rye flour.

Table 3
Analysis of variance (ANOVA) for different sensory attributes of assessed wheat genotypes.

Source of variation	DF	†O-Graham flour (wet) (Q1)	O-Rye flour (Q2)	O—Corn (raw) (Q3)	O-Cooked rice (white) (Q4)	ᵘA-Gray (Q5)	A-Beige (Q6)	¥TM-Grittiness (sandy) (Q7)	Expected Mean Squares
Replication	2	4.79	3.34	7.11	10.32	0.72	2.64	10.88	–
Genotype	16	52.44***	68.97***	28.87***	34.95***	139.95***	82.23***	105.1***	$\sigma_e^2 + r\sigma_g^2$
Residual	32	6.83	3.45	5.00	3.86	5.26	5.71	3.87	σ_e^2
Source of variation	DF	TM-Sturdiness/ Compact (Q8)	§T-Umami (Q9)	T-Sweetness (Q10)	T-Bitterness (Q11)	©F-Graham flour (Q12)	F-Rye flour (Q13)		
Replication	2	19.79	3.61	2.78	14.56	2.07	2.81		
Genotype	16	143.12***	36.14***	6.93***	11.20***	26.04***	92.27***		$\sigma_e^2 + r\sigma_g^2$
Residual	32	6.86	2.27	0.97	1.72	4.55	5.69		σ_e^2

G: genotype; r: replication; σ_e^2: error variance; σ_g^2: genotypic variance; *** represent significant at $p < 0.001$, respectively.
† O: indicative of odour; ᵘA: indicative of appearance.
¥ TM: indicative of Mouth Feel or Texture.
§ T: indicative of Taste.
© F: indicative of Flavour; DF: degree of Freedom.

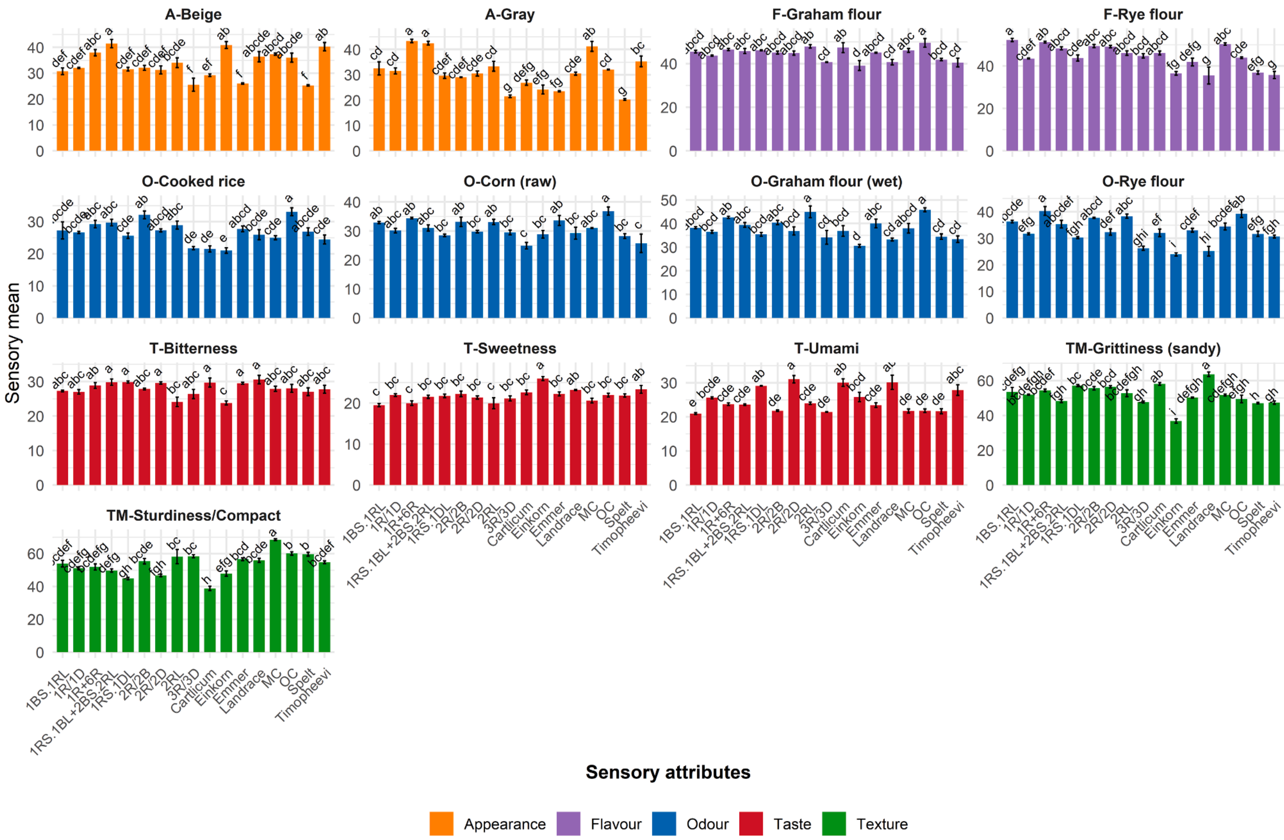

Fig. 1. Mean Sensory Trait Intensities by Wheat Genotype Group: Mean intensity scores (±SE) for 13 sensory attributes as evaluated by a trained panel across genotype groups: rye introgressed lines, modern cultivars (MC), old cultivars (OC) ancient wheats (einkorn, emmer, *T. Timopheevi*), spelt, *T. Carthlicum* and landraces.

3.3. Genotypic segregation and multivariate sensory characterization

The principal component biplot (Fig. 3A) illustrates the distribution of 17 wheat genotype groups based on 13 sensory attributes. Principal components 1 and 2 (PC1 and PC2) together explained 63.3 % of the total variation, with PC1 accounting for 43.8 % and PC2 for 19.5 %. The genotype groups were broadly separated into three clusters along PC1, although the 1R/1D substitution and emmer genotypes showed overlap between clusters, indicating intermediate sensory profiles. Nine sensory attributes (O-Graham flour (wet), Q2 – O-Rye flour, Q3 – O—Corn (raw), O—Cooked rice (white), A-Gray, A-Beige, TM-Sturdiness/Compact, F-Graham flour, F-Rye flour loaded positively along PC1 and were associated with six genotype groups (MC, 2RL, OC, 2R/2B, 1R+6R, and 1RS.1BL+2BS.2RL, including emmer). In contrast, T-sweetness (Q10) loaded in the opposite direction, aligning with spelt, einkorn, T. *Timopheevi*, 3R/3D, and 1R/1D Additionally, three attributes, TM-grittiness (Q7), T-umami (Q9), and T-bitterness Q11, loaded toward landrace, *T. Carthlicum*, 1RS.1DL, and 2R/2D, and were negatively associated with sturdiness/compactness (Q8).

A two-dimensional heatmap with hierarchical clustering (Fig. 3B) grouped the 49 genotypes and 13 sensory attributes based on Z-score normalized intensity values. The genotypes were divided into three major clusters. Cluster 1, comprising MC, 1R+6R, 1RS.1BL+2BS.2RL, 2RL, OC, emmer, 1BS.1RL, and 2R/2B, showed the highest average sensory intensity. Cluster 2 included *T. Carthlicum*, 1R/1D, 1RS.1DL, 2R/2D, landrace, and *T. Timopheevi*, while Cluster 3, which consists of einkorn, 3R/3D, and spelt, showed the lowest intensity across traits. The sensory traits were also grouped into three clusters based on response patterns across genotypes: Cluster 1 (Q1, Q2, Q3, Q4, Q8, Q12, Q13), Cluster 2 (Q5, Q6), and Cluster 3 (Q7, Q9, Q10, Q11), reflecting distinct sensory dimensions in terms of appearance, texture, and flavour attributes.

Linear discriminant analysis (Fig. 3C) effectively separated the 17 genotype groups into three distinct clusters based on their sensory profiles. The separation was primarily driven by LD1 and LD2, which captured the most discriminating features. Cluster 1, with LD1 scores ranging from 1 to −4 and LD2 scores from 1 to 5, included OC, 1R+6R, MC, 2R/2B, 2RL, 1BS.1RL, 1RS.1BL+2BS.2RL, and emmer. Cluster 2, characterized by LD1 scores of 6 to 10.2 and LD2 scores of −1.5 to −2.5, included 1R/1D, 2R/2D, 1RS.1DL, *T. Carthlicum*, and landrace. Cluster 3, comprising 3R/3D, spelt, *T. Timopheevi*, and einkorn, was defined by more negative LD1 scores (−8 to −10) and LD2 scores between 1.9 and −3.5, indicating a contrasting sensory profile from the other two clusters.

4. Discussion

The present study clearly demonstrated the high diversity of sensory quality attributes present within the material, which indicates that the material can be utilized to develop wheat varieties with specific sensory characters, and that the sensory properties of the material need to be considered while using the material in plant breeding for other characters, such as resistance and nutrition. Previous studies have shown that genotypes evaluated in the present study exhibit a range of interesting traits in terms of resistance/tolerance to abiotic and biotic stresses and nutritional compound content (Hussain et al. 2010; Johansson et al. 2020; Lan 2024). For certain traits, particularly disease resistance, specific governing genes have been identified (Ashraf et al. 2023; Rahmatov et al. 2016b; Yazdani et al. 2025a; b) and are currently being transferred to adapted wheat lines (e.g. Yazdani et al. 2025a). If these genotypes are to be used in breeding for resistance/tolerance to abiotic and biotic stresses and enhanced nutritional content, their sensory attributes are equally important, as consumers ultimately choose products that taste good (Spiller and Belogolova 2017). Integrating sensory

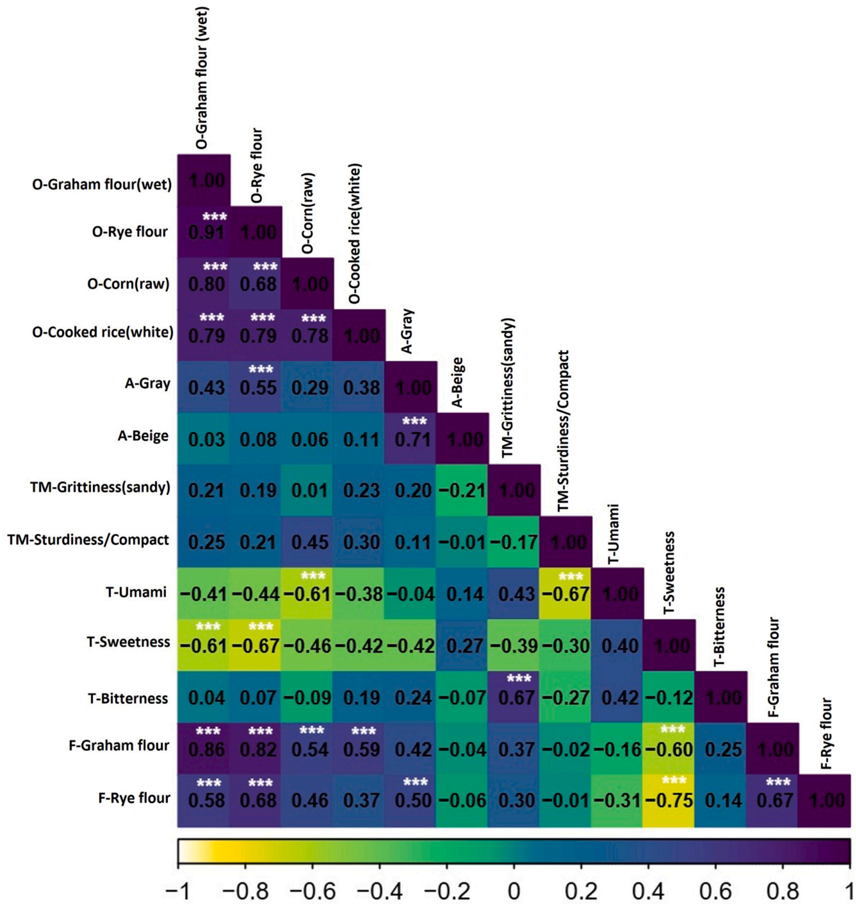

Fig. 2. Pearson's correlation matrix among 13 sensory attributes across 49 wheat genotypes. The matrix displays correlation coefficients (r-values) with significance levels indicated by asterisks ($p < 0.001$). Strong positive and negative correlations are highlighted, revealing relationships among odour/aroma, appearance, texture, taste and flavour descriptors. Colour scale ranges from −1 (yellow, strong negative correlation) to +1 (purple, strong positive correlation).

quality into resistance and nutritional trait goals is therefore essential not only for consumer acceptance but also for advancing sustainable wheat production systems that balance productivity, resilience, and dietary quality (Paux et al. 2022; Wendin et al. 2020). The present study was conducted under uniform field agronomic conditions to minimize environmental variation and allow for the reliable attribution of sensory differences to genetic factors. This approach was essential for establishing a baseline understanding of the inherent sensory diversity of the material. However, this design limits the ability to assess genotype × environment ($G \times E$) interactions, particularly in relation to how sensory attributes may vary under different growing conditions. Therefore, future studies should include multi-environment trials to evaluate the stability and adaptability of sensory traits, including their potential links with the nutritional compound profiles of wheat.

4.1. Sensory differentiation across genotypes

The ANOVA results demonstrated significant genotypic variation across all 13 sensory traits ($p < 0.001$), underscoring the strong influence of genetic background on the odour, appearance, texture, taste, and flavour characteristics of whole-meal wheat porridge. Post-hoc analysis with Tukey's HSD further revealed that modern cultivars, older cultivars and rye-introgressed lines (e.g., 1RS.1BL+2BS.2RL, 2R/2B, 1R+6R, 2RL) consistently showed higher intensity for odour descriptors (such as graham flour, rye flour, corn, and cooked rice), distinct appearance traits (gray and beige hues), and firmer texture. In contrast, ancient wheat, including spelt, einkorn, and *T. Timopheevi*, displayed milder sensory profiles, particularly for odour and flavour. Texture perception also varied markedly: rye-rich genotypes like 2R/2B and 1BS.1RL exhibited higher compactness, whereas *T. Carthlicum* and landrace wheats were characterised by a grittier mouthfeel. Taste attributes followed distinct patterns as well, bitterness and umami were most pronounced in *T. Carthlicum* and 1RS.1DL, while einkorn, spelt, and 1R/1D were notably sweeter.

These findings are consistent with those of earlier studies reported by Starr et al. (2013, 2015), who demonstrated significant sensory variation among wheat species and showed that porridge is a reliable medium for capturing aroma and flavour profiles reflective of genotype, as well as other researchers who had profiled wheat genotypes for sensory attributes (Frankin et al. 2023; Vindras-Fouillet et al. 2021). Our results expand on these studies by demonstrating that sensory differences are robust across a broader and more diverse panel of genotypes and that these differences are quantifiable and statistically significant.

4.2. Correlation patterns among sensory attributes

Pearson correlation analysis revealed significant interrelationships among sensory traits, providing further insight into the underlying sensory architecture. Odour descriptors were strongly intercorrelated ($r = 0.68$–0.91), suggesting that these traits likely stem from shared or co-expressed volatile compound profiles. A notable positive correlation between flavour intensity (F-Graham flour) and texture firmness ($r = 0.72$) underscores the sensory interplay between mouthfeel and perceived taste strength. Conversely, sweetness showed moderate to strong negative correlations with most odour and flavour attributes ($r \approx$ –0.60 to –0.75), indicating potential sensory trade-offs, particularly

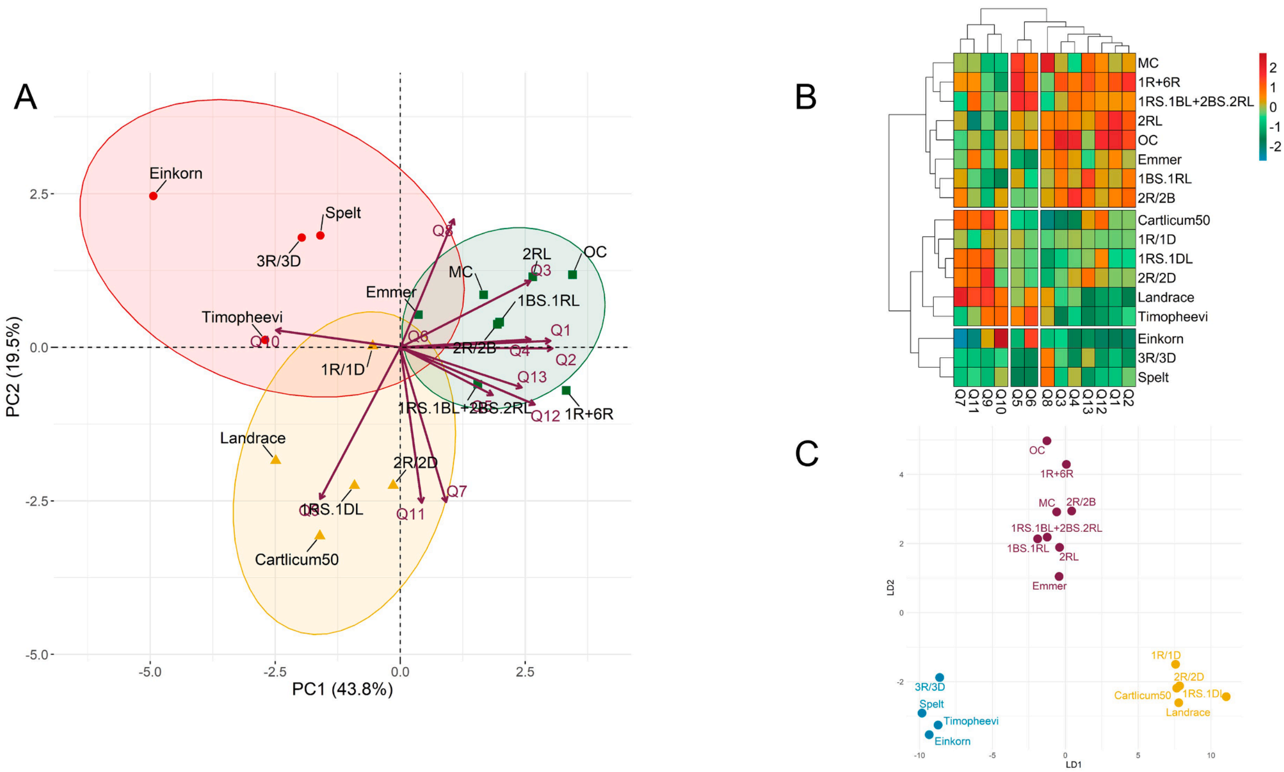

Fig. 3. Multivariate analysis of sensory attributes across 17 wheat genotype groups. **(A)** Contribution of the first two principal components (PC1 and PC2) explaining the variation among genotypes and 13 sensory traits. **(B)** Two-dimensional heatmap dendrogram displaying the clustering of genotype groups (rows) and 13 sensory attributes (columns) based on Z-score standardisation. **(C)** Linear discriminant analysis (LDA) of genotype groups, showing differentiation based on sensory profiles. Sensory traits include: Q1 – O-Graham flour (wet); Q2 – O-Rye flour; Q3 – O—Corn (raw); Q4 – O—Cooked rice (white); Q5 – A-Gray; Q6 – A-Beige; Q7 – TM-Grittiness (sandy); Q8 – TM-Sturdiness/Compact; Q9 – T-Umami; Q10 – T-Sweetness; Q11 – T-Bitterness; Q12 – F-Graham flour; Q13 – F-Rye flour.

relevant when balancing palatability and nutritional targets. These associations are consistent with known biochemical interactions between sugars and aroma-active compounds in cereal matrices (Zhao et al., 2020), and underscore the importance of an integrated approach in breeding programs aimed at optimizing both taste and nutritional quality.

4.3. Linking sensory traits to genetic background

Multivariate analyses supported and extended the univariate findings, offering a comprehensive view of genotype differentiation based on sensory attributes. PCA accounted for 63.3 % of the total variance across the first two components, with PC1 effectively separating odour and texture-intensive genotypes, such as modern cultivars, emmer, and rye-introgressed lines, from those characterised by sweetness, bitterness, and grittiness, including ancient wheats and landraces. Hierarchical clustering of the heatmap further delineated three main sensory-intensity groups: (1) a high-intensity cluster of modern and introgressed lines, (2) a transitional cluster including *T. Carthlicum* and some landraces, and (3) a mild-profile cluster comprising ancient wheats like spelt and einkorn. LDA validated these groupings, highlighting clear sensory differentiation among genotypic classes.

Importantly, these clusters aligned with known nutritional trends: emmer and rye-introgressed genotypes often combine high sensory intensity with elevated Fe and Zn and low Cd levels (Chatzav et al. 2010; Lan et al. 2024a; b; Peleg et al. 2008) and ancient wheat, while often nutrient-dense (Roumia et al. 2023; Shewry et al. 2012; Zhao et al. 2009), are typically more neutral in sensory perception. These findings reinforce earlier reports of genotype-specific sensory research (Castellari et al. 2023; Starr et al. 2013) and emphasize the potential dual agronomic and sensory value of rye-introgressed lines (Merker and Rogalska 1984; Olalekan 2024; Rahmatov et al. 2016a). Such integrative patterns underline the potential of sensory profiling in guiding breeding efforts aimed at producing nutritionally superior and consumer-acceptable wheat varieties.

4.4. Implications across the wheat value chain

The observed sensory diversity among wheat genotypes holds significant potential across the entire value chain, from breeding to processing and marketing. Genotypes such as einkorn and spelt, noted for their natural sweetness (Roumia et al. 2023), and *T. Carthlicum* and 2R/2D, which exhibit umami-rich profiles, present clear opportunities for differentiated product development. This is particularly relevant for wholegrain applications, where flavour and mouthfeel are often barriers to consumer acceptance (Foster et al. 2020; Heiniö et al. 2016). Sensory preferences strongly influence purchasing behaviour, especially in health-oriented segments where wholegrain products are perceived as less palatable (Drewnowski and Gomez-Carneros 2000; Foster et al. 2020; Wendin et al. 2020). As such, tailoring sensory characteristics through genotype selection is a practical strategy to enhance consumer satisfaction and market reach.

Therefore, it is critical that breeders carefully avoid selecting genotypes that could compromise these desirable sensory traits, as maintaining flavour and texture is essential to consumer acceptance and market success. At the same time, farmers, producers, and other food system actors can leverage the unique sensory profiles of specific genotypes to create niche and value-added products that not only meet diverse consumer preferences but also support local economies and promote agrobiodiversity. Such targeted product development contributes to more sustainable and diversified food systems. Furthermore, selecting genotypes based on sensory preferences can help reduce food waste by improving consumer acceptance and encouraging regular consumption. This strategy supports circular food systems and promotes sustainability across the entire field-to-fork chain.

Food processors can harness genotype-dependent traits to fine-tune texture and aroma, while marketers may emphasize both sensory and nutritional advantages to attract a growing segment of health-conscious consumers (Hayakawa, 2017; Szakály and Kiss, 2023). At the same time, breeders are strategically positioned to integrate favourable traits by selecting from both modern and traditional genetic resources. These include introgressed lines such as 1R, 2RL, and 6R, which combine agronomic resilience with sensory and nutritional benefits (Bhagat et al. 2025; Johansson et al. 2024; Lan et al. 2024a), as well as ancient wheat types like einkorn, emmer, and spelt (Roumia et al. 2023; Szakály and Kiss 2023). This diverse pool of actionable genetic variations supports the development of innovative wheat-based products (such as porridges, fermented blends, or fibre-rich breakfast foods) tailored to diverse consumer groups, including older adults, post-COVID sensory-impaired individuals, and those pursuing nutrient-dense, sustainable diets. By leveraging genotype-specific sensory and nutritional profiles, food producers and breeders can foster the development of diverse, sustainable wheat-based products that meet consumer preferences while reducing food waste and supporting environmentally responsible food systems.

Moreover, consumer acceptance is influenced by evolved taste preferences, including an innate liking for sweetness and an aversion to bitterness, especially in staple foods (Drewnowski and Gomez-Carneros 2000). This highlights the importance of sensory screening in breeding programs. For instance, einkorn and certain spelt and introgressed lines (e.g., 2RL, 3R/3D) not only deliver high mineral content and abiotic stress tolerance (Johansson et al. 2020, 2024; Roumia et al. 2023) but also exhibit low bitterness (Roumia et al. 2023), enhancing their appeal to a broader audience. In contrast, landraces, 1RS.1DL, and 2R/2D, while nutritionally rich (Adhikari et al. 2022; Saini et al. 2023; Sönmez et al. 2023), tend to be more bitter and less sweet, traits that could limit consumer acceptance unless mitigated through blending, processing, or targeted product positioning strategies.

4.5. Strategic alignment with food system transformation goals

The findings of this study align closely with key objectives of the Swedish national food strategy (Government Offices of Sweden 2017), particularly the goals of increasing sustainable domestic food production, promoting healthier eating habits, and enhancing the competitiveness of the Swedish food sector through high-quality, consumer-focused innovations. By integrating sensory attributes with nutritional and agronomic traits, this research provides actionable insights that directly contribute to these strategic priorities. Enhancing sensory appeal alongside nutrient density addresses key consumer barriers to wholegrain consumption, supporting sustainable dietary transitions critical for public health and environmental outcomes. Genotypes such as 1R+6R, 2RL, and 1RS.1BL+2BS.2RL, which scored highly for desirable sensory traits like aroma, flavour intensity, and texture firmness, offer strong potential for breeding nutritionally enhanced, climate-resilient wheat varieties. Likewise, ancient wheat such as einkorn and spelt, characterized by sweetness and smooth mouthfeel, represents promising options for value-added, wholegrain products tailored to health-conscious consumers and specific dietary needs. This genetic diversity not only underpins sensory and nutritional variation but also represents a valuable reservoir of climate resilience and agro-biodiversity. Leveraging such diverse genotypes aligns with sustainable intensification goals, helping to secure food production in the face of climate change.

Importantly, integrating sensory quality into the development of food products, including cereals such as wheat, not only improves consumer acceptance but also supports the creation of more sustainable and health-promoting food systems. (Gobara Hamid et al. 2025; Roumia et al. 2023; Yang and Lee 2019). This integration enhances breeding strategies by emphasizing the selection of genotypes that balance sensory appeal, nutritional value, and environmental resilience with yield, thus directly contributing to sustainable intensification and agricultural goals. Such a practical, multidimensional breeding focus is critical for developing cultivars that meet both consumer preferences and agro-ecological demands. This interdisciplinary approach, linking sensory science, plant genetics, and nutrition, can potentially inform future breeding pipelines, product development, and policy design. Moreover, it aligns with broader national and EU-level goals for biodiversity, climate adaptation, and dietary improvement (EIP-AGRI 2020; Formas 2022). By leveraging genotype-specific sensory profiles, breeders and industry stakeholders can support multi-disciplinary collaboration, consumer-driven innovation, and the broader uptake of resilient, nutrient-rich cereal varieties, thereby contributing to a more inclusive and sustainable food system.

5. Conclusion

This study demonstrated that sensory attributes in wheat are strongly influenced by genetic background, with significant variation in odour, texture, appearance, taste, and flavour among 49 genotypes classified into 17 distinct groups. While improvements in agronomic performance, processing quality, and nutritional traits of wheat have contributed to global food security, this study reflects a timely shift toward integrating sensory attributes, an increasingly important factor driving consumer demand and sustainability goals. Using a wholegrain porridge model and a suite of statistical approaches, we identified clear genotype clusters that reflect sensory intensity and complexity. Modern cultivars and wheat-rye introgression lines demonstrated heightened odour, flavour, and firmness, while ancient wheats, such as einkorn and spelt, exhibited a smoother mouthfeel and sweeter taste profile. These insights can directly inform wheat breeding strategies and product development for diverse consumer preferences.

Importantly, the results align with national and international policy frameworks that aim to promote healthier and more sustainable food systems. The Swedish National Food Strategy highlights the need for increased domestic food production with lower environmental impact, improved public health through better diet, and enhanced competitiveness of the food sector. Our identification of high-performing, climate-resilient, and sensory-appealing genotypes such as 1R+6R, 2RL, and 1RS.1BL+2BS.2RL supports these goals. Meanwhile, ancient wheats offer pathways for premium niche products that may appeal to health-conscious consumers. These findings highlight the potential for integrating sensory attributes with nutritional and agronomic qualities to support the development of wheat varieties that promote sustainable production and consumption, reduce food waste, and enhance biodiversity. By leveraging genotype-specific traits, this study contributes to the broader goals of food system transformation, including climate resilience, health-oriented dietary transitions, and the creation of value-added wholegrain products that align with environmental and public health objectives.

5.1. Limitations of the study

This study offers valuable insights into sensory and nutritional variation among diverse wheat genotypes. Some limitations should be considered when interpreting these findings. First, a sensory evaluation was conducted with a trained panel under standardized laboratory conditions, excluding consumer study. Future studies could involve consumer panels to explore the liking, preferences, and attitudes toward sensory attributes and their implications for product development and market adoption. Second, this study focused solely on wholegrain porridge as the model food. Although this provided a standardised platform for comparison, it may not capture the full sensory potential of each genotype in other food applications, such as bread, pasta, or baked goods, where processing can significantly influence aroma, texture, and flavour and thus have a great impact on consumer liking.

Third, the genotype panel encompassed a diverse range of modern, ancient, and wheat types, with an uneven representation across all groups. Some groups, such as 1R/1D (13 genotypes) and Emmer (7 genotypes), were well-represented, whereas others, including 1BS.1RL, 2RL, and *Triticum timopheevii*, were represented by only a single genotype due to their rarity. This limited within-group replication should be considered when interpreting the variability across groups. Nonetheless, these genotypes were included to capture the maximum genetic and sensory diversity relevant to breeding and food systems. The use of a replicated experimental design enabled us to determine that each genotype was statistically well-represented. Fourth, all genotypes were cultivated under standard field management practices to minimize environmental variability and determine whether sensory differences are genetically driven. While this design provides a controlled baseline for characterizing inherent sensory variation, it limits the conclusions about GxE interactions. Future studies should expand this approach through multi-environment trials to explore the environmental stability of sensory traits. Finally, while the discussion considered nutritional qualities relevant to breeding, the study did not directly correlate micronutrient content with sensory attributes. Integrating biochemical, sensory, and genomic data in future studies would provide a more comprehensive basis for breeding high-quality, consumer-preferred wheat varieties.

Ethical statement

The study received the approval of the University-wide Ethics Council of Kristianstad University (Dnr-U2025–2.1.12–299) on February 14, 2025.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Olawale Olalekan: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Darlison:** Writing – review & editing, Visualization, Validation, Supervision, Investigation. **Nikwan Shariatipour:** Writing – review & editing, Visualization, Validation, Supervision, Software, Formal analysis, Data curation. **Karin Wendin:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Marcus Johansson:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Tina Henriksson:** Writing – review & editing, Visualization, Validation, Resources, Conceptualization. **Karin Gerhardt:** Writing – review & editing, Visualization, Validation, Conceptualization. **Thomas Björklund:** Writing – review & editing, Visualization, Validation, Conceptualization. **Firuz Odilbekov:** Writing – review & editing, Visualization, Validation, Resources. **Eva Johansson:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Mahbubjon Rahmatov:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Supplementary materials

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