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Sensory profiles and consumer acceptance of plant-based 'meaty' sauces derived from yeast-flavourzyme hydrolysates via maillard reaction

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ABSTRACT

The lack of meaty flavour in novel plant-based foods is one of the biggest current challenges in mimicking meat products. The present study aims to assess the sensory profile of plant-based 'meaty' sauces that are developed through proteolysis and Maillard reaction (MR) with glucose or xylose with nutritional yeast. It also seeks to understand consumer acceptance of these sauces through the use of different front-of-pack (FOP) labels. In the sensory study, a semi-trained panel (n=22) evaluated a range of MR-produced sauces alongside positive (animal-based) and negative (yeast-based) controls, and paired with plain (rice), wheat (seitan ball) and soy (tofu puff) carriers. Higher meaty flavour intensity was perceived in all the glucose-MR sauces and one xylose-MR sauce when paired with the wheat carrier. Relative to the positive control, two sauces from the respective glucose-MR and xylose-MR samples which imparted higher meaty flavour intensity, were shortlisted for the subsequent consumer test. The perceived sensory characteristics, liking, healthiness and willingness-to-purchase of these sauces were accessed among 129 consumers, in blind condition or presented with different FOP labels such as 'protein source' and 'low sodium' claims. Results suggest that meaty-related sensory attributes are the primary drivers of consumer preference. Sensory characteristics are more influential than FOP labelling effects in consumer acceptance, while the sauces with FOP labels are preferred over those without labels. Taken together, our findings highlight the potential of MR-produced sauces in improving meaty flavour profiles and consumer acceptance in novel plant-based foods.

1. Introduction

Flavour is one of the key sensory attributes contributing to the quality of meat, which involves the perception of gustation, olfaction, and trigeminal sensation (Flores, 2017). Lack of meaty flavour and off-flavours generated from lipid oxidation of unsaturated fatty acids in plant-based meat alternatives (PBMAs) are the current challenges in successfully mimicking authentic meat products (Fiorentini et al., 2020).

PBMAs generally exhibit lower levels of these lipid-derived compounds but higher concentrations of beany aldehydes (e.g., hexanal, produced by soybean lipoxygenase activity) and secondary oxidation products, resulting in notes reminiscent of grass, green, or cardboard (Yang et al., 2023). Instrumental analyses (e.g., GC–MS) have shown that pyrazines, thiophenes, and Strecker aldehydes are positively associated with roasted, nutty, and meaty attributes, whereas excess aldehydes such as hexanal and (E)-2-nonenal are linked to oxidised or beany flavours (Sun et al., 2023b).The meaty flavour of PBMAs could be enhanced by adding the beef bone extract or incorporating bovine myoglobin, however, through this approach, the products can no longer be suitable for consumers following vegetarian or vegan diets (Chiang et al., 2020; Devaere et al., 2022). Thus, volatile flavour compounds such as pyrazine and thiophene present in food-grade yeast extract are further developed and combined with non-volatile flavour precursors (e.

Abbreviations: MRPs, Maillard reaction products; FOP, Front-of-pack; QDA, Quantitative descriptive analysis; PBMA, Plant-based meat alternatives; PC, Positive control; NC, Negative control; G, Glucose; X, Xylose; P, Plain; W, Wheat; S, Soy; NL, No label; IM, packaging with informed meat label; IP, packaging with informed plant label; LS, packaging with low sodium claim.

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g., reducing sugars) upon heating to deliver desire roasted meat aroma in PBMAs (Li & Li, 2020).

Most of the meat flavour precursors are lipids and water-soluble components. A series of flavour compounds such as aldehydes, ketones, alkenes, esters, ethers and sulfur-containing compounds are to be formed from thiamine degradation, lipid oxidation and Maillard reactions, upon heating (Kanokruangrong et al., 2019; Li & Li, 2020). Maillard reaction is one of the important processes, which is responsible for the flavour and colour development in cooked meat. It involves the formation of covalent bonds between carbohydrates (e.g., reducing sugars) and proteins (e.g., amino acids) during heat treatment, resulting in a group of sensorially related compounds, known as Maillard reaction products (MRPs) (Liu et al., 2020). The precursors of Maillard reaction, such as xylose, glucose, ribose, cysteine, methionine and threonine are recently proposed as a solution to potentially improve the meaty aromas in PBMAs (Li & Li, 2020).

The flavour properties of MRPs are dependent on several factors, such as types of sugars and amino acids, reaction time, pH and temperature (Liu et al., 2022). Higher amounts of volatiles from MRPs, such as pyrazines, aldehydes, furans and ketones, were produced from soybean meal hydrolysate and ribose through Maillard reaction, compared to other reducing sugars (xylose, glucose, fructose and galactose). Whereas xylose-MRPs and ribose-MRPs were reported to have higher overall acceptance (Sun et al., 2023b). Another recent study showed 50 MRPs with good continuity, high meaty, mellow and delicate flavour can be formed when xylose was used as reducing sugar with addition of 10% cysteine under the reaction time of 120 min at 120°C (Huang et al., 2023). However, none of the studies provide detailed information on how the sensory study was carried out, only with a focus on instrumental analysis. Hence, a conclusive outcome on the sensory properties of the MRPs cannot be drawn.

Besides sensory properties, food labelling is one of the important factors influencing customers' purchase decision on a food product. From a consumer perspective, food labels provide nutritional information and composition to guide food choices and behaviours. Front-of-pack (FOP) labels are a simplified format of food labelling which can be used to inform consumers the health information and nutrition content (e.g., low sodium, sugar-free) of the food products for making healthier choices, and hence reduce or prevent certain diet-related chronic diseases such as obesity, diabetes and cardiovascular diseases (Ikonen et al., 2019; Penzavecchia et al., 2022). Research demonstrated that consumers were willing to pay more for pasta fortified with microalgae proteins which were labelled as organic, rather than those with vegan and Nutri-Score labels (Van der Stricht et al., 2023). Another study reported that the Health Star Rating labels (a system created by the Australian government to assist in comparing the healthiness of products) on plant-based foods significantly influenced the healthiness perception of the product in Australian consumers (Ang et al., 2023; Department of Health, 2021). These studies highlighted consumers' perception on novel plant-based foods can be largely influenced by FOP labels. However, little is known about if the impacts vary between different FOP labels, and whether are there any differential effects of FOP labels on consumer perception and acceptance across different product categories, i.e. PBMAs *vs.* animal-based products.

To address the above research gaps, we first aimed to assess the sensory profiles of in-house developed yeast-based 'meaty' sauces that produced using different reducing sugars (i.e. glucose, xylose), enzyme-to-substract (E/S), and protein-to-sugar ratios through the Maillard reaction, evaluated by a semi-trained sensory panel. We then compared these sauces with the commercial animal- (positive control) and yeast-based sauces (negative control). Since yeast extracts are commonly used to mimic the meaty and umami characteristics of meat-based sauces in plant-based formulations, a yeast-based sauce provides an appropriate negative control for comparison (Kale et al., 2022).The plant-based 'meaty' sauces with most desired sensory profiles were shortlisted for a subsequent consumer study to further examine the effects of different FOP lables ('protein source' and 'low sodium' claims) on the perceived sensory, liking, healthiness and willingness-to-purchase in plant-based sauces *vs.* animal-based sauce among Singaporean consumers.

2. Materials and methods

In this study, the yeast-based 'meaty' sauces were developed through Maillard reaction between reducing sugars (glucose and xylose) and proteins (polypeptides and amino acids) from nutritional yeast after undergoing enzymatic hydrolysis with Flavourzyme which consists of a blend of endo- and exo-peptidases. In preliminary study, the volatile compounds of these sauces were identified. Subsequently, human sensory evaluation and consumer study were conducted.

2.1. Maillard reaction samples

The Maillard reaction products (MRPs) in sauce form were produced from enzymatic hydrolysis followed by heat treatment (Maillard reaction), following the method described by Chiang and others (Chiang et al., 2022). A 10% w/w nutritional yeast extract (Bob's Red Mill, 48.17 ± 0.47% protein; Oregon, United States) dispersion was prepared and stirred overnight at room temperature. The dispersion was adjusted to pH 6 using 1 M NaOH, followed by incubating with Flavourzyme® (1000 Leucine Amino Peptidase Units g-1, Batch: HPN00565; Bagsværd, Denmark) at enzyme-to-substrate (E/S) ratios at varying compositions based on enzyme-to-protein weight (see Table 1). The hydrolysis reaction was conducted at 50°C for 2 hours, using a temperature-controlled orbital shaker (Max Q6000, ThermoFisher Scientific, USA) at 150 rpm. The enzyme was then inactivated by heating the hydrolysate in a 95°C water bath for 15 min. The hydrolysates with glucose (Phoon Huat Pte Ltd, Singapore) or xylose (Sigma Aldrich, Singapore) were mixed in different protein-to-sugar ratios (see Table 1), with the pH of the mixtures being adjusted to 6.5 with 1M NaOH. The Maillard reaction of the hydrolysates was carried out in a temperature-controlled shaking water bath (BT-350D, Yihder Technology, Taiwan) at the following conditions: 100°C, 2 hours at 120 rpm. The resultant MRPs were cooled and kept at 4°C until further analysis. The three E/S (enzyme-to-substrate) and P/S (protein-to-sugar) ratio combinations for glucose- and xylose-based Maillard reaction products (MRPs) were selected based on a prior optimisation study using multi-task Bayesian optimisation (MTBO). This approach systematically explored the design space of E/S and P/S ratios and identified optimal combinations that maximised flavour precursor generation (e.g., amino acids, reducing sugars) while maintaining process feasibility and sensory relevance. The three final combinations for each sugar type (Table 1) represent the most promising candidates predicted to deliver desirable meaty aroma profiles and were used for subsequent sensory evaluation.

2.1.1. Volatile compound analysis

Volatile compound of the MRP sauce samples were pre-analysed following Theng et al. (2024), using headspace solid-phase microextraction (HS-SPME; PAL RSI 120 autosampler, Agilent, USA) combined with gas chromatography-mass spectrometry (GC-MS; GC, 7890B,

Table 1
Composition of MRP samples used in sensory evaluation.

Glucose-Maillard reaction product (G-MRP)			Xylose-Maillard reaction product (X-MRP)		
Sugar used: Glucose			Sugar used: Xylose		
Sample Code	E/S ratio	P/S ratio	Sample Code	E/S ratio	P/S ratio
G-MRP1	1.343	2.312	X-MRP1	0.700	0.322
G-MRP2	3.640	2.896	X-MRP2	3.070	2.441
G-MRP3	0.698	0.261	X-MRP3	4.960	2.848

Glucose and xylose were labelled as "G" and "X", respectively. The "E/S ratio" and "P/S ratio" represent enzyme-substrate ratio and protein-to-sugar ratio.

Ailgent, USA; MS, 5977B, Agilent, USA). Briefly, the process involved mixing 1 g of sauce sample with 1 g of 30% sodium chloride solution in a headspace vial and adding 2-methyl-3-heptanone as an internal standard. The sample was equilibrated and then exposed to a conditioned SPME fiber (Superlco, Bellefonte, USA) for extraction. A GC-MS system with a ZB-WAXplus™ capillary column (Zebron, Phenomenex, USA) was used, applying a specific temperature program and helium (1.0 ml/min) as the carrier gas. Identification of volatiles was done by comparing spectra and retention indices to NIST14 database. Quantification used standard curves from the internal standard, and retention indices were calculated using an n-alkane series (C8-C24). The odour profiles of detected volatiles (single measurement) are available in Table A1.

2.2. Human sensory evaluation

2.2.1. Test samples

Concentration of the MRP samples was determined and prepared based on the pilot results (n=12) and using a modified recipe from Chiang (2020) (results not reported). All MRP samples were diluted with water (77.6%) and seasoned with sugar (2%) and salt (1%). The negative control (yeast extract; Marmite, Unilever, United Kingdom) was diluted with filtered water in the ratio of 1:10, while positive control (pork bone broth; Mmmm!, Singapore) was not diluted. These sauces are mostly flavour enhancers that will not be eaten alone; therefore, we paired them with different plant-based carriers (e.g., plain-, wheat- and soy-based) for both human sensory and consumer evaluation. Approximately 2 grams of each sauce was cooked, prepared and paired with a carrier and served together as a sample for evaluation (See Table 2 & Table A2). A total of three carriers were included to evaluate which best pairs with the MRP sauce for achieving an ideal meaty flavour. All samples were kept warm in the water bath at a constant temperature of 55 ± 5°C before serving.

2.2.2. Selection of sensory panel

22 healthy participants (8 males) aged between 21 and 50 years old were recruited from general public Singapore through advertisement, social media, email and word of mouth, and from our own database of previous participants. All participants were screened using a taste recognition test to confirm their ability to identify five basic tastes. Participants were not eligible for the study if they had glucose-6-phosphate dehydrogenase (G6PD) deficiency, active tuberculosis or receiving treatment for TB, major chronic diseases or infections, sinus problems that affected taste and smell, food allergies or intolerances to foods or common food ingredients, took insulin or drugs known to affect glucose metabolism, followed specific dietary restrictions, were smokers, carrier of Hepatitis B Virus (HBV), Hepatitis C Virus (HCV), Human Immunodeficiency Virus (HIV), pregnant, member of research team or their immediate family members, or concurrently enrolled in other research studies judged not be scientifically or medically compatible with the study at the Clinical Nutrition Research Centre (CNRC). All eligible participants provided informed consent and were compensated for their time. The study was approved by the Institutional Review Board (IRB) for the Agency for Science, Technology and Research (A*STAR), Singapore (IRB ref: 2022-075), and complied with the Declaration of Helsinki for research involving human participants.

Table 2
The serving size and cooking conditions of samples for sensory evaluation.

Carrier	Serving size	Cooking condition
Plain (Medium grain white rice; FairPrice, Singapore)	5 (± 0.5) grams	Cooked and kept warm in the rice cooker
Wheat (Deep-fried seitan puff; FV Foods, Singapore)	One-half piece	Steamed with sauce samples for 15 min
Soy (Deep-fried tofu puff; Unicurd, Singapore)	One-quarter piece	Steamed with sauce samples for 15 min

2.2.3. Panel training

Of 22 panelists, two-thirds were experienced and involved in sensory training for previous plant-based meat products studies. Before evaluation session, all panelists underwent prior training to familiarise themselves with the test samples and evaluation procedure. The panel underwent two consecutive weeks of training, with at least three sessions per week, each lasting 30 minutes. Two dummy samples were given repeatedly during training. Each of the samples was paired with three respective carriers (plain, wheat and soy). A total of six dummy samples were evaluated in duplicates across three session days. The dummy samples were used to calibrate and maintain consistency between panelists and across sessions. During training, panelists rated the intensity of 12 sensory attributes of aroma, flavor and taste of six dummy samples (see Table 3) on 100-point visual analogue scale (VAS), anchored from 'low' (0) to 'high' (100). The panel was checked whether they used the same range of scale, scored the samples in the same magnitude, perceived the same sensory attributes and scored the products consistently across the session days. Oral feedback was given to panelists after each training session. Overall, the panel reproduced similar sensory scores of the samples over replicates, except for bitter taste (product*replicate effect, $F(5,105)=2.91, p=0.02$), off-flavour ($F(5,105)=2.52, p=0.03$) and astringency ($F(5,105)=3.20$, $p=0.01$). Prior to the training, a provisional list of sensory attributes and definitions was prepared and modified from the sensory lexicon of soy sauce (Cherdchu and Chambers, 2014; Imamura, 2016). During training sessions, panelists clarified and refined unclear sensory terms, and the final list of attributes and definitions is summarised in Table 3.

2.2.4. Descriptive sensory evaluation

Twenty-four test samples were evaluated, including six MRPs and two controls (positive and negative controls). Samples were paired with either plain, wheat or soy carriers, and evaluated across six separate evaluation days and in duplicates. All samples were presented in random 3-digit codes and served warm in a porcelain crucible and covered with a lid. Panelists evaluated the odour attributes first by lifting the lid, taking a whiff of the sample and rating the odour intensity before placing the sample in their mouths. Across all measures, sample ratings were separated by a one-minute inter-stimulus break for palate cleansing with filtered water and water crackers (Carr's, United Kingdom).

All samples were randomized and rated by the panelists in duplicate.

Table 3
List of sensory attributes and their description.

Attribute	Description
Meaty Odour Intensity	The odour intensity associated with meat/poultry (e.g., cooked beef, chicken).
Off-odour Intensity	The intensity of non-characteristic odour (e.g., charred, chemical, rancid, metallic, medicinal, musty) in the sample.
Meaty Flavour Intensity	The intensity of meat flavour associated with meat/poultry (e.g., cooked beef, chicken).
Salty Taste Intensity	The intensity of salty taste associated with sodium chloride (e.g., table salt).
Sweet Taste Intensity	The intensity of sweet taste associated with table sugar.
Savoury Taste Intensity	The intensity of savoury taste associated with monosodium glutamate (MSG).
Sour Taste Intensity	The intensity of flavour notes associated with the impression of all sour substances (e.g., pickled vegetables, vinegar).
Bitter Taste Intensity	The intensity of bitter taste associated with caffeine.
Off-flavour Intensity	The intensity of non-characteristic tastes (e.g., charred, chemical, rancid, metallic, medicinal, musty) in the sample.
Astringency	The drying, puckering sensation on the tongue and other mouth surfaces.
Meaty Aftertaste Intensity	The intensity of lingering meat flavour after swallowing the sample.
Off-flavour Aftertaste Intensity	The intensity of lingering non-characteristic taste of the sample after swallowing.

Each sensory attribute was rated on a 100-point visual analogue scale (VAS), anchored from 'low' (0) to 'high' (100). All data was collected using data acquisition software (Compusense Cloud, Guelph, Ontario, Canada) in sensory booths that conformed to international standards for the design of test rooms.

2.2.5. Statistical analysis

Normality and intra-class correlation tests were carried out to confirm the normality of data distribution and reliability of replicate results prior to further analysis. The estimated means (± SE) were calculated for each sensory attribute using linear mixed model with sample as a fixed effect, and a random participant effect. Differences in the sensory profiles between test samples and carriers were assessed, and significant main effects were compared using post-hoc Bonferroni test with 5% statistical significance ($p < 0.05$). The mean differences between sensory attributes of the food samples paired with various carriers were analysed and illustrated using Principal Component Analysis (PCA) with sensory intensity as loadings and samples with carriers as scores.

The statistical analyses were completed using SPSS (Version 26, Armonk, New York), and the PCA bi-plot was analysed with XLSTAT 2019 (Addinsoft, USA).

2.3. Consumer acceptance test

2.3.1. Test samples

Based on the sensory findings, the yeast-based 'meaty' MRP sauces with high meaty flavour profiles were then shortlisted for a subsequent consumer study. Shortlisted MRP sauces paired with wheat carrier (the most ideal carrier) were evaluated for acceptance and compared to positive control (pork bone broth). The samples followed the same cooking and preparation method (see Section 2.1.1), steamed for 20 min and held in a 65°C water bath until evaluation.

Each sauce was presented under three different labelling conditions, (i) blind (without FOP), (ii) FOP labelled with specific protein sources, and (iii) with FOP labelled as 'low sodium'.This makes up a total of nine sauce samples for testing. The FOP labels tested in this study include 'informed protein sources' (e.g. '100% natural meat product' and 'plant-based' labels) and 'product claims' (e.g. the Singapore Health Promotion Board's 'Healthier Choice Symbol – Lower in Sodium' claim) (see Fig. 1).

2.3.2. Consumer panel

129 healthy participants who based in Singapore (51 males) were recruited. This study was approved by A*STAR's IRB (IRB ref: 2022-075), and the participants' eligibility criteria followed the protocol described in Section 2.1.1. Participants provided written consent and were reimbursed for their participation.

2.3.3. Consumer perception & preference ranking test

During the consumer testing session, warm-up samples were first presented to prevent first-order bias and were not included in the final analysis. All test samples were coded with unique three-digit codes, randomised and presented in sets of three. A one-minute inter-stimulus break was applied between samples for thorough palate cleansing with filtered water and water crackers (Carr's, United Kingdom). The study was carried out in the sensory evaluation laboratory at CNRC.

Participants were presented with ten samples (including a warm-up sample) in blind, with FOP that specified protein source, and with FOP labelled as 'low sodium'. Participants were instructed to first rate the perceived intensity of each attribute in the order of 'odour', 'flavour/taste' and 'aftertaste', followed by their liking of the sample odour, flavour/taste, aftertaste and overall acceptability. They were then instructed to rate the perceived healthiness of the sample and their willingness-to-purchase the product. Lastly, participants ranked all test samples from most preferred (position 1) to least preferred (position 9). All sensory attributes were rated on a 100-point VAS, anchored from 'low' (0) to 'high' (100), whereas sample liking, perceived healthiness and willingness-to-purchase were evaluated on 9-point likert scales.

2.3.4. Statistical analysis

Normality test, intra-class correlation test and linear mixed model analyses were performed for the consumer study, as described in Section 2.1.4. Ranking test was analysed using the Friedman test. Statistically significant results were further analysed with the Wilcoxon signed-rank test to examine differences between samples. Bonferroni adjustment was used to make multiple comparisons. A new significant level of 0.006 (where a significant level, 0.05, is divided by the number of samples, 9) was used in the test. Internal preference mapping was performed using XLSTAT 2019 (Addinsoft, USA) to explore the relationship between consumer liking scores for odour, flavour and aftertaste with their perceived sensory attribute ratings of the samples.

3. Results

3.1. Sensory profiles of yeast-based 'meaty' sauces paired with different carriers

Fig. 2 and Table A3a-c show the sensory profiles of the six in-house developed yeast-based 'meaty' sauces, commercial pork bone broth, and commercial yeast sauces, either paired with plain, wheat or soy carriers. When paired with the plain carrier, the negative sensory attributes (off-odour, off-flavour, off-flavour aftertaste, sourness, bitterness and astringency) were highly perceived in yeast, and the xylose-derived MR sauces with higher E/S and protein-to-sugar ratios (X-MRP2 and X-MRP3), whereas all glucose-derived MR sauce samples (G-MRPs) had a noticeable sweetness and savouriness profile. Similarly, a significant higher intensity of off-odour, off-flavour, off-flavour aftertaste, sourness,

Fig. 1. Mock-up sauce packaging with and without front-of-pack (FOP) labels.

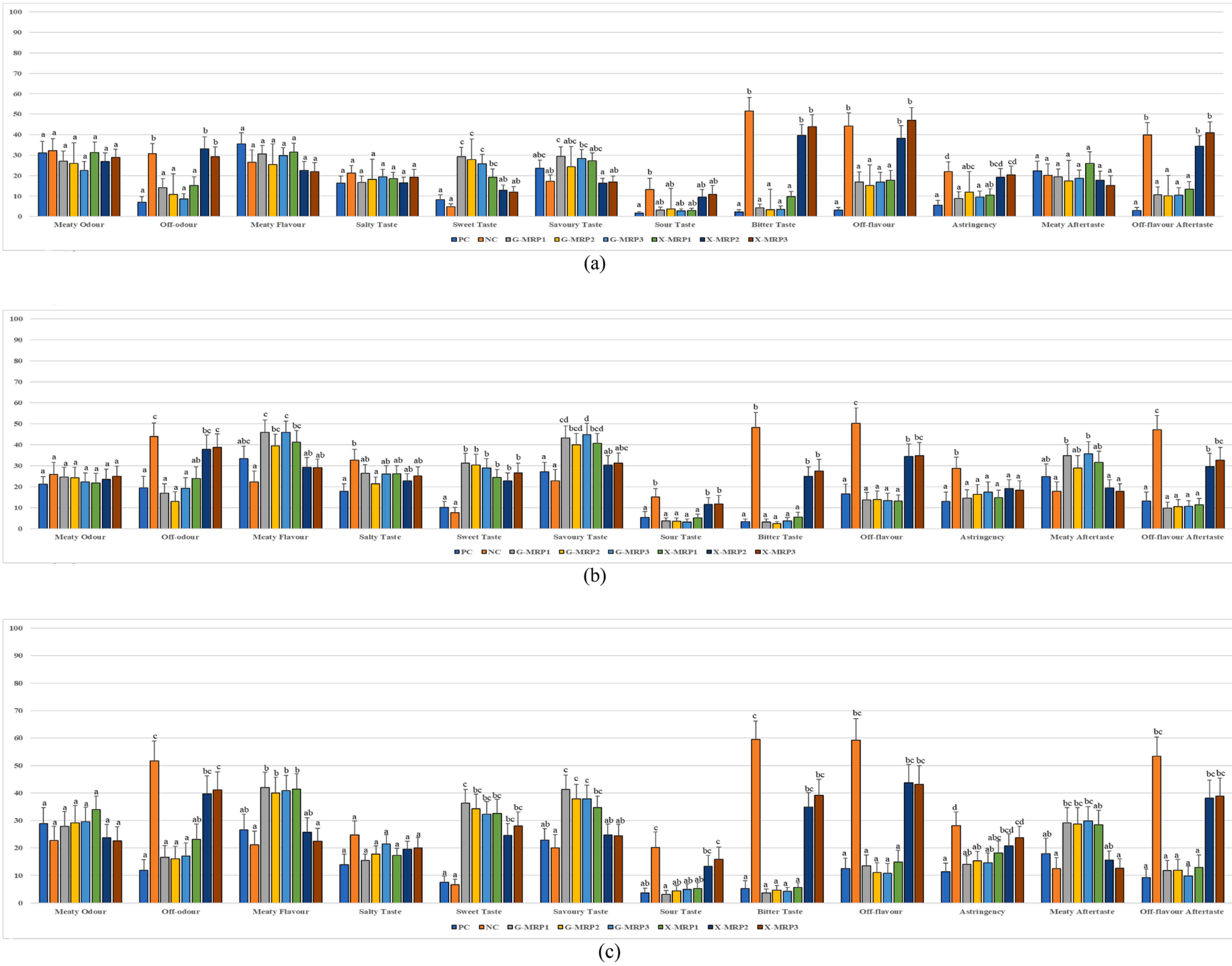

Fig. 2. Sensory ratings of sauce samples paired with (a) plain, (b) wheat and (c) soy carriers evaluated by a sensory panel. Within each attribute, bars without a common letter indicate differences (Bonferroni post-hoc test, $p < 0.05$). PC = Positive Control, NC = Negative Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.

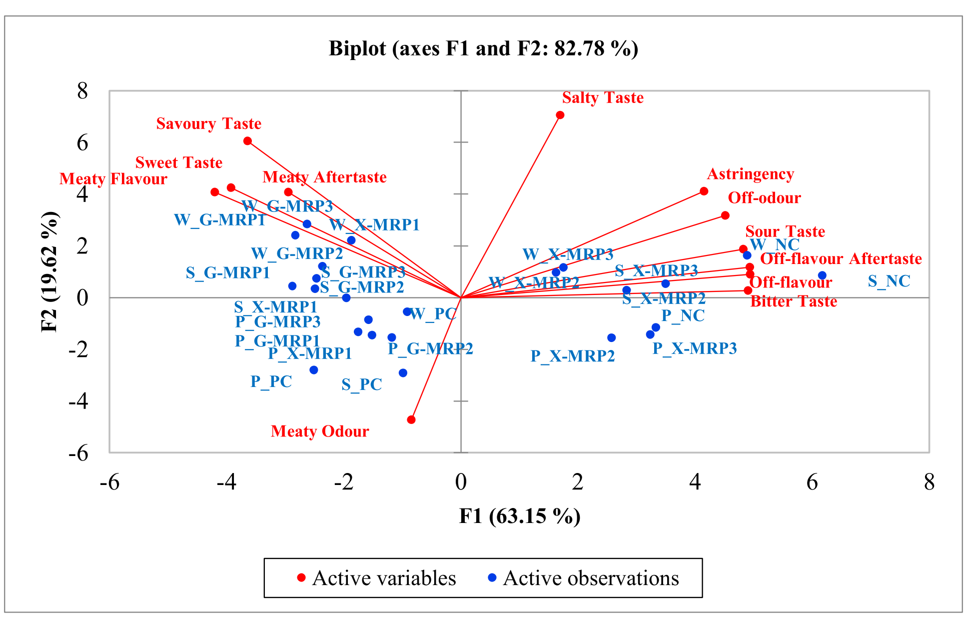

Fig. 3. Principal Component Analysis (PCA) biplot of the descriptive sensory profiles of sauce samples paired with plain (P), wheat (W) and soy (S) carriers, respectively. PC = Positive Control, NC = Negative Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.

and bitterness was perceived for yeast, and the xylose-derived MR sauces with higher E/S and protein-to-sugar ratios (X-MRP2 and X-MRP3) when paired with wheat and soy carriers, except for astringency, which was only strongly perceived in yeast sauce with wheat carrier. On the other hand, high-intensity levels of meaty flavour, meaty aftertaste and savouriness were perceived in X-MRP1 sauce which has a lower E/S and protein-to-sugar ratios, and all glucose-derived MR sauce samples paired with wheat and soy carriers. No significant differences were found in meaty odour, meaty flavour, meaty aftertaste and salty taste intensities across all sauce samples when they were consumed with plain carrier (Fig. 2 **(a)**, Table A3a). The perceived meaty odour intensity was also not different across all sauces neither they were paired with wheat (Fig. 2 **(b)**, Table A3b) nor soy (Fig. 2 **(c)**, Table A3c) carriers.

The principal component analysis was used to study the relationship among 12 sensory attributes within sauce samples paired with different carriers. The factor loadings of analytical variables are tabulated in Table A4. The PCA bi-plot demonstrated that both components 1 and 2 explained a total of 82.78% variance (Fig. 3). The "negative" sensory attributes, including astringency, off-odour, sour taste, off-flavour aftertaste, off-flavour and bitter taste were positively correlated to most of the xylose-derived MR sauces with higher E/S and protein-to-sugar ratios (X-MRP2, X-MRP3) and the negative control (yeast), whereas the savoury taste, meaty aftertaste, sweet taste and meaty flavour were positively correlated to all glucose-derived MR sauces, the positive control (pork bone broth) and one xylose-derived MR sauce with lower E/S and protein-to-sugar ratios (X-MRP1). A negative correlation was observed between salty taste and meaty odour.

3.2. *Consumer perceived sensory, healthiness, likings, and willingness-to-purchase on yeast-based 'meaty' sauces across different FOP labelling conditions*

Glucose- and xylose-derived MR sauces with most desired sensory profiles were shortlisted to further compared with positive control (animal-based sauce) in different FOP labelling conditions. In consumer testing, all three sauce samples were paired with the wheat carrier.

The perceived sensory of the sauce samples paired with the wheat carrier, across different FOP labelling conditions, i.e. with and without FOP labels are demonstrated in Fig. 4. No significant differences were observed in off-odour and off-flavour aftertaste intensities across all samples, regardless the labelling conditions. The off-flavour intensity of pork bone broth (positive control) was perceived as significantly higher than xylose-derived MR sauce when no FOP labels applied, but was reported to have a similar off-flavour intensity as the two other MR sauces when with FOP labels. A significant higher intensity of sweet, salty and savoury taste was perceived in both glucose- and xylose-derived MR sauces when compared to control, regardless of labelling condition. The highest meaty odour, flavour and aftertaste intensities were perceived in the xylose-derived MR sauce, followed by glucose-derived MR sauce, lastly the positive control, and this trend was consistently observed across three labelling conditions.

Hedonic liking, perceived healthiness and willingness-to-purchase, across three FOP labelling conditions is illustrated in Fig. 5. Overall liking for odour of xylose-derived MR sauce was significantly higher than glucose-derived MR sauce and positive control. Furthermore, significantly higher ratings of overall liking for flavour and aftertaste for both glucose- and xylose-derived MR sauces were observed compared to control, regardless of their FOP labels. Within each sample, the perception of healthiness was rated higher when FOP labels applied compared to those without FOP label. In positive control, higher healthiness was only perceived when labelled with low sodium claim, whereas in both glucose- and xylose-derived MR sauces, higher healthiness perception was reported when labelled as "plant-based" and "low sodium". Willingness-to-purchase was significantly higher in MR test samples (G-MRP3 and X-MRP1) than the positive control, regardless of their FOP labelling. The FOP label with low sodium significantly influenced the healthiness perception of the products but not on overall liking and willingness-to-purchase. Animal-based sauce sample labelled

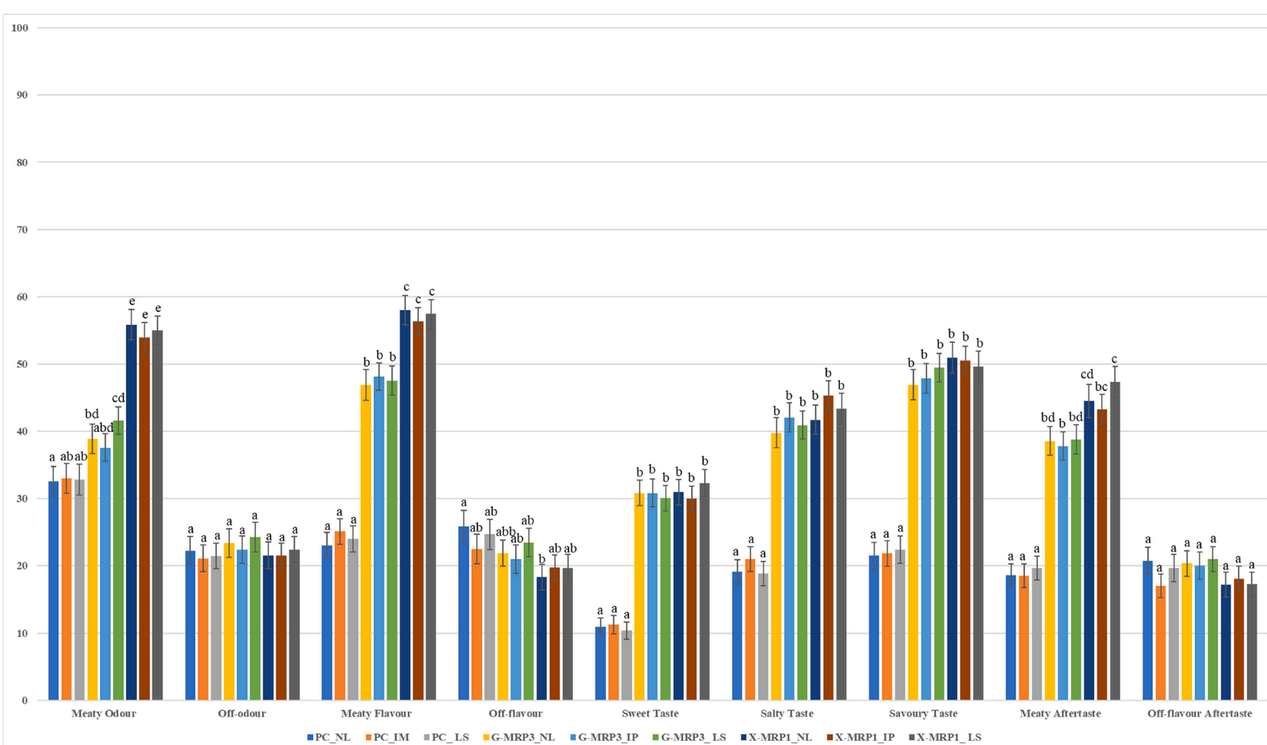

Fig. 4. Sensory perception of sauce samples in the consumer study. The samples rated with no label (only packaging is displayed), packaging with informed meat label, packaging with informed plant label and packaging with low sodium claim are denoted as NL, IM, IP, and LS, respectively. PC = Positive Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.Ratings labelled with different letters within a particular attribute indicate significant differences at $p < 0.05$.

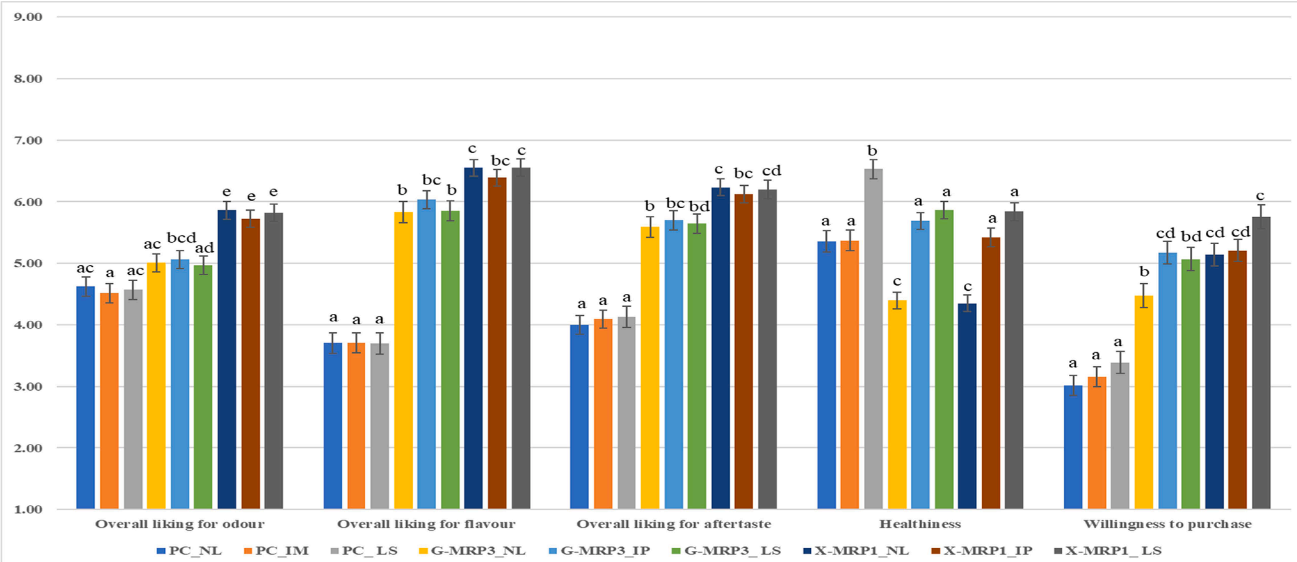

Fig. 5. Consumer rating of sauce samples and PC paired with the wheat carrier using a 9-point hedonic scale. The samples rated with no label (only packaging is displayed), packaging with informed meat label, packaging with informed plant label and packaging with low sodium claim are denoted as NL, IM, IP, and LS, respectively. PC = Positive Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product. Ratings labelled with different letters within a particular attribute indicate significant differences at $p < 0.05$.

as ‘low sodium’ had the greatest perceived healthiness compared the two plant-based sauces with the same ‘low sodium’ label. Overall, higher intensity of meaty odour, meaty flavour, sweetness, saltiness, savouriness and meaty aftertaste were perceived for the glucose- and xylose-derived MR sauce samples compared to animal extract.

The preference ranking of three sauce samples in three FOP labelling conditions is shown in Table 4. There was an overall statistically significant difference ($p < 0.001$) among the mean ranks. Xylose-derived MR sauce was the most preferred, followed by glucose-derived MR sauce and positive control. Within each sauce type, participants preferred the samples labelled with low sodium claims the most, followed by samples labelled with protein sources. Samples without FOP labels were the least preferred. The significant differences of these ranking results were further tested using the Wilcoxon signed-rank test (see Table 5). No significant difference of FOP labels was reported in positive control. Whereas significant differences were observed in glucose-derived MR sauces which labelled as “plant-based” ($p = 0.002$) and “low sodium” ($p = 0.001$) when compared to the non-labelled,

Table 4
Mean ranks of the sauce samples and commercial animal extract in three FOP labelling conditions using the Friedman test.

Sample	Ranking Score (1 - 9)
X-MRP1_LS	2.99
X-MRP1_IP	3.43
X-MRP1_NL	3.62
G-MRP3_LS	4.18
G-MRP3_IP	4.25
G-MRP3_NL	4.99
PC_LS	6.93
PC_IM	7.27
PC_NL	7.34

The samples were ranked according to preference, where position 1 is the most liked, and position 9 is the least liked. The samples ranked with no label (only packaging is displayed), packaging with informed meat label, packaging with informed plant label and packaging with low sodium claim are denoted as NL, IM, IP, and LS, respectively. PC = Positive Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.

suggesting the labelled glucose-derived MR sauces were better liked compared to non-labelled counterpart. The xylose-derived MR sample with “low sodium” label was significantly more preferred compared to non-labelled xylose sample ($p = 0.005$) within the xylose-derived MR sauce type.

The internal preference maps for overall liking for odour (a), flavour (b) and aftertaste (c) with the relative positioning of consumers (red points), sauce samples (blue points), and sensory attributes (green points) are illustrated in Fig. 6. The high perceived sensory attributes such as meaty odour,meaty flavour, and meaty aftertaste, as well as sweet, salty and savoury taste were located in regions corresponding to the liking of the majority of consumers; whereas off-flavour was negatively correlated with the preference vectors.

The Xylose-derived MR sauce (X-MRP1) were positioned towards the right-hand side of the map, where consumers were clustered, compared to glucose-derived MR sauce (G-MRP3), regardless of labelling condition. These Xylose-derived MR samples were perceived as high in meaty-related sensory attributes. In contrast, the positive controls (PC), which were the least preferred irrespective of labelling conditions, were positioned in the left quadrants across all three internal preference maps; in which these areas had relatively fewer consumers and were associated with high perceived off-flavour (see Fig. 6). Similarly, the glucose-derived MR samples were less preferred, and were consistently positioned near the off-odour attribute and away from the main consumer cluster across the three internal preference maps.

4. Discussion

The current research evaluated sensory profiles of ‘meaty’ sauces developed through Maillard reaction with reducing sugars (glucose and xylose) when paired with plain, wheat and soy carriers, as compared to commercial animal and yeast-based sauces (as controls), using a semi-trained sensory panel. The consumers’ perception of sensory, liking, healthiness and willingness-to-purchase of the shortlisted glucose- and xylose-derived MR sauce in comparison with pork bone broth (positive control) was evaluated in three labelling conditions, (i) no FOP label, (ii) labelled with protein type, (iii) labelled with “low sodium”. In sensory study, our findings demonstrated that all glucose-derived MRP sauces and xylose-derived MRP sauce with lower E/S and protein-to-sugar

Table 5
Wilcoxon signed-rank test on the significant level of the sauce samples and commercial animal extract in three FOP labelling conditions.

Sample	PC_NL	PC_IM	PC_LS	G-MRP3_NL	G-MRP3_IP	G-MRP3_LS	X-MRP1_NL	X-MRP1_IP	X-MRP1_LS
PC_NL	-	NS	NS	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
PC_IM	NS	-	NS	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
PC_LS	NS	NS	-	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
G-MRP3_NL	$p < 0.001$	$p < 0.001$	$p < 0.001$	-	0.002	0.001	$p < 0.001$	$p < 0.001$	$p < 0.001$
G-MRP3_IP	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.002	-	NS	NS	0.003	$p < 0.001$
G-MRP3_LS	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.001	NS	-	NS	NS	$p < 0.001$
X-MRP1_NL	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	NS	NS	-	NS	0.005
X-MRP1_IP	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.003	NS	NS	-	NS
X-MRP1_LS	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.005	NS	-

The significant difference is indicated by $p \leq 0.006$. The insignificant difference is expressed as NS (Not Significant). The samples ranked with no label (only packaging is displayed), packaging with informed meat label, packaging with informed plant label and packaging with low sodium claim are denoted as NL, IM, IP, and LS, respectively. PC = Positive Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.

ratios had significantly higher savoury taste, meaty aftertaste, sweet taste and meaty flavour intensities; whereas "negative" sensory attributes, including astringency, off-odour, sour taste, off-flavour aftertaste, off-flavour and bitter taste were positively correlated to xylose-derived MR sauces with higher E/S and protein-to-sugar ratios. This suggests that glucose-derived MR sauces and xylose-derived MR sauces with lower E/S and protein-to-sugar ratios showed a great potential in improving 'meaty' flavour in plant-based food applications. In consumer testing, results showed that meaty-related sensory attributes were the primary drivers of consumer preference. Sensory characteristics of the sauce samples (X-MRP1 and G-MRP3) are more influential in driving consumer acceptance than the effect of FOP labels. The FOP labels were found to significantly influence the healthiness perception of products but not on overall liking and willingness-to-purchase. However, within the same sauce sample, sauces labelled with informed plant protein source and low sodium were preferred over those without FOP labels.

Glucose has been used as a reducing sugar to generate flavour-related Maillard reaction products (Fu et al., 2020); while xylose has shown strong potential for flavour development via Maillard reaction due to its reactivity with different hydrolysed vegetable proteins (Kale et al., 2022). Previous research demonstrated that a nutty, toasty, sweet, caramel-like aroma can be developed by combining glucose and xylose with fish (*Collichthys niveatus*) hydrolysate through Maillard reaction (Zhao et al., 2015). A product's meaty flavour can also be derived and enhanced via Maillard reaction between xylose and different hydrolysates such as soybean, rapeseed, flaxseed, sesame seed and thiamine (Fadel et al., 2015; Fu et al., 2020; Shen et al., 2021; Song et al., 2013; Wei et al., 2018; Zhao et al., 2011). In the present study, lower enzyme-to-substrate (E/S) and protein-to-sugar (P/S) ratios in sauces were found to improve meaty flavours in plant-based foods, particularly when yeast-flavourzyme hydrolysates reacted with xylose. This is in agreement with a previous study, that is at an optimal E/S ratio, meaty-related compounds such as furans, pyrazines, and thioethers were detected when a lower wheat protein-to-glucose ratio was used (Chiang et al., 2022). This is also further supplemented by volatile compound analysis (Table A1), where the highest concentrations of meaty-related compounds (dimethyl trisulfide, methylpyrazine, 2,6-dimethylpyrazine, 2-ethyl-5-methylpyrazine, and 2-ethyl-3,5-dimethylpyrazine) were detected in xylose-derived sauce with low E/S and P/S ratios (X-MRP1) (Bassam et al., 2022; Begum et al., 2019; Frank et al., 2016; Ko et al., 2005; Raza et al., 2020; Wang et al., 2019;). In contrast, sauces with high E/S and P/S ratios (X-MRP2 and X-MRP3) exhibited elevated levels of compounds associated with negative odour profiles, including 2-methylpropanoic acid, acetic acid, butanoic acid, 3-methylbutanoic acid, and octanoic acid (Begum et a., 2019; Bleicher et al., 2022; Ko et al., 2005; Li et al., 2021; Li et al., 2022; Raza et al., 2020; Wang et al., 2019). These findings align with human sensory data, which showed that negative attributes such as off-odour, off-flavour, sourness, bitterness, and off-flavour aftertaste were more pronounced in samples with higher E/S and P/S ratios across all carrier types. Together, suggest that a high enzyme/substrate and protein/sugar ratios were not ideal for developing sauces that imparted meaty flavours when xylose was used as the reducing sugar via the Maillard reaction.

Aside from sensory flavour/odour profiles, colour development and pH are widely recognised as key indicators of Maillard reaction progression and are closely linked to flavour formation and product appearance of yeast-based "meaty" sauces. Although these parameters were not directly measured in the present study, our previous work on Maillard-reacted yeast-flavourzyme hydrolysates demonstrated a progressive decrease in pH, accompanied by a corresponding increase in browning intensity, as a function of E/S and protein-to-sugar ratios, reflecting the advancement of Maillard reaction and melanoidin formation (Theng et al., 2024). In particular, pentose-derived systems (xylose) exhibited greater pH reduction and higher browning intensity than hexose-derived system (glucose), consistent with their higher reactivity and enhanced formation of aroma-active Maillard reaction products. These physicochemical changes were closely associated with the formation of key volatile compounds associated with roasted and meaty aroma attributes.

There are notable sensory differences in sauce samples when paired with different carriers. All the glucose-derived sauces (G-MRPs) and the xylose-derived sauce with lower E/S and protein-to-sugar ratios (X-MRP1) were positively correlated with desired sensory attributes including sweet taste, savoury taste, meaty flavour and aftertaste when paired with the wheat carrier, compared to pairing with the plain and soy carriers. This is likely due to taste-taste and/ or taste-flavour interaction in composite foods through a food-pairing approach, where the presence of two or more tastants in the composite foods may increase the complexity of perceived characteristics or alter sensory perception. For instance, the dynamic perceptual differences in hazelnut chocolate spreads, which varied in composition (e.g., high sugar/low fat, low sugar/high fat) were reduced when paired with wafers and bread (Gonzalez-Estanol et al., 2022). On the other hand, the use of a carrier (e.g., bun and tomato sauce) could also mitigate the texture defects and off-flavour of plant-based patty made with hemp and soy ingredients (Gonzalez-Estanol et al., 2023). In the present study, a similar sensory profile was reported across different sauces when paired with plain carrier; this is in contrast to previous study where the sensory perceptions of 20 soy sauce samples were modified, even when paired with white rice (Cherdchu and Chambers, 2014).

Compared to plain carrier, the wheat (seitan ball) carrier exhibited a more pronounced perception of desirable sensory attributes, which may be explained by the frying process applied to the wheat carrier.Thermal processing through frying can facilitate Maillard reaction within wheat gluten systems, in which peptide fragments undergo glycation and subsequent cross-linking, generating compounds that enhance umami perception (Sun et al., 2023a). In addition, Maillard reaction between reducing sugars and amino acids from wheat gluten, particularly the sulfur-containing residues (e.g. methionine and cysteine), can produce volatile sulfur-derived compounds, including furanthiols and

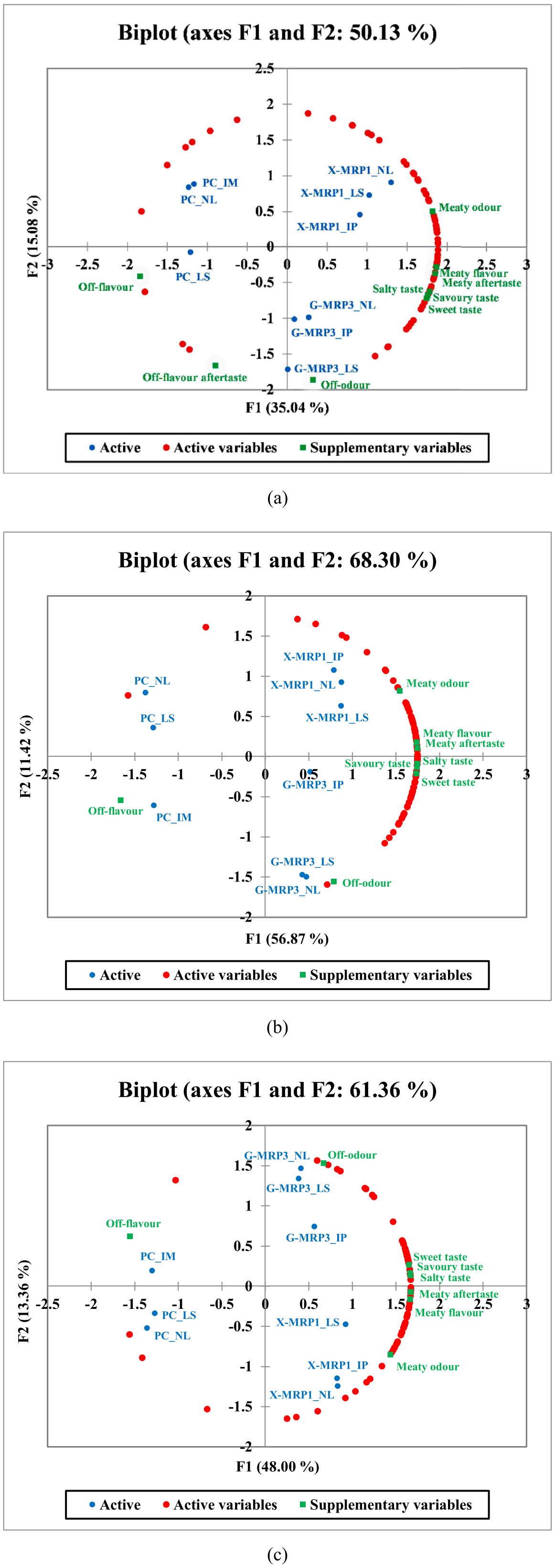

Fig. 6. Internal preference map (biplot) showing the distribution of consumers (red points), sauce samples (blue points) and sensory ratings (green points) based on (a) overall liking for odour, (b) overall liking for flavour and (c) overall liking for aftertaste. PC = Positive Control, NC = Negative Control, G = Glucose, X = Xylose, MRP = Maillard Reaction Product.

thiophenes, which are widely recognised as major contributors to savoury, roasted, and meat-like aromas (Sun et al., 2023a). Wheat gluten also may elicit a more meat-like textural perception compared to soy-based carriers, as its viscoelastic properties arise from the viscous nature of gliadin and the elastic behaviour of glutenin. This combination can produce a chewy texture that more closely resembles that of meat (Wang et al., 2015; Xavier et al., 2025). The current findings demonstrated that MR sauce has the greatest impact on enhancing the meaty flavour when paired with a wheat carrier, as compared with plain and soy carriers, highlighting the potential use of wheat-based analogues in plant-based food applications. Although testing with different food carriers did affect some perceptions, overall, the use of a carrier did not strongly affect the classification of sensory characteristics of MR derived sauce samples.

The internal consumer preference map generated in this work identifies the association between consumers perceived sensory characteristics and rated hedonic liking. The resultant maps revealed that consumers liked a sauce sample with higher perceived meaty-related attributes, sweet, salty and savoury taste with a negative association with off-flavour and, to a lesser extent, off-odour. These highlighting meaty related attributes were the main drivers of consumer preference across odour, flavour, and aftertaste dimensions, which lines with recent research where meat flavour is an important driver for liking across the whole plant-based meat alternative category, regardless of the product format (Giezenaar et al., 2024). In addition, the X-MRP1 samples (xylose-derived sauce with lower E/S and protein-to-sugar ratios), regardless of labeling condition, were consistently more preferred than G-MRP3 (xylose-derived sauce with lower E/S and protein-to-sugar ratios) and positive control samples, suggesting that. X-MRP1 delivered the highest perceived meaty-related attributes, sweet, salty and savoury taste.

The present results revealed that the sensory characteristics of sauce samples are more influential in driving consumer acceptance than the effect of FOP labels. This is in line with previous research findings (McCrickerd et al., 2019; Lima et al., 2019; Liem et al., 2012). Adult consumers' choices were driven by sensory characteristics rather than FOP labels (i.e., the traffic light system and nutritional warnings) after tasting grape nectar and chocolate flavored milk. (Lima et al., 2019). A similar observation was found in another study that used different FOP labels (e.g. reduced salt, the healthy choices tick logo, and a combination of both) (Liem et al., 2012). Perceived salty taste intensity, liking, or desire-to-consume the chicken soup samples were not affected by the FOP labels, but were impacted by their sensory characteristics. However, only 48 participants were involved, and a larger sample size is needed for more robust conclusions. Together, these findings suggested that FOP labels alone are insufficient to alter consumer behavior when making food choices. Reformulation should instead focus onto making those products healthier while maintaining their palatability through taste enhancement to compensate for any loss of desirable flavors.

Perceived healthiness of a food product depends on several factors, including sensory properties, product information (e.g., ingredient list and nutritional information), and the packaging's physical appearance (Plasek et al., 2020). In the current study, FOP labels were reported to affect the healthiness perception but not on overall liking and willingness-to-purchase. Compared to plant-based sauces, consumers perceived animal-based sauce with overall low sensory intensities as healthier, when the 'low sodium' FOP label was presented. This is further supported by previous findings where the effectiveness of FOP labels may vary by product category (Ikonen et al., 2019; Stoltze et al., 2021)., and the 'unhealthy=tasty' belief in which healthy foods are often perceived as non or less tasty among consumers (Raghunathan et al., 2006). A recent study demonstrated that the effectiveness of the Health Star Rating (a FOP labeling system in Australia designed to promote healthier food choices) on perceived healthiness was greater for animal-based patty burgers than plant-based patty burgers when perceived believability of information increased (Ang et al., 2023). In other words, the strength of FOP labels' influence on consumers healthiness perception could depend heavily on how believable they perceive the package information (Beltramini et al., 2000; Fajardo and Townsend, 2016; Kowitt et al., 2017). However, no data were collected in current study regarding the believability of product package information; therefore, exploring the role of perceived believability in the effectiveness of FOP labels for the food product should be considered in the future. Although no significant association was reported between the FOP labels and overall liking and willingness-to-purchase, samples with FOP labels were more preferred over unlabelled ones. This is in line with previous studies showing that consumers preferred soymilk and instant noodles when additional test labels (e.g., healthier choice symbol, reduced sugar, or reduced MSG) were presented compared to the same products without test labels (McCrickerd et al., 2019).

Our study demonstrated the potential to apply specific plant-based 'meaty' sauces derived from yeast-flavourzyme hydrolysates via Maillard reaction to mitigate the current sensory challenges in plant-based food prototype applications. Meaty flavour profiles of xylose-derived sauces with lower E/S and protein-to-sugar ratios were enhanced when paired with a wheat carrier, compared to animal extract, suggesting reformulation possibilities for incorporating MR derived sauces with specific composition into a wheat-based plant-based matrix to impart optimal meaty flavour while maintaining consumer appeal. The interplay between FOP labels, consumers' acceptance and product taste and texture cues in these novel sauces has been found stark, i.e. sample sauces with higher meaty profiles and labelled were preferred over others, indicating that the label cues should integrated the sensory characteristics of the product in a two-way manner to improve consumers' appeal. However, the acceptance is largely dependent on sensory characteristics rather than the effect of FOP labels.

A few limitations of the present study should be acknowledged. Direct quantitative correlations between volatile compounds and sensory attributes were not established, as the instrumental volatile analysis was conducted on undiluted sauces without carriers, whereas sensory evaluations involved diluted samples paired with different food matrices. External preference mapping could not be performed due to the absence of labelling conditions in descriptive sensory evaluation using a semi-trained panel. However internal preference mapping was performed to provide insights into the relationship between perceived sensory attributes and consumer preferences. Current findings cannot be generalised to different consumer segments following different diets (e.g., omnivore, vegetarian, flexitarian), and future research warrants for investigation.

5. Conclusion

Sensory and consumer studies were applied to showcase the potential use of sauces developed through Maillard reaction between hydrolysed nutritional yeast and reducing sugar (glucose or xylose) for future application in alternative proteins. Our findings demonstrated that in-house glucose-derived MR sauces and xylose-derived MR sauces with lower E/S and protein-to-sugar ratios showed great potential in improving 'meaty' flavour in plant-based food applications. FOP labels were generally found to significantly influence the healthiness perception of products but not on overall consumers' liking and willingness-to-purchase. However, consumers preferred sauce samples when additional FOP test labels were presented compared to the same products without test labels. Sensory characteristics of plant-based sauces are still more influential in driving consumer acceptance than effect of FOP labels, highlighting the need of sensory development of plant-based products to enhance consumers' acceptance. Future studies should include objective physicochemical analyses, such as measurements of salt content, umami-related nucleotides and amino acids, colour attributes and pH, and viscosity. Integrating these parameters with sensory evaluation data would enable a more comprehensive understanding of how compositional and physical characteristics influence flavour perception and consumer acceptance.

Ethical statement – studies in humans

The study was approved by the Institutional Review Board (IRB) for the Agency for Science, Technology and Research (A*STAR), Singapore (IRB ref: 2022-075), and complied with the Declaration of Helsinki for research involving human participants.

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CRediT authorship contribution statement

Pik Han Chong: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Jie Ying Michelle Choy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hui Ping Alicia Theng:** Writing – review & editing, Resources, Investigation. **Jie Hong Chiang:** Writing – review & editing, Resources, Funding acquisition. **Pey Sze Teo:** Writing – review & editing, Validation, Supervision, Methodology, 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.

Appendix

Table A1
The volatiles and their corresponding odour profiles of the sauce samples.

Compounds	Odor profile	References	Concentration (ppm)					
			G-MRP1	G-MRP2	G-MRP3	X-MRP1	X-MRP2	X-MRP3
2-methyl-propanal	aldehydic, floral	Sasanam et al. (2021); Mu et al. (2023)	N.D.	N.D.	N.D.	N.D.	0.507	0.459
2-methylfuran	green, cocoa, nutty, almond, coffee	Begum et al. (2019)	N.D.	N.D.	N.D.	0.350	0.232	0.224
Dimethyl disulfide	sulfurous, garlic-like, onion	Li et al. (2021); Raza et al. (2020)	N.D.	N.D.	N.D.	0.073	0.379	0.054

(continued on next page)

Table A1 (*continued*)

Compounds	Odor profile	References	Concentration (ppm)					
			G-MRP1	G-MRP2	G-MRP3	X-MRP1	X-MRP2	X-MRP3
Heptanal	green, herbal	Rochat and Chaintreau (2005); Van Ba et al. (2013)	0.095	0.074	0.098	0.097	0.074	0.059
2-(2-propenyl)-furan	-	-	N.D.	N.D.	N.D.	N.D.	0.029	0.029
1,3-Diazine	-	-	0.020	0.019	0.008	0.013	N.D.	N.D.
Methylpyrazine	roasted, popcorn	Wang et al. (2019)	0.022	0.018	0.016	0.079	0.035	0.032
2-Octanone	cheese, earthy, dairy	Bassam et al. (2022)	0.008	0.007	0.008	N.D.	N.D.	N.D.
1-hydroxy-2-Propanone	sweet, caramellic	Mu et al. (2023)	0.008	0.007	0.009	0.059	0.007	0.019
2,6-dimethylpyrazine	nutty, roasted, roasted beef	Wang et al. (2019)	0.023	0.025	0.027	0.056	0.028	0.010
Ethyl pyrazine	nutty, roasted, meaty	Cherniienko et al. (2022)	0.012	0.014	0.012	0.009	0.023	0.007
Dimethyl trisulfide	alliaceous, sulfurous	Raza et al. (2020)	N.D.	N.D.	N.D.	0.060	0.016	0.057
2-ethyl-5-methylpyrazine	nutty, roasted	Bassam et al. (2022); Frank et al. (2016)	0.017	0.017	0.021	0.028	0.023	0.019
Acetic acid	sour, sharp, vinegar	Li et al. (2021)	N.D.	N.D.	N.D.	0.102	0.334	0.181
3-ethyl-2,5-dimethylpyrazine	nutty, roasted	Wang et al. (2019)	0.164	0.109	0.125	0.162	0.172	0.154
Methional	meaty, baked potato, cooked	Frank et al. (2016); Pham et al. (2008); Wang et al. (2019)	N.D.	0.008	N.D.	0.008	0.035	0.040
Furfural	coffee, nutty, roasted	Sasanam et al. (2021); Wang et al. (2019)	0.011	0.014	0.006	0.489	55.879	56.989
2-ethyl-3,5-dimethylpyrazine	nutty, roasted, potato	Begum et al. (2019); Ko et al. (2005)	0.021	0.021	0.022	0.031	N.D.	N.D.
3,5-diethyl-2-methylpyrazine	nutty, roasted, meaty	Gao et al. (2014)	0.030	0.030	0.031	0.031	0.034	0.029
1-(2-furanyl)Ethanone	sweet, caramellic, and nutty	Raza et al. (2020)	N.D.	N.D.	N.D.	0.015	0.406	0.408
2,3,5-Trimethyl-6-ethylpyrazine	nutty, roasted	Birk et al. (2021)	0.034	0.032	0.034	0.053	0.107	0.079
Benzaldehyde	fruity, almond	Li et al. (2021)	0.152	0.153	0.165	0.219	0.277	0.240
2-methyl-5-(2-propenyl) pyrazine	-	-	0.018	0.016	0.021	0.015	0.024	0.015
2-methylpropanoic acid	acidic, dairy, buttery, rancid	Raza et al. (2020)	0.118	0.083	0.065	0.407	0.569	0.447
1-(2-furanyl)-1-Propanone	fruity	Raza et al. (2020)	N.D.	N.D.	N.D.	0.028	0.229	0.205
2,2′-Bifuran	-	-	N.D.	N.D.	N.D.	N.D.	1.115	1.236
2,2′-methylenebis-Furan	roasted	Laukaleja and Koppel (2021)	N.D.	N.D.	N.D.	N.D.	0.027	0.025
2-fluorobenzaldehyde	-	-	N.D.	N.D.	N.D.	0.052	0.032	0.021
Butanoic acid	rancid	Ko et al. (2005); Wang et al. (2019)	0.081	0.040	0.021	0.109	0.146	0.107
Benzeneacetaldehyde	green, sweet, floral	Li et al. (2021); Raza et al. (2020)	N.D.	N.D.	N.D.	N.D.	0.182	0.174
2-Furanmethanol	medicine, burnt, vitamin-like	Begum et al. (2019); Liu et al. (2015); Pham et al. (2008)	0.116	0.131	0.050	0.112	0.392	0.260
3-methylbutanoic acid	cheese, dairy, acidic, sour	Bleicher et al. (2022); Li et al. (2022)	0.207	0.135	0.113	0.761	1.032	0.792
Hexanoic acid	fatty, cheesy	Mahajan et al. (2004); Wang et al. (2019)	0.022	0.022	0.015	0.034	0.030	0.019
Butylated Hydroxytoluene	phenolic	The Good Scents Company (2025a)	0.083	0.085	0.031	0.008	0.009	0.009
4-(2-furanyl)- 3-Buten-2-one	balsamic, warm, spicy	The Good Scents Company (2025b)	N.D.	N.D.	N.D.	0.006	0.074	0.090
Phenylethyl Alcohol	sweet, floral	Gao et al. (2014); Wang et al. (2019)	0.059	0.056	0.078	0.076	0.085	0.060
p-Cresol	phenolic	Jayasena et al. (2013); Wang et al. (2019)	0.019	0.016	0.012	0.017	0.022	0.015
Octanoic acid	fatty, cheesy, rancid	Begum et al. (2019); Wang et al. (2019)	N.D.	N.D.	N.D.	0.077	0.113	0.087

N.D.: Not Detected

Table A2

Product image of sauce samples pairing with different carriers.

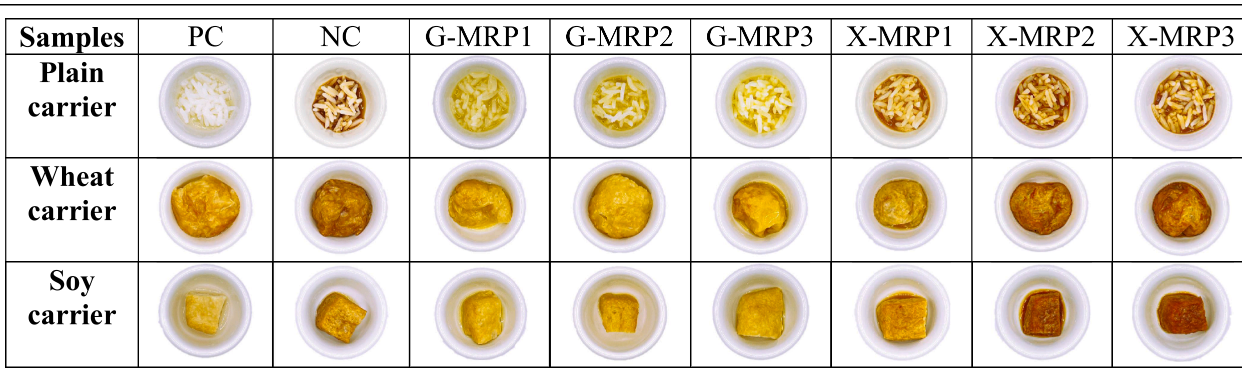

Table A3a
Mean (±SEM) sensory ratings of positive and negative control samples paired with plain, wheat and soy carriers.

Samples	Meaty Odour	Off-odour	Meaty Flavour	Salty Taste	Sweet Taste	Savoury Taste	Sour Taste	Bitter Taste	Off-flavour	Astringency	Meaty Aftertaste	Off-flavour Aftertaste
Positive control												
Plain	31.01 (5.10)^{a}	7.03 (4.08)^{a}	35.44 (5.57)	16.24 (3.52)	8.24 (2.41)	23.49 (4.19)	1.69 (1.87)	2.25 (1.85)	3.05 (3.45)^{a}	5.52 (3.33)^{a}	22.30 (5.39)	2.94 (3.16)^{a}
Wheat	21.10 (5.10)^{a}	19.44 (4.08)^{b}	33.28 (5.57)	17.85 (3.52)	10.19 (2.41)	27.09 (4.19)	5.36 (1.87)	3.29 (1.85)	16.63 (3.45)^{b}	13.00 (3.33)^{b}	24.79 (5.39)	13.12 (3.16)^{b}
Soy	28.76 (5.10)^{a,b}	11.94 (4.08)^{a,b}	26.59 (5.57)	13.90 (3.52)	7.53 (2.41)	22.82 (4.19)	3.61 (1.87)	5.27 (1.85)	12.44 (3.45)b	11.32 (3.33)^{b}	17.87 (5.39)	9.16 (3.16)^{a,b}
P-value	0.035	0.018	0.114	0.408	0.53	0.409	0.119	0.336	0.002	0.003	0.219	0.018
Negative control												
Plain	32.20 (5.44)	30.64 (6.15)^{a}	26.53 (5.27)	21.20 (4.55)^{a}	4.70 (1.97)	17.45 (4.39)	13.14 (4.96)	51.42 (6.67)	44.20 (7.05)^{a}	21.94 (4.87)	20.14 (4.62)	39.76 (6.43)^{a}
Wheat	25.86 (5.44)	43.81 (6.15)^{b}	22.17 (5.27)	32.70 (4.55)^{b}	7.70 (1.97)	22.89 (4.39)	15.18 (4.96)	48.20 (6.67)	50.13 (7.05)^{a,b}	28.73 (4.87)	17.72 (4.62)	47.15 (6.43)^{a,b}
Soy	22.75 (5.44)	51.72 (6.15)b	21.09 (5.27)	24.67 (4.55)^{a}	6.59 (1.97)	19.99 (4.39)	20.15 (4.96)	59.44 (6.67)	59.26 (7.05)^{b}	28.06 (4.87)	12.44 (4.62)	53.43 (6.43)^{b}
P-value	0.091	<0.001	0.33	0.003	0.254	0.176	0.12	0.058	0.008	0.039	0.073	0.045

P-value indicates the main effect of carrier type on each of the ratings. Ratings labelled with different letters within each attribute (column) are different at $p \leq 0.05$, using Bonferroni corrected comparisons to compare the sauce samples.

Table A3b
Mean (±SEM) sensory ratings of glucose-derived MRP samples paired with plain, wheat and soy carriers.

Samples	Meaty Odour	Off-odour	Meaty Flavour	Salty Taste	Sweet Taste	Savoury Taste	Sour Taste	Bitter Taste	Off-flavour	Astringency	Meaty Aftertaste	Off-flavour Aftertaste
G-MRP1												
Plain	27.08 (4.89)	14.07 (4.28)	30.53 (5.16)^{a}	16.65 (3.25)^{a}	29.30 (4.63)^{a}	29.46 (5.10)^{a}	3.22 (1.37)	4.25 (1.48)	16.88 (4.07)	8.78 (3.44)	19.41 (4.82)^{a}	10.56 (3.41)
Wheat	24.63 (4.89)	16.86 (4.28)	45.77 (5.16)^{b}	26.29 (3.25)^{b}	31.15 (4.63)^{a,b}	43.18 (5.10)^{b}	3.68 (1.37)	3.23 (1.48)	13.65 (4.07)	14.53 (3.44)	34.83 (4.82)^{b}	9.75 (3.41)
Soy	27.75 (4.89)	16.60 (4.28)	42.08 (5.16)^{b}	15.40 (3.25)^{a}	36.27 (4.63)^{b}	41.24 (5.10)^{b}	3.11 (1.37)	3.71 (1.48)	13.48 (4.07)	13.97 (3.44)	29.15 (4.82)^{b}	11.81 (3.41)
P-value	0.683	0.672	<0.001	<0.001	0.034	6.368	0.748	0.792	0.442	0.056	<0.001	0.816
G-MRP2												
Plain	26.03 (5.22)	10.80 (4.00)	25.44 (5.09)^{a}	18.04 (3.07)	27.77 (4.91)	24.24 (4.67)^{a}	3.71 (1.71)	3.35 (1.35)	15.14 (4.16)	11.93 (3.94)	17.40 (5.27)^{a}	10.04 (3.42)
Wheat	24.21 (5.22)	13.01 (4.00)	39.41 (5.09)^{b}	21.41 (3.07)	30.25 (4.91)	40.01 (4.67)^{b}	3.49 (1.71)	2.38 (1.35)	13.84 (4.16)	16.34 (3.94)	28.90 (5.27)^{b}	10.53 (3.42)
Soy	29.15 (5.22)	15.96 (4.00)	40.06 (5.09)b	17.71 (3.07)	34.19 (4.91)	37.93 (4.67)^{b}	4.36 (1.71)	4.69 (1.35)	11.08 (4.16)	15.30 (3.94)	28.66 (5.27)^{b}	11.96 (3.42)
P-value	0.565	0.485	0.002	0.182	0.133	<0.001	0.274	0.144	0.395	0.278	0.008	0.809
G-MRP3												
Plain	22.57 (4.53)	8.65 (4.22)a	29.72 (4.90)^{a}	19.44 (3.54)^{a}	25.74 (4.51)	28.30 (4.80)^{a}	2.69 (1.45)^{a}	3.48 (1.47)	16.84 (3.91)^{b}	9.56 (3.80)^{a}	18.66 (4.92)^{a}	10.42 (3.30)
Wheat	22.32 (4.53)	19.16 (4.22)^{b}	45.81 (4.90)^{b}	26.05 (3.54)^{b}	28.81 (4.51)	44.82 (4.80)^{b}	3.21 (1.45)^{a,b}	3.72 (1.47)	13.37 (3.91)^{a,b}	17.38 (3.80)^{b}	35.64 (4.92)^{b}	10.61 (3.30)
Soy	29.47 (4.53)	16.95 (4.22)^{a,b}	40.93 (4.90)^{b}	21.40 (3.54)^{a,b}	32.15 (4.51)	37.83 (4.80)^{b}	4.91 (1.45)^{b}	4.28 (1.47)	10.78 (3.91)^{a}	14.56 (3.80)^{a,b}	29.77 (4.92)^{b}	9.83 (3.30)
P-value	0.177	0.02	<0.001	0.042	0.245	<0.001	0.031	0.667	0.043	0.012	<0.001	0.946

P-value indicates the main effect of carrier type on each of the ratings. Ratings labelled with different letters within each attribute (column) are different at $p \leq 0.05$, using Bonferroni corrected comparisons to compare the sauce samples.

Table A3c
Mean (±SEM) sensory ratings of xylose-derived MRP samples paired with plain, wheat and soy carriers.

Samples	Meaty Odour	Off-odour	Meaty Flavour	Salty Taste	Sweet Taste	Savoury Taste	Sour Taste	Bitter Taste	Off-flavour	Astringency	Meaty Aftertaste	Off-flavour Aftertaste
X-MRP1												
Plain	31.15 (4.81)^{a,b}	15.50 (4.98)	31.37 (5.08)^{a}	18.53 (3.03)^{a}	19.18 (4.33)^{a}	27.26 (4.21)^{a}	2.88 (1.68)	9.63 (2.17)	17.71 (3.89)	10.45 (3.65)^{a}	26.01 (5.29)	13.27 (3.72)
Wheat	21.78 (4.81)^{a}	23.83 (4.98)	41.15 (5.08)^{b}	26.25 (3.03)^{b}	24.32 (4.33)^{a,b}	40.60 (4.21)^{b}	5.17 (1.68)	5.51 (2.17)	13.10 (3.89)	14.78 (3.65)^{a,b}	31.46 (5.29)	11.33 (3.72)
Soy	33.92 (4.81)^{b}	23.16 (4.98)	41.45 (5.08)^{b}	17.36 (3.03)^{a}	32.50 (4.33)^{b}	34.56 (4.21)^{a,b}	5.20 (1.68)	5.71 (2.17)	14.91 (3.89)	18.11 (3.65)^{b}	28.41 (5.29)	12.90 (3.72)
P-value	0.014	0.16	0.014	0.005	0.005	0.004	0.143	0.073	0.36	0.013	0.333	0.254
X-MRP2												
Plain	26.91 (4.51)	33.07 (6.25)	22.44 (4.67)	16.38 (2.91)^{a}	12.72 (3.53)^{a}	16.23 (3.60)^{a}	9.43 (3.58)	39.63 (4.89)^{b}	38.24 (6.11)	19.10 (4.21)	17.71 (3.75)	34.38 (5.82)
Wheat	23.47 (4.51)	37.82 (6.25)	29.26 (4.67)	22.89 (2.91)^{b}	22.82 (3.53)^{b}	30.36 (3.60)^{b}	11.49 (3.58)	24.94 (4.89)^{a}	34.40 (6.11)	19.06 (4.21)	19.44 (3.75)	29.61 (5.82)
Soy	23.71 (4.51)	39.68 (6.25)	25.66 (4.67)	19.61 (2.91)^{a,b}	24.58 (3.53)^{b}	24.63 (3.60)^{b}	13.33 (3.58)	34.95 (4.89)^{a,b}	43.66 (6.11)	20.72 (4.21)	15.63 (3.75)	38.13 (5.82)
P-value	0.575	0.335	0.151	0.016	0.004	<0.001	0.349	0.004	0.293	0.83	0.403	0.362
X-MRP3												
Plain	28.87 (4.52)	29.72 (5.86)^{a}	21.88 (4.30)	19.17 (3.87)	11.96 (4.14)^{a}	16.85 (3.92)^{a}	10.72 (4.27)	43.88 (5.58)^{b}	47.01 (6.28)^{b}	20.38 (4.25)	15.18 (3.86)	40.94 (5.87)
Wheat	24.96 (4.52)	38.67 (5.86)^{a,b}	29.10 (4.30)	25.15 (3.87)	26.59 (4.14)^{b}	31.18 (3.92)^{b}	11.68 (4.27)	27.43 (5.58)^{a}	34.72 (6.28)^{a}	18.28 (4.25)	17.84 (3.86)	32.58 (5.87)
Soy	22.58 (4.52)	41.16 (5.86)^{b}	22.39 (4.30)	20.06 (3.87)	28.02 (4.14)^{b}	24.42 (3.92)^{a,b}	15.82 (4.27)	39.11 (5.58)^{a,b}	43.16 (6.28)^{a,b}	23.67 (4.25)	12.57 (3.86)	38.91 (5.87)
P-value	0.205	0.013	0.13	0.157	<0.001	<0.001	0.104	0.004	0.045	0.271	0.297	0.221

P-value indicates the main effect of carrier type on each of the ratings. Ratings labelled with different letters within each attribute (column) are different at $p \leq 0.05$, using Bonferroni corrected comparisons to compare the sauce samples.

Table A4
Factor loadings of the analytical variables.

Variables	F1	F2	F3	F4	F5
Meaty odour	-0.168	-0.523	0.819	0.048	0.149
Off-odour	0.896	0.351	0.063	0.118	-0.095
Meaty flavour	-0.835	0.451	0.235	-0.058	-0.163
Salty taste	0.337	0.780	0.007	-0.409	0.333
Sweet taste	-0.586	0.451	-0.006	0.647	0.175
Savoury taste	-0.723	0.669	0.043	0.103	-0.033
Sour taste	0.957	0.206	0.046	0.098	-0.056
Bitter taste	0.974	0.030	0.167	-0.006	-0.036
Off-flavour	0.980	0.100	0.041	0.076	-0.005
Astringency	0.824	0.454	0.225	0.066	-0.085
Meaty aftertaste	-0.779	0.469	0.287	-0.207	-0.164
Off-flavour aftertaste	0.979	0.129	0.097	0.068	-0.024

Data availability

Data will be made available on request.

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