



Sensory characteristics of plant-based milk alternatives: Product characterisation by consumers and drivers of liking

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ABSTRACT

Like other plant-based (PB) product categories, PB milk alternatives (PBMA) are in ascendency as part of the green consumer transition and a greater focus on personal health. However, consumption remains far below that for cow's milk, and among multiple barriers to uptake, inferior sensory properties is one problem, nutritional inadequacies another. While exceptions exist in both instances, a general need for improved products remains. The present research is situated in this nexus, and its primary aim was to contribute new consumer-centric insight regarding the sensory drivers of liking/disliking in the PBMA category. This was achieved through a central location study with adult New Zealanders ($n = 143$, not regular PBMA consumers) who tasted 18 different PBMA samples spanning a broad range of PB ingredients (soy, oat, coconut, almond, rice, cashew, peanut, macadamia, lentil, hemp, sesame) in different product types (single PB source, blends, barista style) with varying nutritional profiles. The most liked sample (6.5/9), which was made from soy, had the nutritional profile that most approximated cow's milk (3 g/100 mL protein), as well as a milky appearance and taste. Its mouthfeel was smooth, and this sensory characteristic was also paramount for barista-style PBMA being well-liked (>5.9/9) regardless of their constituent PB ingredient (oat, almond, coconut). Opportunities for product innovation within this type of PBMA was identified including for using barista-style beyond hot beverages, as these samples received positive liking scores on average. The same applied to blends as multiple-source PBMA can facilitate improved nutritional composition, and significant scope seemed to exist to identify more liked vs less liked PB ingredient combinations (e.g., almond/rice vs coconut/sesame). By identifying, through penalty/lift analysis that positive sensory drivers of PBMA liking span all sensory modalities (appearance, taste, flavour, texture and mouthfeel), it becomes easier to appreciate that products in this category are complex and challenging to optimise. A second minor research aim was focused on the modulating influence of PBMA consumption frequency on product liking and the sensory drivers of liking. The key result was a positive association between liking and higher consumption frequency, and greater appreciation of sweet, coconut, nutty and cereal/oaty characteristics of PBMA.

1. Introduction

1.1. The plant-based food transition and challenges

Evidence-based dietary recommendations are to predominantly follow a plant-based (PB) diet (Willett et al., 2019). This hinges on the fact that high consumption of animal products, especially beef and dairy, can negatively impact personal health (McClements, Newman, & McClements, 2019). There are also important environmental gains to adopting a dominantly PB diet. Abundant supplies from different supply

chains are needed in meat and dairy production (Rohmer, Gerdessen, & Claassen, 2019) and the reduction of animal-based and animal-derived food consumption is as a means to lower worldwide greenhouse gas emissions (Smedman, Lindmark-Månsson, Drewnowski, & Edman, 2010). Overall, there is much interest in shifting towards PB diets when it comes to environmentally friendly and balanced nutrition to support personal, community, and planetary health (Gibbs & Cappuccio, 2022). By-and-large, consumers agree that dietary transition can contribute to advancing sustainable development goals (Chen, Chaudhary, & Mathys, 2022; Holotová, Horská, & Nagová, 2021), but in the Western world

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only a minority consume a mostly plant-based diet, and many experience challenges in trying to make significant and enduring dietary changes (Medawar, Huhn, Villringer, & Witte, 2019; Reipurth, Hørby, Gregersen, Bonke, & Perez Cueto, 2019).

While protein-rich PB foods have been consumed for centuries as a traditional part of various cultures (Arora et al., 2023; Jeske, Zannini, & Arendt, 2018), the current interest in PB foods is largely focused on the transition away from animal-based and animal-derived foods through increased consumption of PB alternatives to meat and dairy, and the global market for such “replacement” products is expanding rapidly (Jeske et al., 2018). Identifying and commercialising PB sources of protein is paramount for this transition (Aiking, 2011), as is determining the impact on human health. The latter is an area of controversy. One point of view is favourable towards PB sources of protein and posits that such proteins can deliver equivalent nutritional quality at lower costs while fulfilling the world’s priority of reducing greenhouse gas emissions and limiting destruction of land (e.g., Dijkstra, Linnemann, & Van Boekel, 2003), and that the right combination of plant proteins can ensure the supply of sufficient amounts of essential amino acids for human health requirements (Day, 2013; Garnett, 2009). However, there is also a less favourable view which posits that PB proteins are associated with negative environmental and health issues associated with such products (Henchion, Hayes, Mullen, Fenelon, & Tiwari, 2017), and especially that PB diets are nutritionally inferior to diets including animal products (Jeske et al., 2018).

1.2. PB milk alternatives and challenges

Dairy products are a key target for the green consumer transition, and to date PB alternatives to cow’s milk have received most attention (Moss et al., 2022). A wide range of PB milk alternatives made from a variety of sources such as legumes (chickpea, soybean), cereals (oat, rice), pseudo-cereals (quinoa, teff, buckwheat), nuts (almond, cashew, coconut) or seeds (sesame, hemp) have become commercially available (Silva, Silva, & Riberio, 2022). Their sensory characteristics and nutritional properties vary greatly depending on PB raw material, processing, fortification, and the presence of other ingredients such as sweeteners and flavouring additives (Mäkinen, Wanhalinna, Zannini, & Arendt, 2016). Despite experiencing major growth worldwide and out-numbering dairy milks in the number of product launches (Insights, 2023), PBMA face important challenges.

Inferior sensory properties and reduced consumer acceptability compared to dairy milk are paramount among these (Alcorta, Porta, Tárrega, Alvarez, & Vaquero, 2021; Giacalone, Clausen, & Jaeger, 2022). For instance, legume-based milks (e.g., soy) often suffer from a beany flavour (Sethi, Tyagi & Anurang, 2016; Vanga & Raghavan, 2018; Moss et al., 2022), whereas seed-based milks (e.g., hemp) tend to possess a hay-like smell (Vaikma, Kaleda, Rosend, & Rosenvald, 2021). Nut-based milks (e.g., almond, peanut) are often characterised by chalkiness (Diarra, Nong, & Jie, 2005; Lipan et al., 2021), while cashew milks are closely associated with woody and musty (Moss et al., 2022). Other PBMA, such as coconut milk, present additional challenges such as oily and metallic (Moss et al., 2022; Vaikma et al., 2021). Oat milk is associated with varied colour tonalities (Moss et al., 2022; Vaikma et al., 2021), whereas rice milks are often penalised for their cereal flavour and astringency (Cardello, Llobell, Giacalone, Roigard, & Jaeger, 2022; Vaikma et al., 2021). In addition, sensory variation within the same PB material exist. A previous study has showed that rice-based milks with lower sugar content were associated with starchy, fermented smells, cardboard-like and raw flavours, and were less preferred (Pramudya et al., 2019), highlighting that even within the same PB ingredient category, the use of added ingredients can also impact sensory drivers of liking/disliking.

Although dairy milk often outperforms PBMA from single material or blends in consumer studies, a nuanced perspective on the category is necessary, and it is important to acknowledge the varying degrees of

acceptance for different PBMA. Notably, oat and soy milk emerge as a strong contender often surpassing other PBMA in hedonic ratings (Cardello et al., 2022; Mäkinen, Uniacke-Lowe, O’Mahony, & Arendt, 2015; Oduro, Saalia, & Adjei, 2021; Moss et al., 2022). For instance, Jeske et al. (2019) showed that oat (6.2 of 9), rice (6.0), almond (5.75), soy (5.6) and lentil-based milk (5.5) were found to be score significantly higher than hemp (4.45) for overall liking. Frühauf, Egea, Hernandez, and Takeuchi (2023) found that soybean beverage had the highest acceptability and cashew nut beverage the lowest (3.4). On the other hand, Cardello et al., 2022 reported that a oat/rice/coconut blend (6.0) and soybean milk (5.9), scored significantly higher than a low-fat dairy milk (5.4) as well as oat and rice milks (5.1), showing that in some instances PBMA can perform relatively well from a hedonic standpoint.

Ways to improve PBMA palatability include addition of salt and sugar to improve taste and flavour, while gums, stabilizers, and emulsifiers are used to improve texture and mouthfeel (Ramsing et al., 2023). However, these additions not only modify the sensorial profile, they also change the nutritional value (Mäkinen et al., 2016; Scholz-Ahrens, Ahrens, & Barth, 2020), and some PBMA are classified as ultra-processed by the US Department of Agriculture (Drewnowski, 2021). This can negatively impact PBMA uptake since consumers increasingly value “natural” and “clean-label” as motives for daily food choices (Chang & Chen, 2022). For a closely related product category - PB alternatives to meat – these consumer concerns are already documented (Varela et al., 2022).

Lack of nutritional equivalence to dairy milk is the third major issue facing PBMA. They can be a part of a healthy diet, but many healthcare professionals argue that, in general, dairy products have a higher nutritional value (Clark, Pope, & Belarmino, 2022). If PBMA contain less protein than dairy milk ($\leq 3\%$) they are unsuitable as a complete replacement (Food Standards Australia & New Zealand, 2016), but a significant proportion fail on this criterion. An Australian market audit comprising 115 commercially available PBMA found that only 23.5 % of the products met the minimum protein concentration requirement, with the majority of these originating from legumes, specifically soy (Ramsing et al., 2023). Additionally, PBMA contain fewer mineral elements, and for this reason, they are often fortified to provide the maximum amount of nutrients and better match the nutritional content of dairy milk (Ramsing et al., 2023).

1.3. Research aims and empirical strategy

The present research primarily sought to contribute new knowledge regarding consumer acceptability of PBMA and its sensory drivers (Aim 1). This is important knowledge to guide product innovation and overcome the barrier to uptake that inferior sensory properties in this class of products constitute. The scientific advancement was primarily achieved by including a wider range of PBMA than in previous studies (Cardello et al., 2022; Moss et al., 2022; Vaikma et al., 2021) in order to span the sensory PBMA space (appearance, taste/flavour, and texture/mouthfeel) more widely, and provide more nuanced insights regarding the sensory drivers of liking than currently exists. The expectation was that it would also confirm previously established sensory drivers, and such “replication” is important because it adds robustness to research findings and gives product developers more certainty regarding which formulation efforts to target.

Three strategies were used to widen the sensory product space were inclusion of PBMA from diverse plant sources, PBMA blends and barista PBMA. The inclusion of more/novel PB sources widens the sensory space because their flavour profiles often reflect the raw base material (Vaikma et al., 2021). Regarding PBMA blends, past research indicates that this can be an effective strategy to increase consumer liking (e.g., Cardello et al., 2022; Oduro et al., 2021; Chung et al., 2022). Barista PBMA were included because they contribute texture and mouthfeel properties that are not common in “regular” PBMA. These are achieved by adding texturing agents to facilitate the frothing process that is

critical for their use in hot coffee products like latte and cappuccino (Chung et al., 2022; Zakidou, Varka, & Paraskevopoulou, 2022). Indirectly, the effort to widely span the sensory PBMA space also influenced the nutritional diversity of the samples. As such, it was possible to be mindful of this PBMA challenge, without it becoming an explicit research aim.

A second and smaller aspect of the present research (Aim 2) was to compare groups of participants with different PBMA exposure/familiarity level for liking and sensory drivers of liking. A hypothesis was that consumers with greater PBMA familiarity would like the samples more, on average, than those with less category familiarity. Support for this hypothesis rested on previous studies which have showed that liking is significantly correlated with degree of familiarity, and increased familiarity correlated with increased liking, overall (Hwang & Hong, 2013). This effect has been observed in the context of PB foods, such as Niimi et al. (2022), and in various other product categories, as reported by Choi and Seo (2023), Tan, Verbaan, and Stieger (2017), and Nguyen and Wismer (2020).

2. Materials and methods

2.1. Participants

Participants (n = 143) were recruited through a consumer database managed by the Food Experience and Sensory Testing (Feast) Laboratory at Massey University (Palmerston North, New Zealand). To be eligible, participants had to satisfy the criteria: willing to taste plant-based milk alternatives, willing to attend two one-hour research

sessions one week apart, aged between 18 and 65 years old, not allergic or intolerant to ingredients listed in the participant information sheet (see [Supplementary Material, Table S1](#)), not pregnant or lactating. Age and gender quotas were not implemented, and the participants were predominantly female (76 %) with a mean age of 38.8 ± 12.4 years.

2.2. Samples

2.2.1. Samples used in the study

Sample selection was directly informed by the research aim which mandated that a large and sensorially diverse set of samples be included in the study. The final set of samples were selected through a stepwise process that began with consideration of 46 PBMA commercially available in New Zealand and one sample (S18, lentil) that was manufactured in a food-grade certified pilot plant at Massey University. In two steps, these 47 candidates were reduced to 28 by eliminating samples with similar sensory profiles (e.g., different brands of soy milk) and then further to 18 samples which was deemed the maximum number of samples that consumers could evaluate in two one-hour research sessions. The selection was done by an in-house panel (n = 5) from the Feast team which comprised students and staff members with relevant experience.

The 18 selected samples are shown in [Fig. 1](#) and listed in [Table 1](#). They were made from different raw materials (e.g., soy, coconut, macadamia, rice) and some were blends (e.g., almond/coconut, coconut/sesame). Increased sample diversity with respect to appearance, taste, flavour, texture, and mouthfeel characteristics was achieved by inclusion of samples from the same raw materials that varied in other ways (e.

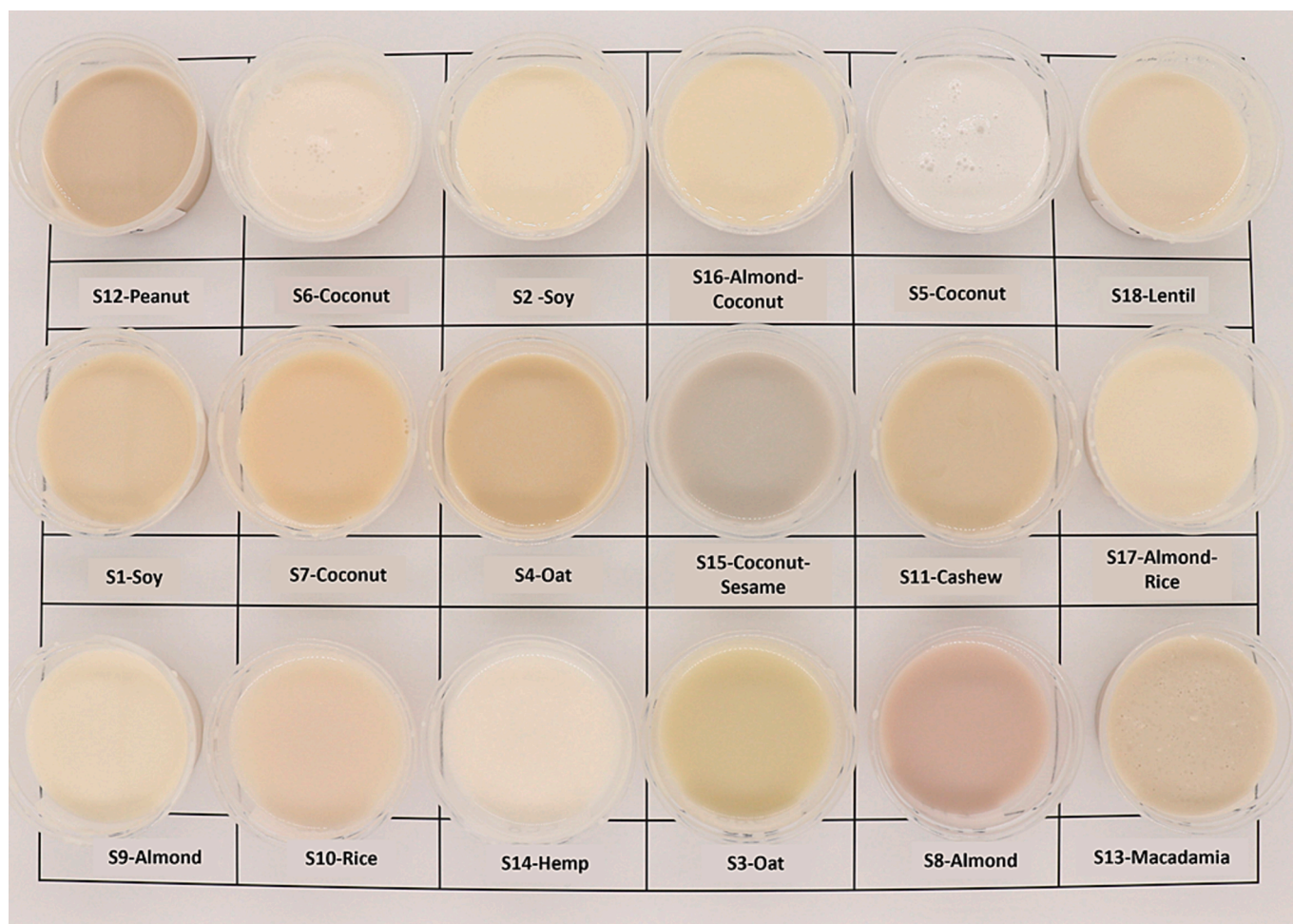


Fig. 1. Samples used in the study, as served to consumers. Refer to [Table 1](#) and [Table S2](#) in [Supplementary Materials](#) for more sample details.

Table 1

Samples (S1 to S18) of plant-based milk alternatives (PBMA) used in the study with nutritional information and product information from packaging front label. Sample names indicate the primary plant-based ingredients. For PBMA blends, the major raw material is listed first. [Supplementary Material](#) has further sample details in [Table S2](#).

ID	Main PB ingredients	Specific	Energy (kJ)	Protein (g/100 mL)	Fat (g/100 mL)	Carbohydrate (g/100 mL)	Sugar (g/100 mL)	Sodium (mg/g)	Product information/claim from packaging (front label, if applicable)
S1	Soy	Whole soybeans (min. 14 %)	162	3.0	1.8	2.5	1.6	80.0	Low sugar, milky taste, <2 % fat, 25 % less carbs, 1/3 of daily calcium
S2	Soy	Soy protein (3.5 %)	273	3.2	3.5	5.1	2.0	40.0	Regular, half your daily calcium, 8 g of protein
S3	Oat	Oats (12 %)	182	0.6	1.4	6.7	4.0	48.0	Original, no added sugar
S4	Oat	Oats (12 %)	229	0.6	2.7	6.6	4.0	40.0	Barista grade, no added sugar
S5	Coconut	Coconut extract (19 %)	255	<1.0	6.0	0.7	<1.0	10.0	Light, 60 % less fat
S6	Coconut	Organic coconut milk (20 %)	242	0.5	2.7	7.8	3.8	61.0	Unsweetened
S7	Coconut	Coconut milk (3.5 %)	135	1.5	1.4	3.3	3.3	40.0	Barista, with soy, plant-based shiny microfoam
S8	Almond	Organic whole activated almonds (7 %)	123	0.6	1.7	2.9	1.4	45.0	Unsweetened, with rice, whole 7 % activated almonds
S9	Almond	Ground almonds (3 %)	164	0.8	2.6	2.8	1.6	39.0	Barista edition, low in sugars
S10	Rice	Whole brown rice (min. 13 %)	185	0.2	1.2	8.0	5.8	65.0	Unsweetened
S11	Cashew	Ground cashew nuts (3 %)	73	0.4	1.4	0.8	0.1	40.0	Unsweetened, high in calcium, vitamins B12 + B2
S12	Peanut	Peanuts (8 %)	216	2.0	4.0	1.8	0.8	1.0	Unsweetened
S13	Macadamia	Macadamias (2.5 %)	125	0.5	1.9	2.6	1.7	40.0	For coffee, designed to texture and stretch
S14	Hemp	Hemp seed base (4 %)	108	<1.0	2.7	1.0	<1.0	20.0	Hemp seed, light & tasty, sugar-free, omega 3
S15	Coconut + Sesame	Coconut water (50 %), coconut extract (20 %), black sesame (0.3 %)	109	0.2	1.5	3.0	2.7	34.0	None
S16	Almond + Coconut	Ground almonds (2.5 %), Coconut cream (1 %)	72	0.5	1.5	0.3	0.2	31.0	Unsweetened, high in calcium
S17	Almond + Rice*	Ground almonds (1.8 %) and Whole brown rice (5.2 %)	172	0.6	2.0	4.9	4.4	49.4	N/A
S18	Lentil	Black gram lentils (10 %)	191	1.6	2.5	4.2	3.3	25.0	N/A

Table notes: *) 60:40 ratio by weight of samples S9 and S10. Nutritional values calculated as pro-rata of the constituent samples.

g., unsweetened, low fat, barista-style). Although barista-style PBMA are specially formulated for use in coffee drinks their inclusion in the study was warranted because of their different texture and mouthfeel properties (Zakidou et al., 2022). All samples were unflavoured (in the sense of not containing added flavours such as strawberry, vanilla, etc.) to avoid differing consumer flavour preferences influencing the results in unintended ways. Please refer to [Supplementary Materials](#) for further sample details (Table S2).

2.2.2. Sample serving

Samples were served chilled (~4 °C) in 60-mL clear and odour-free plastic cups that were covered with a lid and labelled with 3-digit random codes. Portion serving size was ~35 g, ensuring that participants could re-taste the sample at least 3 times throughout session completion. Participants were instructed to gently invert the cup once before tasting, remove the lid and drink directly from the sample cup for the assessment. Sample preparation took place the day before use (18–24 h), where they were poured, covered, and stored in a refrigerator (~3 °C) until the beginning of each session.

2.3. Empirical procedures

2.3.1. Response variables

Two types of responses were obtained for each sample. The first was overall liking which was rated on a fully labelled 9-point category scale from “dislike extremely” (1) to “like extremely” (9) (Peryam & Pilgrim, 1957). Sensory product characterisation was next and performed using three CATA (check-all-that-apply) questions which were modality specific: 1) appearance (10 terms), 2) taste and flavour (18 terms) and 3) texture and mouthfeel (9 terms) (all terms are listed in full in [Section 3](#) and term explanation is provided in [Table S3](#)). Using extant literature as

inspiration (Cardello et al., 2022; Pointke et al., 2022; Vaikma et al., 2021), consumer-friendly terms were selected following pilot work for their ability to describe and discriminate samples.

PBMA consumption frequency, perceived situational appropriateness and past product use was measured with a short questionnaire at the end of sample evaluation.

2.3.2. Data collection

Evaluation of the 18 samples was evenly divided across the two research sessions (9 per session, evaluated by the same 143 participants) and presentation was monadic according to an experimental design based on a Williams Latin Square. There was a forced 2 min-break between each sample, and to minimize carryover effects participants were instructed to cleanse their palate during this time, in a consistent manner (bite of water cracker (Fine Food Holdings Pty Ltd, Victoria, Australia) followed by filtered water, or only filtered water).

Within participants, the allocation of the 18 samples across the two days of testing ensured that different PB ingredients were represented each day according to a balanced design. Within CATA questions, the presentation order of terms was balanced both across samples and participants according to [Ares et al. \(2015\)](#).

At the first research session, prior to starting sample evaluation, participants were briefed with the study procedures. At this time, they also received a familiarisation sample (Sample 3) to introduce the PBMA category (no formal sample evaluation).

The study was conducted as a central location test at the Feast Laboratory at Massey University where participants attended in groups of 15 people. Samples were evaluated under white lighting at room temperature (21 ± 1 °C). Compusense20 (Compusense Inc., Guelph, Ontario, Canada, version 23.0.31) was used for data collection.

2.4. Data analysis

Generalised linear models (GLMs) were estimated with liking scores as the dependent variable and specifying sample as a fixed effect and consumer as a random effect. A second GLM introduced included PB milk consumption frequency (two groups) as a second fixed factor and in this model the interaction between two fixed effects were also estimated. The group of participants with “higher” consumption frequency was defined by those 77 people (54 %) who stated that they consumed PBMA weekly or more often. The remaining participants ($n = 66$, 46 %) defined the “lower” consumption frequency group (fortnightly consumption or less including never).

On the aggregate sample, clustering on liking ratings was performed using a hierarchical agglomerative method (Euclidean distance, Ward’s method).

In accordance with Meyners, Castura, and Carr (2013), Cochran’s Q test was performed for each of the CATA terms and the Sheskin procedure was used for post-hoc tests. Correspondence Analysis (CA) (chi-square distances) was performed separately on terms within a CATA question (appearance; taste and flavour; texture and mouthfeel) and across all terms. The contingency tables were formed by crossing samples (rows) and CATA terms (columns). The null hypothesis of independence between rows and columns was always rejected following a chi-square test ($p < 0.0001$). Four-dimensional solutions, which accounted for >70 % of variance in the data were retained.

Penalty-lift analysis was performed for each CATA term to determine the mean impact of term presence on liking (Meyners et al., 2013). A threshold of 10 % citation frequency was used to test the significance of the mean impact. When performing penalty-lift analysis in the two groups of consumers with different PBMA consumption frequency, a threshold of 20 % citation frequency was used to test the significance of the mean impact. This was to compensate for smaller sample sizes in each consumer group.

All analyses were performed in XLSTAT v2023.1.4 (Lumivero, 2023) using a 5 % level of significance for inference tests.

3. Results

3.1. Participant characteristics relating to PBMA

In Table 2, participant consumption and use of PBMA is provided. Regarding stated consumption frequency, participants were diverse with regular users (2–3 times weekly or more often) comprising 41 % of the sample. People with more sporadic use (weekly to monthly) made up 30 % of the sample, and a similar proportion (29 %) were infrequent users or not product users at all. The latter (8 %) were retained, as product use was not an eligibility criterion. Consumption in coffee was the most common use situation for PBMA (56 %) (and much higher than use in tea (19 %)), followed by use in smoothies and shakes (42 %). Uses commonly occurring at home – in cooking, with cereal, drink on its own, in porridge, in desserts and baking – grouped with citation frequencies from 36 % to 26 %. Four types of PBMA were commonly and similarly used – almond (74 %), soy (73 %), coconut (72 %) and oat (70 %). PBMA from rice and cashew had been used much less frequently, respectively 34 % and 13 % of consumers. Blends and options from hemp and peanut had been very infrequently used by the participants (5 % or less). Lentil-based PBMA was excluded from this survey as it is not commercially available.

3.2. PBMA liking

3.2.1. Aggregate level

Mean ratings (1 = “dislike extremely” to 9 = “like extremely”) for the 18 PBMA samples were significantly different ($p < 0.0001$) and spanned between 6.5 and 2.6 for, a sample from soybeans with some added sugar (S1) and a sample from hemp seed with no added sugar (S14),

Table 2

Information about stated frequency of consumption, use occasions and past product use for plant-based milk alternatives (PBMA) among the 143 consumers in the study.

Frequency of consumption	Percentage (%)
Daily	15
2–3 times a week	26
Once a week	13
Once a fortnight	8
Once a month	9
Less than once a month	21
Never	8
Use occasions[#]	
In coffee	56
In a smoothie or shake	42
As a cooking ingredient	36
On cereal	35
I drink on its own	35
In a porridge e.g. oat porridge	31
In a dessert	27
For baking	26
In tea	19
In hot chocolate	1
Past product use[#]	
Almond milk	74
Soy milk	73
Coconut milk	72
Oat milk	70
Rice milk	34
Cashew milk	13
Hemp milk	3
Peanut milk	1
Blended products	5

Notes. [#]) Participants could select multiple responses options.

respectively (Table 3). Of the 18 samples, four had mean ratings between 6 and 7 (respectively, “like slightly” and “like moderately”) and were from different PB raw ingredients – soy (S1), oat (S4), coconut (S7) and a blend of almond and rice (S17). The extent of dislike for the hemp seed sample (S14) was illustrated by only 6 participants (4.1 %) rating this sample as 6 or above (i.e., “like slightly” or more). With mean scores between 5.9 and 6.4, the three barista-style PBMA – S4 (oat), S7 (coconut) and S9 (almond) – were more liked than disliked on average.

Table 3

Mean overall liking for plant-based milk alternative (PBMA) samples ($n = 18$) included in the study (sorted from highest to lowest). Participants ($n = 143$) were asked to rate how much they liked each sample on a fully labelled 9-point category scale from ‘dislike extremely’ (1) to ‘like extremely’ (9). Samples which share a letter were not significantly different according to Tukey’s HSD (5 % level).

Sample	Main ingredient/s	Average	Std. Dev.
S1	Soy	6.5 ^a	1.5
S4	Oat	6.4 ^a	1.7
S7	Coconut	6.3 ^{ab}	1.8
S17	Almond + Rice	6.2 ^{ab}	1.5
S3	Oat	5.9 ^{abc}	1.8
S9	Almond	5.9 ^{abc}	1.6
S10	Rice	5.8 ^{abc}	1.8
S2	Soy	5.7 ^{bc}	2.0
S5	Coconut	5.5 ^c	1.8
S13	Macadamia	4.8 ^d	1.7
S15	Coconut + Sesame	4.4 ^{de}	2.3
S16	Almond + Coconut	4.2 ^{def}	2.0
S6	Coconut	4.1 ^{efg}	1.6
S8	Almond	4.1 ^{efg}	2.0
S18	Lentil	4.0 ^{efg}	2.0
S11	Cashew	3.6 ^{fg}	1.7
S12	Peanut	3.5 ^g	1.8
S14	Hemp	2.6 ^h	1.4

Mean liking ratings differed significantly between PBMA made from the same raw material. For example, the mean ratings for the two almond-based samples were close to “dislike slightly” ($M_{S8} = 4.1$; S8) and “like slightly” ($M_{S9} = 5.9$; S9), respectively, and the difference in liking tentatively reflected the impact of different formulations. The lesser liked S8 was an unsweetened sample, while S9 (barista-style) was low in sugars. PBMA made with soy presented another example with significant differences in mean scores for S1 and S2 (6.5 vs 5.7). There were also significant differences between the three coconut PBMA ($M_{S7} = 6.3$, $M_{S5} = 5.5$ and $M_{S6} = 4.1$) (Table 3).

For completeness, an exploratory analysis was performed to establish if average sample liking was related to nutrition content (data not shown). Correlation analysis failed to establish significance at the 5 % level for energy, protein, fat, and carbohydrate. However, for sugar and sodium content, positive associations were established (both $r = 0.51$, $p = 0.03$). For sugar, higher content tended to drive higher scores. In the case of sodium, the association seemed to vary by low content in the more disliked samples (Tables 1 and 3).

3.2.2. Consumer segmentation

Measures of dispersion around the mean ratings of liking (Table 3) revealed that heterogeneity was most pronounced for S15 (coconut-sesame blend) (std. dev. = 2.3) and least pronounced for S14 (hemp seed) (std. dev. = 1.4). The latter was the least liked sample, on average. An exploratory cluster analysis on mean-centred scores identified two approximately evenly sized clusters ($n = 64$ and $n = 79$) that had relatively similar profiles but diverged majorly on S15 (coconut-sesame) which participants in one cluster liked significantly more than participants in the other cluster (mean difference in average liking scores was ~2.5 scale points) (Supplementary Material has further details, Table S4). On this basis, further exploration of liking-based consumer segmentation was not pursued.

However, a comparison of liking scores among groups of participants who consumed PBMA more vs less frequently was performed. Recall that two approximately evenly sized clusters were formed by grouping those who stated that they consumed PBMA at least weekly and those who consumed less frequently or never. Across all samples, the “higher” consumption frequency group gave significantly higher ratings of liking than did those in the “lower” consumption frequency group, although the difference was only 0.3 scale points ($M(SD)^{\text{higher}} = 5.1(2.2)$ and $M(SD)^{\text{lower}} = 4.8(2.0)$, $p < 0.001$). When considering individual samples, a GLM identified significant main effects, but the interaction was non-significant ($p = 0.27$) (data not shown). Thus, there were no major differences between the two consumption frequency groups in their ratings of like/dislike for different samples, but a visual comparison of ratings revealed that the overall group difference primarily stemmed from the more acceptable samples receiving higher ratings in the “higher” consumption frequency group (7 of 18 samples had average scores between 6.1 and 6.8). Differences between groups decreased as samples became more disliked (Supplementary Material has full details, Fig. S3).

3.3. Sensory product characterisation

3.3.1. Appearance

The samples were significantly discriminated on all appearance terms according to Cochran’s Q test (Table 4). Fig. 2 presents biplots following CA, with Fig. 2a showing the space spanned by the first and second dimensions, and Fig. 2b showing the space spanned by the third and fourth dimensions. Collectively, the first four dimensions accounted for 82 % of the inertia in the data. The greatest perceived differences between the PBMA samples related to colour with the first dimension separating samples with predominantly white colour (notably hemp seed (S14) and two coconut samples (S5 and S6)) from one of the samples made from almond (S8) with a particular light pink colour. Samples with darker colours in shades of brown, grey and green were positioned on

Table 4

Results from Cochran’s Q test for sample differences showing p-values (Column 2). Results from Penalty/Lift analysis showing average term citation frequency (%) across all plant-based milk alternative (PBMA) samples in the study (Column 3) and mean impact on liking^s when CATA term is selected (latter when mean impact was different from zero at the 5 % level of significance) (Column 4).

Response type and term	P-value from Cochran’s Q test	Average citation frequency (%)	Mean impact on liking ^s
Appearance			
Light green colour	<0.0001	2.1	0.7 ^{n/a}
Cream colour	<0.0001	41.4	0.6 ***
Foam/Bubbles	<0.0001	12.5	0.4 ***
Light brown colour	<0.0001	24.8	0.1 ns
Thick/Viscous	<0.0001	21.3	0.0 ns
Oily	<0.0001	16.8	-0.5 ***
Light pink colour	<0.0001	9.7	-0.4 ^{n/a}
Light grey colour	<0.0001	13.4	-0.4 ***
White colour	<0.0001	26.9	-0.3 ***
Thin/Runny	<0.0001	43.2	-0.1 ns
Taste			
Sweet	<0.0001	40.1	1.5 ***
Bitter	<0.0001	8.9	-1.6 ^{n/a}
Salty	<0.0001	7.4	0.0 ^{n/a}
Umami/Savoury	0.002	7.1	0.0 ^{n/a}
Sour	<0.0001	3.5	-1.4 ^{n/a}
Flavour			
Milky	<0.0001	22.8	1.5 ***
Cereal/Oaty	<0.0001	31.5	0.8 ***
Tropical Fruit	<0.0001	5.1	0.7 ^{n/a}
Coconut	<0.0001	21.4	0.5 ***
Nutty	<0.0001	24.2	0.4 ***
Roasted nuts	<0.0001	10.5	0.4 **
Rice	<0.0001	20.4	0.0 ns
Fish-like	<0.0001	3.1	-2.1 ^{n/a}
Cardboard-like	<0.0001	15.0	-2.0 ***
Bland/Weak flavour	<0.0001	21.7	-1.4 ***
Earthy	<0.0001	18.8	-1.2 ***
Beany/Legume	<0.0001	21.2	-0.3 **
Peanut	<0.0001	8.7	-0.2 ^{n/a}
Texture and mouthfeel			
Smooth	<0.0001	53.0	1.4 ***
Mouthcoating	<0.0001	33.1	0.2 *
Powdery/Chalky	<0.0001	20.1	-0.9 ***
Gritty	<0.0001	5.7	-0.7 ^{n/a}
Mouth drying	<0.0001	16.6	-0.7 ***
Slimy	<0.0001	9.4	-0.6 ^{n/a}
Oily	<0.0001	16.0	-0.4 ***
Thin/Runny	<0.0001	52.5	-0.3 ***
Thick/Viscous	<0.0001	17.5	-0.1 ns

Notes.

^s) 9-point liking response scale: 1 = dislike extremely, 9 = like extremely.

^{*)} Significance level indicated by *** if $p < 0.001$, ** if $p < 0.01$ and * if $p < 0.05$. Else ns.

^{s)} Significance testing not performed if average citation frequency < 10 %. Indicated as ‘n/a’.

the negative pole of Dimension 2. The separation of samples with these darker colours occurred on subsequent dimensions, with variation in light grey being captured by Dimension 3 and variation in light green being captured by Dimension 4. For both dimensions, a single sample was the main source of difference, respectively S15 (coconut-sesame blend) for Dimension 3 and S3 (oat) for Dimension 4. In the case of S15, the light grey colour was likely associated with the black sesame seeds that were an ingredient in this sample.

Further insights regarding sample differences relating to appearance was gained by inspection of the frequency table and post-hoc results (Supplementary Material, Table S5). This revealed that the lentil-based

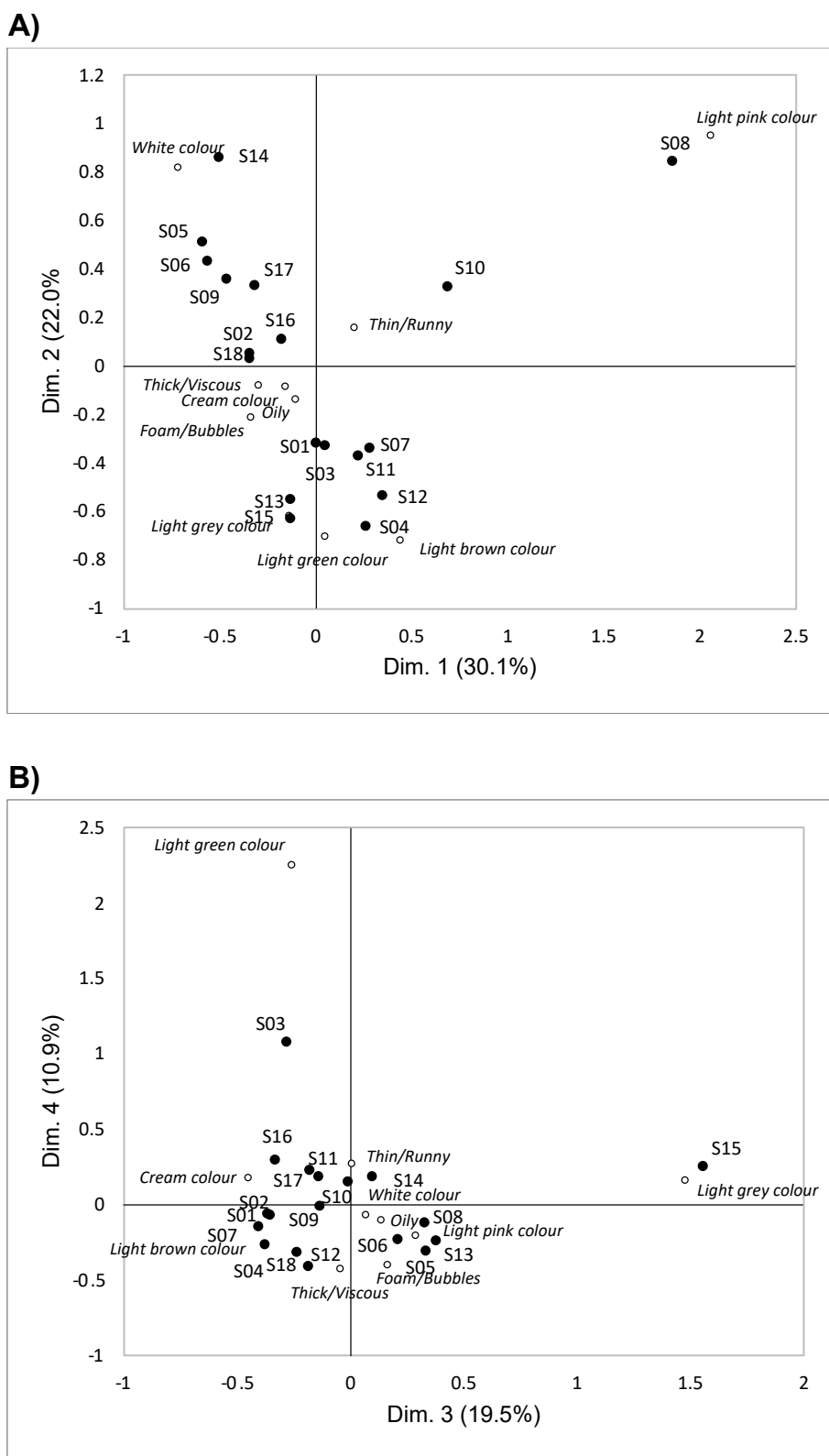


Fig. 2. Biplots from Correspondence Analysis of appearance terms. **2A)** Space spanned by Dimensions 1 and 2; **2B)** Space spanned by Dimensions 3 and 4. Samples (S01 to S18) are shown as black filled circles, while appearance terms are shown as unfilled circles and text in italic font. Refer to [Table S5](#) in [Supplementary Materials](#) for more details on frequency citation for appearance terms across samples.

PBMA (S18) was perceived as much more *thick/viscous* than the other samples, followed by coconut (S5) and macadamia nut (S13) PBMA. The samples that looked most *thin/runny* were S14 (hemp seed), S10 (rice) and S8 (almond). While S8 was also most *oily*, it was interesting

that another sample also made from almond (S17, almond-rice blend) was least *oily*. The attribute *foam/bubbles* was never used to describe S14 (hemp seed) or S10 (rice), while it most frequently applied to S13 (macadamia nut).

3.3.2. Taste and flavour

Table 4 showed that the samples were also significantly discriminated on all taste and flavour terms according to Cochran's Q test. The first two dimensions from the CA accounted for 70 % of the inertia in the data, and the corresponding bi-plot is shown in Fig. 3a. Dimension 1 spanned between *coconut*, *tropical fruit* and *sweet* on the positive pole and *fish-like*, *bland/weak* and *cardboard-like* on the negative pole. Thus, it was a continuum that captured positive vs negative flavour characteristics. The PBMA made with coconut had the highest citation frequency for this flavour attribute, in particular S5 which was a tinned product. The other two coconut samples (S6 and S7) and the blend with sesame (S15) were also distinctively coconut-flavoured. This was, however, not the case in the almond-coconut blend (S16), where citation frequency for *coconut flavour* was only 19 % (compared to 92 % in S5). Citation frequency for *tropical fruit* was highest in the coconut barista sample (S7) and the coconut blend samples (S15 and S16), and significantly less applicable to S5. Sample S5 was also less *sweet* than all other samples containing coconut (single ingredient or blend). Sample S14 (hemp seed) was never perceived as *sweet* (0 % citation frequency). On the opposite pole of Dimension 1, *fish-like* was most applicable to S14 (hemp seed), and the only sample to which this attribute did not apply was S1 (soy), the most liked sample overall. Sample S14 was also the sample that was most frequently perceived as *bland/weak* and *cardboard-like* (Table S6 in Supplementary material).

The flavour attributes *cereal/oaty* and *milky* loaded on the negative pole of the second dimension (Fig. 3a), and the former was most applicable to the two samples made from oats (S3 and S4), but also relevant for S1 (soy-based) and S10 (rice-based) samples. The four samples (S1, S2, S9 and S17) that *milky* applied to most (citation frequencies between 50 % and 41 %, Table S6) were made from different raw ingredients (soy, rice, almond). Dimensions 3 and 4 separated the two least liked samples from the other PBMA included in the study (Fig. 3b). *Peanut flavour* defined Dimension 3 and was much higher in S12 (52 %) than any other sample (2 % to 13 %). For Dimension 4, the defining sample-attribute combination was S14 (hemp seed) and *fish-like*.

Flavours specific to PB ingredients – *rice* and *beany/legume* – were generally highest for the corresponding samples. Thus, *rice flavour* was highest in the rice-based PBMA (S10) and *beany/legume* was high in the lentil-based PBMA (S18). However, this attribute was not more frequently used to characterise samples containing soy (S1, S2) than to characterise many other samples. *Earthy flavour* was not found to be particularly associated with one PB ingredient (Table S6) but seemed to more generally reflect perceived 'off flavour' by the participants (–1.2 drop in liking, Table 4). A taste characteristic with notable differences between samples, was *salty*, which was highest for S2 (soy) at 18 %, compared to 10 % or less for other samples (Table S6). *Umami/savoury* was highest for the lentil-based sample (S18) and lowest for the PBMA from macadamia nut (S13), at respectively, 13 % and 2 %. Citation frequency for *sour* was less than 10 % for all samples and ranged between 1 % (S7) and 24 % (S18) for *bitter* (Table S5).

3.3.3. Mouthfeel

As for the other sensory modalities, samples were significantly discriminated on all mouthfeel terms according to Cochran's Q tests (Table 4). A two-dimensional CA solution accounted for 82 % of the inertia in the data, and the corresponding biplot is shown in Fig. 4a. Dimension 1 captured variation in consistency and was spanned between *thick/viscous* and *thin/runny*. *Thick/viscous* was highly applicable to the lentil-based PBMA (S18, 83 % citation frequency), and the sample this descriptor was second most applicable for only had a citation frequency of 36 % (S13, macadamia nut). *Thin/runny* was highly applicable to some samples, where the least *thick/viscous* and most *thin/runny* was S14 (hemp seed), and again there was a large difference between S14 and the sample that was second most *thin/runny* (S8, almond) (82 % vs 54 % citation frequency) (Table S7).

The second dimension captured sample differences on a continuum from *smooth* (negative pole) to *gritty* and *powdery/chalky* (positive pole). One sample stood out as much more *gritty* than the others – S6 (coconut) (45 % citation frequency) – and similarly to what was observed on Dimension 1 there was a big difference to the second most *gritty* sample (S12, peanut) (11 % citation frequency). *Smooth* was highly and similarly applicable to three samples made from different ingredients – S4 (oat), S7 (coconut) and S17 (almond-rice blend) (73 % to 78 % citation frequency), and, conversely, it was infrequently used to describe S6 (coconut) (11 % citation frequency). The barista PBMA samples – S4, S7 and S9 – all had high citation frequencies for *smooth* (Table S7).

Dimensions 3 and 4 accounted for less inertia in the data (14 %, Fig. 4b) but added insight regarding sample differences by differentiating *gritty* and *powdery/chalky* (Dimension 3) and identifying variation linked to *slimy* (Dimension 4). Whilst S12 (peanut) was much less *gritty* than S6 (coconut) (11 % vs 45 % citation frequency), both samples were perceived as *powdery/chalky* (respectively, 62 % and 52 % citation frequency). Thus, S12 was primarily *powdery/chalky* while both of the descriptors applied to S6 and captured an absence of *smooth mouthfeel*. *Slimy mouthfeel* applied most to S18 (lentil) (36 % citation frequency) and this descriptor was second most applicable to S13 (macadamia nut) (20 % citation frequency) (Table S7).

The two remaining descriptors – *mouthcoating* and *mouth drying* – applied to the samples in accordance with expectations. *Thick/viscous* samples were also perceived as *mouthcoating*. For *mouth drying*, highest and lowest applicability was seen for S11 (cashew nut) and S17 (almond-rice blend) (respectively, 32 % and 10 % citation frequency, Table S7).

3.4. Penalty/lift analysis

3.4.1. Aggregate level

Penalty/lift analysis provided insight about the sensory drivers of liking for the studied set of 18 PBMA. The results are given in Table 4, where the last two columns show the average citation frequency and mean impact for each of the sensory terms. The terms are grouped by sensory modality – appearance, taste/flavour and texture/mouthfeel – and within each modality they are sorted from most positive to most negative mean impact. Where the mean impact was significantly different from zero, the p-value is indicated when lower than 0.05, 0.01 or 0.001, except for those terms where average citation frequency is less than 10 %.

A first insight from Table 4 was that appearance tended to impact mean liking less than other sensory modalities. The range in mean impact values ranged between 0.7 and –0.5 scale points compared to a range between 1.5 and –2.1 for taste/flavour and a range between 1.4 and –0.9 for mouthfeel/texture.

PBMA colour impacted sample liking differently, with a lift associated with *cream colour*. Conversely, a penalty on liking was associated with *light pink colour*, *light grey colour* and *white colour*. For *light brown colour*, the impact on mean liking was not significantly different from zero. Significance testing was not performed for *light green colour*, due to low citation (2.1 %). Regarding other aspects of PBMA appearance, visible foams and bubbles were a positive driver of liking while oiliness was a negative driver (respectively, 0.4 and –0.5 scale points).

Regarding taste, sensory drivers of liking fitted expectations. *Sweet* contributed positively to sample liking (1.5), while *sour* and *bitter* exerted a negative impact (respectively, –1.6 and –1.4). Due to low average citation frequency, significance tests were not performed for *sour* and *bitter*, so the results must be viewed with caution. The same applied to *salty* and *umami/savoury* which when perceived did not impact mean liking (Table 4).

For flavour, the positive drivers of liking were *milky* (1.5), *cereal/oaty* (0.8), *coconut* (0.5), *nutty* (0.4) and *roasted nuts* (0.4). Significance testing was not performed for *tropical flavour*, as the average citation frequency was too low. Two off-flavours impacted mean liking most

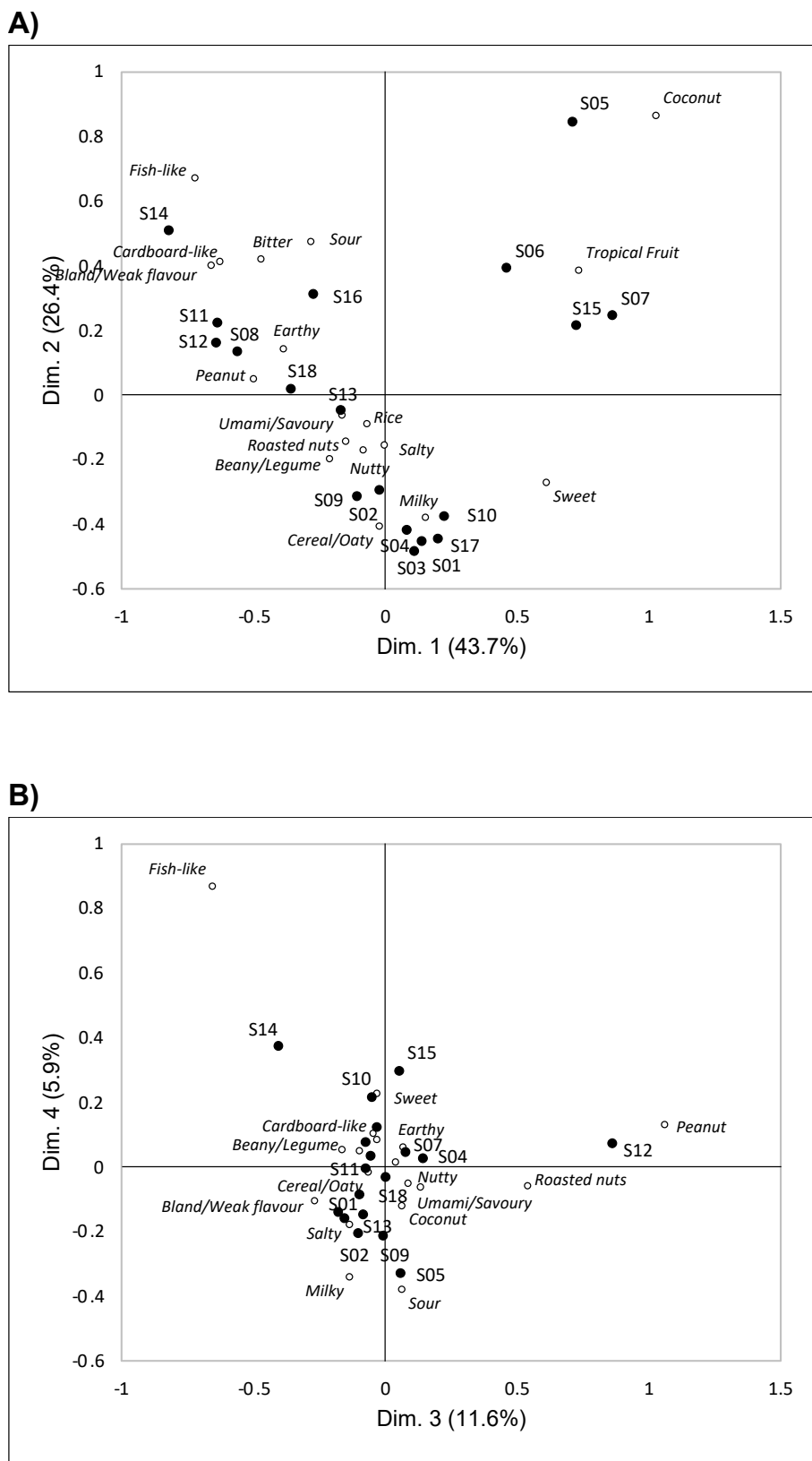
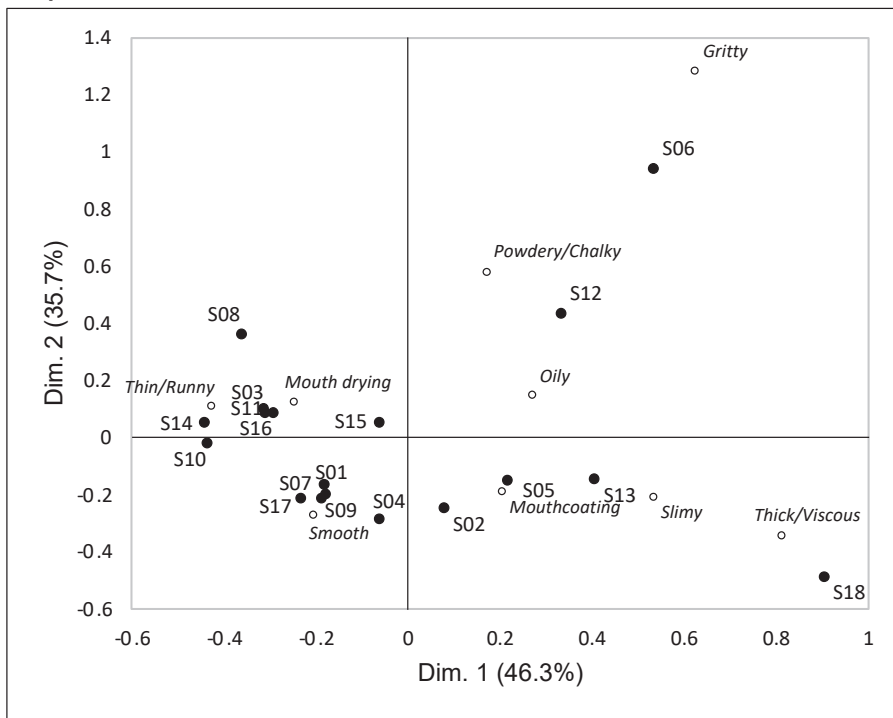


Fig. 3. Biplot from Correspondence analysis of taste and Space spanned by Dimensions 3 and 4 (close to the origin only some samples and terms are labelled). Samples (S01 to S18) are shown as black filled circles, while taste and flavour terms are shown as unfilled circles and text in italic font. Refer to [Table S6 in Supplementary Materials](#) for more details on frequency citation for taste and flavour terms across samples.

4A)



4B)

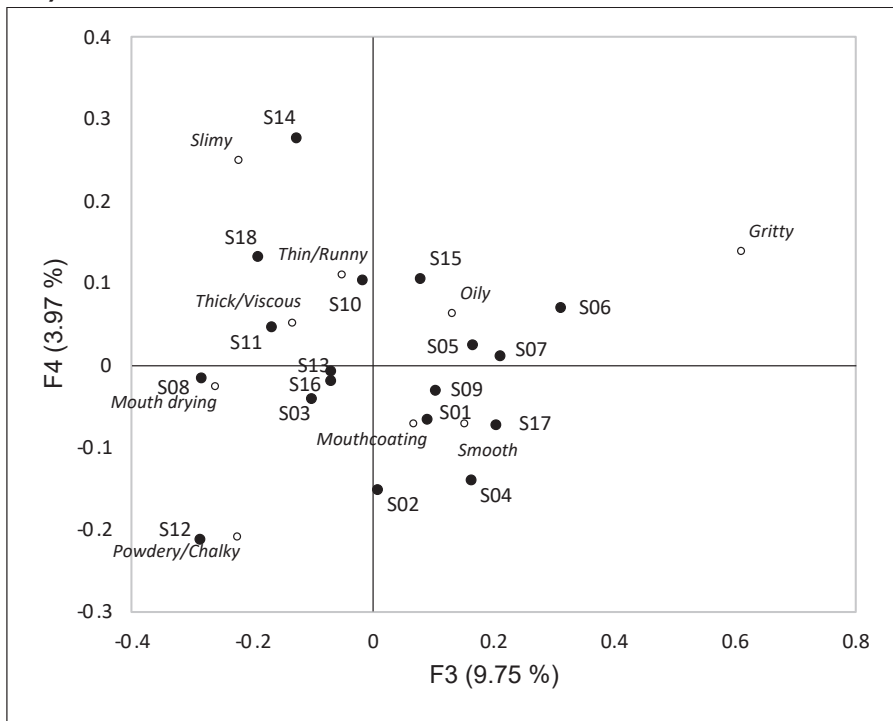


Fig. 4. Biplot from Correspondence analysis of mouthfeel and texture terms. 4A) Space spanned by Dimensions 1 and 2; 4B) Space spanned by Dimensions 3 and 4. Samples (S01 to S18) are shown as black filled circles, while mouthfeel and texture terms are shown as unfilled circles and text in italic font. Refer to [Table S7](#) in [Supplementary Materials](#) for more details on frequency citation for mouthfeel and texture terms across samples.

negatively: *fish-like* (−2.1) and *cardboard-like* (−2.0). Only one sample (S14, hemp seed) had a notably high citation frequency for *fish-like* (23.1 %), which was significantly higher than in all other samples. Cardboard-like was also most intense in S14, but rather than being specifically associated with one sample, this attribute appeared to be correlated with degree of overall sample liking. Other flavours that exerted a negative mean impact on sample liking were *earthy* (−1.2), *beany/legume* (−0.3) and *peanut* (−0.2, no significance test). Low flavour intensity (*bland/weak flavour*) also penalised liking (−1.4) (Table 4).

Among the mouthfeel characteristics, a hedonic lift of 1.4 scale points was found for *smooth*, and this impact on liking was much larger than found for the only other mouthfeel characteristic that positively influenced liking – *mouthcoating* (0.2). The mouthfeel attributes that penalised liking had face validity and the largest impact was associated with *powdery/chalky* (−0.9) followed by *gritty*, *mouth drying*, *slimy*, *oily* and *thin/runny* (−0.7 to −0.3, with significance testing not performed for *gritty* and *slimy* due to low average citation frequency). If a sample was perceived as being *thick/viscous*, there was no significant lift or penalty on liking (Table 4).

3.4.2. Consumer segmentation by stated frequency of PBMA consumption

Penalty/lift analysis, performed separately in the two PBMA consumption frequency groups yielded largely similar results (Table 5) (Aim 2). The average citation frequencies for sensory attributes (across all samples) varied only little (<5 %), and the only two instances where the difference in average citation frequency exceeded 4 % was for *smooth* and *mouth drying*. On average, these CATA terms were used, respectively, more and less in the “higher” frequency consumption group than the “lower” frequency consumption group.

Regarding mean impact on average liking scores, Table 5 shows that the same sensory attributes penalised liking or associated with a hedonic lift in the two consumption frequency groups. While there were no instances where the difference in mean impact between the two consumption frequency groups exceed one hedonic scale point, there were four sensory attributes where the discrepancy was 0.5 scale points or more. Most notable were *sweet* and *weak/bland flavour*. The lift was larger in the “higher” than “lower” consumption frequency group (1.7 vs 1.2) in the case of *sweet*, and the penalty on *weak/bland* was similarly larger (respectively, −1.7 vs −1.0) (Table 5). Also notable were differences in mean impact for *white colour* and *milky flavour*. In the “higher” consumption frequency group there was a significant penalty on *white colour* (−0.4) and a reduced lift for *milky* (1.3 vs 1.7). Finally, in the “higher” consumption frequency group there was a trend that sensory characteristics associated with PB ingredients lifted the liking score more than in the “lower” frequency consumption group: *coconut* (0.6 vs 0.3), *nutty* (0.5 vs 0.3) and *cereal/oaty* (1.0 vs 0.6) (Table 5).

4. Discussion

4.1. Consumer acceptability of PBMA

Low sensory quality and consumer dislike is often cited as a barrier to uptake of PBMA (e.g., Giacalone et al., 2022; Pointke et al., 2022; Oduru et al., 2021). The findings from the present research, conducted with commercially available PBMA in New Zealand, echoed this conclusion (Aim 1). Half of the 18 samples had an average rating in the dislike part of the hedonic continuum (i.e., a mean score below 5), and three of these (cashew, peanut and hemp seed) received mean scores between 2.6 and 3.6. It is important to emphasise that only 35 % of participants declared to drink PBMA on its own. This fact could have influenced the liking scores, as it may not accurately represent participant’s typical product consumption. Furthermore, certain products, such as barista-style variants, are intended for mixing with coffee rather than direct consumption. To put the present findings into further perspective, only four samples had an average rating between “like slightly” (6) and “like moderately” (7) (Table 3). No samples received a mean score above 7,

Table 5

Results from Penalty/Lift analysis showing average term citation frequency (%) across all plant-based milk alternative (PBMA) samples in the study and mean impact on liking[§] when CATA term is selected (latter when mean impact was different from zero at the 5 % level of significance). Shown for consumer segments defined by stated consumption frequency of PBMA – “higher” (weekly or more often) and “lower” (fortnightly or less often, including never).

Sensory attributes	Average citation frequency (%)		Mean impact on liking [§]	
	“Lower” consumption frequency	“Higher” consumption frequency	“Lower” consumption frequency	“Higher” consumption frequency
Appearance				
White colour	25.7	27.9	−0.2 ^{ns}	−0.4 ^{**}
Light grey colour	11.8	14.7	−0.5 ^{**}	−0.4 [*]
Cream colour	41.3	41.5	0.5 ^{***}	0.7 ^{***}
Light brown colour	24.0	25.5	0.0 ^{ns}	0.2 ^{ns}
Light green colour	2.6	1.6	0.5 ^{n/a}	1.0 ^{n/a}
Light pink colour	10.9	8.7	−0.1 ^{ns}	−0.6 ^{ns}
Thin/Runny	42.3	43.9	0.0 ^{ns}	−0.2 ^{ns}
Thick/Viscous	20.3	22.0	−0.1 ^{ns}	0.1 ^{ns}
Oily	18.2	15.7	−0.7 ^{***}	−0.3 [*]
Foam/Bubbles	12.5	12.5	0.3 ^{ns}	0.5 ^{**}
Taste				
Sweet	39.8	40.4	1.2 ^{***}	1.7 ^{***}
Bitter	9.2	8.6	−1.5 ^{n/a}	−1.7 ^{n/a}
Sour	3.1	3.9	−1.1 ^{n/a}	−1.7 ^{n/a}
Salty [#]	7.8	7.1	0.1 ^{n/a}	−0.1 ^{n/a}
Umami/ Savoury [#]	6.8	7.4	0.3 ^{n/a}	−0.2 ^{n/a}
Flavour				
Coconut	21.5	21.4	0.3 [*]	0.6 ^{***}
Peanut	7.7	9.5	−0.5 ^{n/a}	−0.1 ^{n/a}
Rice	19.4	21.2	0.0 ^{ns}	0.0 ^{ns}
Tropical Fruit	4.0	6.0	0.9 ^{n/a}	0.5 ^{n/a}
Nutty	24.6	23.9	0.3 [*]	0.5 ^{**}
Roasted nuts	8.5	12.2	0.5 ^{n/a}	0.2 ^{ns}
Earthy	17.9	19.5	−1.3 ^{***}	−1.1 ^{***}
Fish-like	3.0	3.1	−2.1 ^{n/a}	−2.0 ^{n/a}
Beany/ Legume	19.6	22.6	−0.4 [*]	−0.3 ^{ns}
Cereal/Oaty	30.7	32.3	0.6 ^{***}	1.0 ^{***}
Bland/Weak flavour	23.5	20.2	−1.0 ^{***}	−1.7 ^{***}
Cardboard-like	16.1	14.0	−1.9 ^{***}	−2.0 ^{***}
Milky	22.6	22.9	1.7 ^{***}	1.3 ^{***}
Texture and mouthfeel				
Smooth	50.4	55.1	1.4 ^{***}	1.4 ^{***}
Oily	16.6	15.6	−0.5 ^{**}	−0.2 ^{ns}
Thin/Runny	50.9	53.9	−0.3 [*]	−0.3 ^{**}
Thick/ Viscous	16.2	18.6	−0.3 ^{ns}	0.0 ^{ns}
Powdery/ Chalky	20.3	19.9	−1.0 ^{***}	−0.8 ^{***}
Gritty	5.8	5.7	−0.9 ^{n/a}	−0.5 ^{n/a}
Slimy	8.9	9.9	−0.4 ^{n/a}	−0.8 ^{n/a}
Mouthcoating	32.1	33.9	0.1 ^{ns}	0.2 [*]
Mouth drying	19.1	14.5	−0.8 ^{***}	−0.7 ^{***}

Notes.

¹⁾ Significance level indicated by *** if $p < 0.001$, ** if $p < 0.01$ and * if $p < 0.05$. Else ns.

^{§)} 9-point liking response scale: 1 = dislike extremely, 9 = like extremely.

^{§)} Significance testing not performed if average citation frequency < 20 %. Indicated as ‘n/a’.

^{#)} For completeness it is noted that Cochran’s Q test found significant

differences ($p < 0.007$) between the 18 samples for all sensory attributes except *umami/savoury* for the group with “lower” consumption frequency ($p = 0.053$) and *salty* for the group with “higher” consumption frequency ($p = 0.18$).

anecdotally used in the food and beverage sector as a threshold value for market launch decisions. Nonetheless, the values in Table 4 were higher than those reported by Cardello et al. (2022) who also measured consumer liking/disliking for PBMA among New Zealand consumers. Under similar test conditions, using a participant sample with comparable characteristics, and in response to commercial samples made from soy, cashew, rice, oat and/or coconut, Cardello et al. (2022) reported mean liking scores that were always below 6 (i.e., “like slightly”). Since the two studies were conducted a couple of years apart, it is possible that commercial PBMA have improved and/or that consumers have grown slightly more accepting of PBMA possibly due to a larger exposure to this product category. However, the latter would likely only apply to samples that are not deemed unacceptable by consumers, since an unsweetened PBMA from cashew nuts was very disliked in both studies (3.6 of 9).

The four most liked samples in this study (in decreasing order: S1, S4, S7 and S17, mean liking > 6) were made from different ingredients – soy, oat, coconut, almond and rice blend, respectively, suggesting that other ingredients and processing more so than the primary PB ingredient could influence this flavour characteristic. Two of the four PBMA were barista types (i.e., made for use in coffee) (S4 and S7), and two were sugar sweetened (S1 and S7). The fact that the PB ingredient as well as other aspects of product formulation influenced consumer acceptability was encouraging for PBMA product innovation efforts. This optimism was further supported by observed differences in liking between samples made from the same PB ingredient. The most notable example was S1 and S2. Both were made from soy and contained some added sugar, but there was a significant and considerable difference in their mean liking scores (6.5 vs 5.6; Table 3). The study by Cardello et al. (2022) also found that PBMA from different ingredients could be similarly liked by consumers. Moreover, there was an overlap in the two studies of the raw ingredients in the most liked samples (except for almond, which was not included in Cardello et al. (2022)). Section 4.2 discusses innovation opportunities further.

It fitted expectations that a positive effect of stated PBMA consumption frequency on liking was established (Aim 2), with a higher mean liking score (0.3 of 9) being recorded for the “higher” consumption frequency group. While a similar effect has previously been reported for PB foods (e.g., Niimi et al., 2022) and other food and beverage categories (e.g., Choi & Seo, 2023; Tan et al., 2017; Nguyen & Wismer, 2020), there are also reports of no effect, including the work by Pramudya et al. (2019) on rice-based milk alternatives in Korea. Tentatively, a bigger difference in the overall mean score could have resulted from the “higher” consumption frequency group comprising more people who consumed PBMA daily. Such an effect would derive from findings that consumers are reluctant to consume products that they dislike (e.g., Randall & Sanjur, 1981; Asp, 1999; Jiang, King, & Priyawiwatkul, 2014).

There was little evidence of consumer segmentation based on liking. While unexpected considering the results by Cardello et al. (2022), this result could likely be explained by differences in sample selection. Consumer segmentation is less likely to occur for disliked samples (mean liking below 5), of which there were many in the present research (50 % of samples) and only one in Cardello et al. (2022) (10 % of samples). As a case in point, the most disliked sample in Cardello et al. (2022) was disliked in all four clusters, and often such dislike is driven by an unappreciated sensory attribute like bitterness (e.g., Drewnowski & Gomez-Careros, 2000). Furthermore, in Cardello et al. (2022), which included dairy milk samples as well as PBMA, liking for these two types of milk was the primary determinant of segmentation. Degree of liking for samples with coconut and soy additionally contributed to segmentation in Cardello et al. (2022), and interestingly these two ingredients

also emerged in the present research.

The inclusion of barista samples, a novel aspect of the present research, revealed that consumers were more positive, on average, about this PBMA style than non-barista samples. Because these PBMA, through use in hot coffee beverages to which milk is added (cappuccino, café late, americano, etc.) is a first exposure for many people to dairy milk alternatives (Zakidou et al., 2022), it is important that they provide a positive sensory experience. The present results provide R&D guidance in this regard: smooth mouthfeel was common to the barista samples (68 % – 76 % citation frequency, Table S7), while sweetness varied considerably (34 % – 84 % citation frequency, Table S6). Sensory characteristics that considerably penalised liking were infrequently perceived.

Strong links between nutritional composition of the PBMA samples and their mean liking scores was not established, with the exception of sugar and sodium which were, respectively, positively and negatively associated with liking. In light of many expressed concerns regarding the nutritional quality of PBMA, reminders to select fortified variants (Ministry of Health, 2020), and guidance that PBMA generally should not be regarded as direct substitutes for cow’s milk (e.g., Fructuoso et al., 2021; Vanga & Raghavan, 2018), it was notable that samples with very different nutritional profiles received the same “high” liking scores. Sample S1 (soy) which received the highest mean liking score (Table 3) had a nutritional profile (Table 1) that was not too dissimilar from cow’s milk (see also Zhang, Hughes, & Grafenauer, 2020)). For example, dairy milk product Anchor Lite™, one of the top selling brands in New Zealand, contains 3.3 g/100 mL protein, 1.5 g/100 mL fat, 4.8 g/100 mL carbohydrates and 40 mg/100 g sodium (<https://www.anchor dairy.com/nz>). However, the other three samples with mean liking scores > 6.0 were nutritionally inferior to Anchor Lite™, especially S4 (oat barista) and S17 (almond-rice blend) which contained much less protein (0.6 g/100 mL) and more fat (2.4–2.7 g/100 mL). Innovation efforts (Section 4.2) should be mindful of these differences and seek to optimise nutritional as well as sensory qualities (e.g., Fructuoso et al., 2021; Oduro et al., 2021), and facilitate informed purchase decisions by consumers. Sugar and salt addition should be factored into these decisions as they negatively impact healthiness, but may be needed to improve consumer liking. Tentatively, the lentil PBMA (S18) was an example hereof, although the relatively high sugar content (3.3 g/100 mL) was insufficient to produce a well-liked sample. Another tentative instance involved the comparison between almond-based samples S8 (unsweetened) and the barista-style S9 (low in added sugars). While the sugar content was similar (Table 1), the barista sample performed better with greater smoothness and thickness compared to S8, as was illustrated in Fig. 4.

4.2. Sensory drivers of liking for PBMA

The results (Table 4) revealed expected, as well as unexpected sensory drivers of PBMA liking.

Generally, there was a high degree of overlap with earlier results regarding PB yoghurts among New Zealand consumers (Jaeger, Giacalone, Jin, Ryan, & Cardello, 2023). Here, *milky* flavour was the most positive driver of liking, and was almost double that of *cereal/oaty* and about three times as much as *coconut* and *nutty*. On the other hand, *rice* did not impact liking and *soy/bean-like* penalised liking (Table 4). Thus, in this sample of participants who with few exceptions were not dedicated PBMA drinkers (only 15 % stated consumption frequency as daily), a flavour resembling cow’s milk is preferred to flavours associated with PB raw materials. This fits with recent work by Amyoony et al. (2023) who found that Canadian consumers preferred PB beverages and cheeses with an aftertaste that mimics dairy products. Relatedly, it was interesting to note that the sample with the highest liking score – S1 (soy) – was marketed as having a “milky taste” (Table 1). For many consumers this is likely a positive characteristic, perhaps with the exception of long-term vegetarians or vegans who have relied on a

different type of diet for a long time and may not be actively seeking alternatives that mimic the eating experience of animal-based and animal-derived product (e.g., Faber, Henn, Brugarolas, & Perez-Cueto, 2022).

The results for nut flavour were conflicting in the sense that they pointed to both positive and negative impacts on liking, depending on the specific attribute (Table 4). A hedonic lift was associated with the generic term *nutty* (0.4) and the same was found for *roasted nuts* (0.4). Conversely, *peanut* exerted a possible penalty (−0.2, significance test not performed). The *peanut flavour* was specifically associated with the second most disliked sample (S12), which was also the least *sweet* and least *milky*. Oduro et al. (2021) found that PBMA blends containing peanut were positively received, suggesting that this flavour characteristic may not be a strong deterrent for some consumers. However, other peanut-based commercial products may not exhibit this issue to the same extent as found in the present study. It is also possible that the small impact on mean liking is due to consumer segmentation. Hwang and Hong (2015) reported that consumer segmentation exists for liking of nuttiness in soy milk.

Regarding consistency, the results fitted expectations. While *thin/runny appearance* did not impact liking significantly, the mean impact was negative (−0.1) and this fitted with the significant penalty of *thin/runny consistency* (−0.3). It can be relevant to seek comparative insights from other related product categories to help interpreting current findings. For instance, there has been several reports of a negative impact of thin/runny for PB yoghurt (e.g., Greis et al., 2020; Jaeger et al., 2023; Mehta et al., 2023), and this could be a texture characteristic that consumers generally do not like in these similar dairy categories. However, it was perhaps surprising that the impact of *thick/viscous* (appearance and consistency) was also non-significant, but it could be related to desire for an optimal balance between thick and thin, such that a sample is neither too runny nor too thick but somewhere in between. Just-about-right (JAR) questions could be used for product optimisation in this regard, as could optimal profiling (e.g., Paries, Bougeard, & Vigneau, 2022).

An interesting result was the penalty on *white colour*, even if small (−0.3). Past research with PBMA and PB yoghurt has found that white colour is a positive driver of liking in these product categories (Cardello et al., 2022), or alternatively that dark colour is a negative driver (Pramudya et al., 2019). In this study, there is no dairy milk as an ‘internal control’ (unlike Cardello et al., 2022), nevertheless, the colour tonality expected from a dairy milk is not actually white, but a more cream coloured. The current result could be explained by the most disliked sample (S14, hemp seed) being described as white by consumers who potentially consider dairy milks that are “white coloured” as unnatural or more artificial. Although two of the three coconut samples were also described as white, these samples were more liked ($M_{S5} = 5.5$ and $M_{S6} = 4.1$). Therefore, a white/cream colour tonality cannot compensate for the negative impact of a strongly disliked flavour or mouthfeel product characteristic, which was the case for the hemp sample (S14). Additionally, it cannot be disregarded that the shade of whiteness were not equivalent, and Oduro et al. (2021) made this point in their work on PBMA blends. Oduro et al. (2021) regarded it as positive that none of their samples were whiter than commercial dairy milk because this would prevent consumers from perceiving them as unnaturally white (p. 10). Notably, during pilot work for the present research, it was remarked that S14 had an unnatural white colour which made the sample “too white”. However, PBMA from hemp seed need not be extremely white (McClements et al., 2019), and generally this finding draws attention to the importance of colour shade. In turn, this points to the relevance of exploring white (and other) colour preferences further, possibly using the work of Paakki, Sandell, and Hopia (2019) as inspiration. These authors combined instrumental measures of colour with perceptual responses from consumers to investigate visual attractiveness in food using salad mixes as a case study. In the case of PBMA, digital sample images varying in hue and intensity could be developed and

tested. In this manner results for *light brown colour*, *light pink colour*, *light green colour* and *light grey colour* could be better understood, as could the role of colour for overall acceptance of PBMA. Tentatively, colour acceptance may be moderated by intended use situation. A non-white/cream colour tonality may matter less when used in a coffee beverage or smoothie than when consumed as-is or with cereal, for example.

4.3. Innovation opportunities

4.3.1. PBMA blends

The liking scores obtained in this study suggested that PBMA blends deserve more attention. The blend of almond and rice (S17) was one of the four samples with a mean score above 6 (Table 3), and in Cardello et al. (2022) a tri-blend product containing oat, rice and coconut received a 6.0 score, which numerically was the highest average value (dairy milk samples aside). Blends facilitate improved nutritional composition including higher protein content than many single-source PBMA. A useful approach to product optimisation was illustrated by Oduro et al. (2021) who used a mixture design framework to optimise prototypes of 3-blend PBMA. These authors found that a blend of 50 % coconut milk, 25 % peanut milk and 25 % melon seed milk with 2.16 % protein content was well received by consumers in Ghana (6.55 on 9-point hedonic scale). Their study, like the present one, was performed with blinded samples, and consumers did not know that they tasted PBMA blends. It is unclear if the fact that products are a blend of two or more PB ingredients is positively or negatively perceived by consumers. Noteworthy, however, was the fact that two of the current samples were blends without being promoted as such. Specifically, S7 was sold as a milk alternative from coconut (3.5 %), but it also contained soybeans (2.9 %). S8 was sold as a milk alternative from activated almonds (7 %), but it also contained rice in the formulation (Table 1). Tentatively, a reason for not drawing attention to these ingredients is that soy and rice could be less positively regarded in consumers’ minds than almonds and coconut.

4.3.2. Barista-style PBMA

Barista-style PBMA received positive liking scores on average (Table 3) and this may suggest an opportunity for use beyond coffee and chai beverages. Beyond a well-crafted marketing campaign to promote other uses, one challenge pertains to the additional ingredients used to achieve the defining frothing and foaming characteristics (Zakidou et al., 2022). There could potentially be a negative impact of not having a clean label as the barista effect comes from adding of emulsifiers and texturing agents. Considering consumer demands and clean-label trends for clean labels in plant-based meat alternatives (e.g., Inguglia, Song, Kerry, O’Sullivan, & Hamill, 2023; Delgado-Pando, Ekonomou, Stratakis, & Pintado, 2021), it is reasonable to assume that similar may apply to PBMA. However, a first step important would be to confirm that liking scores remain unaffected when barista-style PBMA are consumed in quantities larger than those served in the present research. It is possible to imagine the development of variant barista-style PBMA that have limited froth/foam characteristics but retain the smooth mouthfeel that was key to their high consumer acceptability in the present study. Tentatively, these could have a “cleaner” label since emulsifiers and texturing agents will not be needed (as much).

4.4. Limitations and suggestions for future research

A total of 143 consumers took part in the study, exceeding recommendations for consumer taste tests (e.g., Hough et al., 2006). While sample sizes in the two segments based on differences in stated consumption frequency for PBMA (66 and 77 people) did not meet these guidelines, they exceeded 50 which Moskowitz (2020) regarded as sufficient for stable estimates. Nonetheless, it would be prudent to confirm the stability of the current results using larger consumer segments and/or segments that were more narrowly defined with regard to

frequency (e.g., low-moderate-high users) and quantity of PBMA consumption. As this was a secondary aim of this research, the approach used here was explorative, and therefore participants were not recruited according to consumption frequency quota. That latter approach would have been meaningful if frequency of consumption was the primary research aim.

To test the hypothesis that exposure to PBMA can be a pathway to uptake among consumers who currently do not use these products or only do so very infrequently, home-use studies are needed, and these should extend over more than a week. They need to last for enough time that participants have a real opportunity to explore how to integrate PBMA in their daily eating and drinking routines and also experience first-hand where these products can replace dairy milk. Among flexitarians, a primary target group for PBMA, past research has found that people stock both types of milk (Clay, Sexton, Garnett, & Lorimer, 2020). However, to achieve the green consumer transition, the needed change is for PBMA to largely replace dairy milk, not be used infrequently alongside it. Based on Martínez-Padilla, Faber, Petersen, and Vargas-Bello-Pérez (2023), the latter is the status quo. According to these authors, most Danish consumers drink less than one glass of PBMA per week. Besides giving people opportunities to develop new routines and overcome barriers to PBMA uptake linked to established habits (Jaeger & Giacalone, 2021), an exposure effect (e.g., Zajonc, 1968) would also be expected to emerge in an extended home-use test. That is, a positive impact on product liking through repeated consumption. For example, for probiotic beverages, Luckow, Sheehan, Delahunty, and Fitzgerald (2005) observed a significant increase in acceptability after daily consumption for one week.

Studying consumer acceptance of PBMA in common use situations may also have merit. With cereal, in milkshakes and in smoothies are obvious candidates since these uses are typical for cow's milk (Harwood & Drake, 2020) and are also suitable for PBMA (e.g., Jaeger & Giacalone, 2021). The benefit would be that natural use situation are emulated while also maintaining a controlled sensory environment, such that differences can be attributed to samples rather than random factors. For example, sensory characteristics that impact liking negatively when PBMA are consumed as-is may have less influence when consumed in combination with a food matrix such as cereal or muesli.

5. Conclusions

In a New Zealand context, the present research investigated liking/disliking for plant-based milk alternatives (PBMA) and associated sensory drivers. Hereby, new consumer-centric insights were contributed that can be further harnessed for product innovation in this expanding product category with global importance for the plant-based dietary transition. A key finding was that it is possible to make, using soy beans, a PBMA that approximates cow's milk both from a sensory and nutritional stand-point. However, the study also included many PBMA that help to explain why the category has a reputation for inferior products. The identification of sensory drivers of liking will serve as a guidance to product developers and inform them of appearance (cream colour with visible foam/bubbles), taste (sweet), flavour (milky, cereal/oaty, coconut, and/or nutty), consistency and mouthfeel (smooth and mouthcoating) characteristics. Barista-style and blended PBMA emerged as interesting candidates for further innovation.

6. Human ethics statement

The study was assessed and considered low risk following the Massey University Human Ethics Committee process (Human Ethics Notification: 4000027351). Prior to attending the first research session, participants received an information sheet that provided all study details. They were asked to read this and then provide informed written consent. They were assured responses would be confidential and that they would be able to withdraw from the study at any time. Participants were

assigned a unique code to ensure anonymity. Upon completion of the study, participants were offered a snack treat and a supermarket voucher (session 1 and 2, respectively) as compensation for their time.

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CRediT authorship contribution statement

Sara R. Jaeger: Conceptualization, Formal analysis, Funding acquisition, Visualisation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Amanda Dupas de Matos:** Data curation, Investigation, Visualisation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Ama Frempomaa Oduro:** Conceptualization, Investigation, Methodology. **Joanne Hort:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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