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Nutritional quality, perceptions, and sensory evaluation of plant-based meat alternatives

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Abstract. ***Background and purpose.*** Plant-based meat alternatives (PBMAs) have gained popularity as sustainable and health-conscious substitutes for conventional meat products. However, there is limited research on their nutritional quality, consumer perceptions, and sensory attributes compared to traditional meat and homemade meat products. The objective of the study is to assess the nutritional quality of plant-based meat alternatives (PBMAs), determine knowledge, attitudes, behaviour, and perception of PBMAs and evaluate their acceptability through sensory evaluation testing. ***Methods.*** Nutrition data of PBMAs and meat products were collected from packaging and assessed against recommended dietary allowances. Knowledge, attitude, behaviour (KAB), and perception of PBMAs were evaluated using questionnaires. Sensory evaluation was conducted using commercial meat products (CMP), homemade products (HMP) and plant-based meat alternatives (PBMA) (nuggets, fish fingers, minced meat, and beef patties). Twenty-six food products were evaluated for nutritional quality. Fifty-two participants completed the KAB questionnaire with twenty-one participants completing sensory evaluation. ***Results.*** PBMAs have higher fibre but lower protein content compared to HMP. PBMAs and CMP have higher saturated fat and sodium due to being ultra-processed. Key predictors of PBMA purchase intent included male gender (OR=4.25, P=0.015), obese BMI (OR=6.67, P=0.034), and positive attitudes towards healthy eating (OR=5.08, P=0.007). Sensory evaluation showed PBMAs are less preferred in taste (mean score: 2.43 for PBMA nuggets vs. 1.24 for CMP nuggets, P<0.001) and texture (mean score: 2.24 for PBMA nuggets vs. 1.52 for CMP nuggets, P=0.028). ***Conclusion.*** The study highlights the need to consider nutritional quality and consumer perceptions when evaluating PBMAs as meat substitutes. Addressing nutritional challenges and improving consumer education can enhance PBMAs' contribution to healthier, sustainable diets.

Keywords: Plant-based meat alternatives, meat analogs, nutritional quality, sensory evaluation

INTRODUCTION

In recent years, plant-based diets have gained mainstream traction as a promising dietary pattern for health. They have been associated with a reduced risk of cancer, cardiovascular disease, diabetes, and overall mortality 1,2. Characteristically, plant-based diets emphasize plant products, such as fruits and vegetables, wholegrains, legumes, nuts and seeds, while limiting or excluding animal-derived products 1 .

Plant-based meat alternatives (PBMAs) are food products made from a mix of legumes and cereals, using various food technologies, with or without added food additives. They are designed to closely resemble the organoleptic attributes (flavour, texture, and appearance) of meat products they are intended to replace 3. In recent years, PBMAs have seen a dramatic increase in production and availability worldwide. This growth is driven by factors such as sustainability concerns, animal welfare, rising population demands, and the perceived health benefits of these foods 4,5.

Research has shown that for PBMAs to effectively replace meat, they must replicate the taste, texture, visual appearance, and cooking methods of meat 6. However, concerns have been raised about the nutritional quality of these products. Studies frequently highlight potential health issues related to the additives used to mimic the sensory characteristics of meats 7. The nutritional composition of PBMAs can vary widely due to different ingredient combinations, making it challenging difficult for consumers to choose the most nutritionally beneficial option. The processing steps involved in producing many PBMAs can affect their macronutrient and micronutrient profiles 8. This is significant because many consumers believe that incorporating PBMAs into their diets will provide similar nutritional advantages to a plant-based diet that primarily consists of whole foods 6,9. Additionally, many processed PBMAs contain flavour enhancers to make them more palatable 8.

Several research groups have published comprehensive reviews on the nutrient content of a wide range of PBMAs 10–12. However, globally, dietary guidelines provide little guidance on the use of PBMAs 13. Therefore, the ramifications of reducing meat consumption on nutrient intake must be considered as meat contributes significantly to nutrient intake globally. In Singapore, the annual consumption of meat (including chicken, pork, beef, and mutton) is estimated to be 62kg per capita in 2021 14. With the "30 by 30" vision to sustainably produce 30% of Singaporean's nutritional needs locally by 2030 14, it is important to first understand the nutritional composition and quality

of meat substitutes available in the market. To our knowledge, there is currently no study evaluating the nutritional quality of PBMAs by comparing the nutrient content against local Recommended Dietary Allowances (RDAs).

Unlike PBMAs, which are considered processed foods, home-cooked meals are increasingly promoted to encourage healthier eating habits and improve overall dietary quality 15. Consumers' inclination to purchase processed PBMAs, conventional meat products, or homemade versions of meat largely depends on their perceived healthiness 11,16. Furthermore, studies have indicated that consumers are more accepting of PBMAs than other types of meat alternatives, although these studies have primarily been conducted in Western populations.

Despite technological advancements, producing PBMAs with sensory attributes similar to animal- based meat products, such as appearance, flavor, odour, and texture 17,18 remains a challenge. To our knowledge, there are few studies that specifically assess consumers' sensory perceptions of plant protein meat alternatives (PBMAs) specifically through taste testing sessions. Most studies analyzed consumer attitudes and intentions through questionnaires and surveys 19,20. Sensory studies evaluating consumer preferences for different meat alternatives are still limited 21.

With the burgeoning popularity and growth in PBMA innovation, little is known about the nutritional quality and consumption patterns of PBMAs in Singapore. Therefore, the aims of the study are to: (1) compile and compare the Nutrition Information Panel (NIP) of existing PBMAs sold in Singapore against the Singapore Recommended Dietary Allowances (RDAs), (2) investigate the knowledge, attitudes and behaviours of participants who consume PBMAs, and (3) evaluate the perceived acceptability and sensory distinctions between PBMAs, conventional meat products, and homecooked meat equivalents through sensory evaluation testing.

MATERIALS AND METHODS

Nutritional Quality Assessment of Plant-based Meat Alternatives (PBMAs)

The nutrition information panel of PBMAs and commercial meat counterparts across three major supermarkets in Singapore (NTUC FairPrice, Cold Storage, Sheng Siong) were collated from November 2022 to November 2023. These supermarket chains accounted for the majority of the Singaporean market shares and were chosen to reflect choices readily available to most Singaporean grocery shoppers. Additionally, four online grocery retailers (RedMart, Shopee, FairPrice Online, Cold Storage Online) were also included as they contributed a proportion of online grocery sales in Singapore 22.

The compilation comprised of commercial meat products, and food products made from plant-based proteins that aim to mimic the taste, texture, and overall consumer experience of meat. Products were further categorized into patties, sausages, and minced meat. Products that were excluded were non-beef patties (e.g. chicken and veggie patties), plant-based foods not meant to imitate meat products such as tofu, tempeh, and falafel, composite meals, and plant-based dairy products.

To ensure data on all relevant and available food products were captured, an additional internet search was carried out via the supermarket and respective manufacturers' websites. This involved using the keywords 'beef burger', 'patty', 'sausage', 'hot dog', 'mince', and 'grounded' for commercial meat products. Search terms for PBMAs included 'meat alternatives', 'meat substitutes', 'meat-free', 'meatless', 'plant-based', 'vegan', and 'vegetarian'.

Information collected from the nutrition information panels included energy, protein, total fat, saturated fat, carbohydrates, dietary fibre, and sodium, all recorded per 100g of each food product. For products without nutritional information per 100g, manual conversions were performed to standardize the data. This ensured consistent comparison of nutrient values across different food products. For homemade meats, the quantity of ingredients used was based on recipes sourced online. The nutritional information of these recipes was tabulated through Foodworks (Xyris, 2024). The nutritional composition of all food products was compared against the Recommended Dietary Allowances (RDAs) based on Singapore guidelines and reported in percentages.

Assessment Of The Perceived Acceptability Of PBMAs

Participants aged between 21 to 60 years old and residing in Singapore were recruited through convenience sampling, word of mouth and social media advertisements (Telegram and WhatsApp). The study recruited 52 participants, comparable with other pilot studies using KAB questionnaires 23,24. The self-administered online KAB survey consisted of 23 questions and was disseminated to recruited participants from April 2023 to August 2023.

Demographic information, including age, gender, height, weight, ethnicity, gross monthly income, tobacco use, weekly alcoholic intake, and dietary preferences were collected using close-ended multiple-choice questions. Additionally, data on health attitudes, perceptions, knowledge, and consumption patterns of PBMAs, as well as barriers and facilitators to PBMA consumption were gathered using 5-point Likert scales. Response options for agreement included 'Strongly agree', 'Agree', 'Neutral', 'Disagree', 'Strongly disagree', and 'Unsure'. The likelihood of purchasing PBMAs and replacing meat products with PBMAs was measured with options such as 'Not likely at all', 'Somewhat likely', 'Moderately likely', 'Very likely', 'Extremely likely', and 'Already doing it'.

Sensory Evaluation Testing

Only participants who had completed the KAB survey and were screened to have no gustatory and olfactory deficits, food intolerance, allergies, or dietary patterns were eligible for the sensory evaluation. A total of 21 participants were recruited to assess their acceptance and sensory differences between PBMAs, conventional meat products, and homemade meat equivalents. The sensory evaluation used a consumer hedonic method, with 10 close-ended survey questions where participants rated the products based on their attributes.

Six different food samples were prepared, consisting of two sets of food products: minced meat and patties. Each set included three different variations: the PBMA, the commercial meat product, and the homemade meat product. The samples were prepared in the sensory lab at the Singapore Institute of Technology (SIT). The selected PBMAs and meat samples were commercially available and purchased frozen from local supermarkets to maintain their sensory qualities during food preparation.

PBMAs and commercial meat products were prepared according to the cooking instructions on their packaging. Homemade meat products were prepared using online recipes. Samples were cooked, portioned into 20g servings, and kept warm during the sensory evaluation to maintain temperature and texture. To reduce potential position bias, the samples served were coded with randomized alphabets.

The sensory analysis took place in the sensory lab in SIT. Environmental settings like ambient light, positive pressure, and airflow were standardized throughout all sessions. Prior to the start of the sensory evaluation, participants were briefed on the food-tasting procedure and instructions.

During the food-tasting session, each set of samples was served one tray at a time, with cutlery provided. Plain water was provided as a palate cleanser before tasting each sample. After tasting, participants filled out an online evaluation form to rate attributes like taste, texture, colour preferences, saltiness and fat content based on the following: 1- most tasty/salty/fatty, 2 – moderately tasty/salty/fatty, 3 – least tasty/salty/fatty; 1- most appealing colour/texture, 2 – moderately appealing colour/texture, 3- least appealing colour/texture. According to current literature, these sensory traits significantly influence food acceptance 6,25. Each sensory evaluation session lasted approximately 45 minutes to 1 hour.

Statistical Analyses

All data analyses were performed using IBM SPSS Statistics Version 29.0. No missing data was reported.

Nutritional Quality

Descriptive statistics were performed to determine the overall nutritional quality of PBMAs, commercial meat products, and homemade meat products.

KAB Survey

Demographic information was analyzed using descriptive statistics, presented in the form of frequency counts and percentages. Multinomial logistic regression was performed to assess the predictors of PBMAs' purchase and replacement intent from the KAB data. Results were reported in odds ratios (ORs) and 95% confidence intervals (CIs). Significance levels were set at $\alpha < 0.05$.

Sensory Evaluation

Median ratings of taste, texture, colour, saltiness, and fat content of plant-based, commercial, and homemade minced meat and patties were compared by non-parametric Friedman's two-way analysis of variance by ranks to determine whether there were significant differences between sensory perceptions across all three meat/meat alternative per food product. When significant differences were observed ($p<0.05$), Wilcoxon signed-rank tests on different pairs of minced meat and patties were carried out to determine their differences. The *p*-value threshold was set at $\alpha < 0.05$.

Ethical Approval

Ethical approval for the involvement of human subjects in this study was granted by SIT Institutional Review Board, reference number 2023059, 28 March 2023. All participants gave informed consent.

RESULTS

Participant Characteristics

Table 1 shows the demographic characteristics of the participants (N=52). Majority of the participants were aged 21 to 30 years old (51.9%) with an equal proportion of males and females (50.0%). Most of the respondents were Chinese (82.7%), within the normal BMI range (46.2%) with a monthly income of less than S$1000 (34.6%). Most of them have never smoked (88.5%) and take alcohol less than once a week (67.3%). Participants were mostly omnivores (86.5%), with few identifying as flexitarian (9.5%), vegetarian (1.9%) and pescetarian (1.9%).

Table 1. Demographic characteristics (N=52)

	n	%
Demographics		
Age (Years)		
21 - 30	27	51.9
31 - 40	8	15.4
41 - 50	8	15.4
51 - 60	9	17.3
Gender		
Female	26	50.0
Male	26	50.0
Body Mass Index (BMI)		
Underweight (< 18.5)	5	9.6
Normal (18.5 - 22.9)	24	46.2
Overweight (23.0 - 24.9)	13	25.0
Obese (≥ 25)	10	19.2
Ethnicity		
Chinese	43	82.7
Non-Chinese1	9	17.3
Monthly income (Singapore dollars)		
Low ($0 - $2000)	21	40.4
Middle ($2001 - $5000)	16	30.8
High (>$5000)	15	28.8
Dietary Habits		
Diet Type		
Omnivore	45	86.5
Others2	7	13.5
Tobacco Use		
Never	46	88.5
Ever3	6	11.5
Alcohol Intake		
Non-drinker	35	67.3
Drinkers4	17	32.7

1 Non-Chinese includes Malay, Indians, and Others.

2 Others includes vegetarian, pescatarian, and flexitarian.

3 Ever includes active smokers and ex-smokers.

4 Drinkers include occasional drinkers.

Nutritional Quality Assessment

A total of 41 food products were evaluated for nutritional quality (Appendix 1). These food products were classified as plant-based meat alternatives (PBMA) or commercial meat-based products (CMP). Homemade meat products were used as a reference. Figure 1-5 compares the composition of macronutrients (protein, carbohydrates, total fat) composition, dietary fibre and sodium content of PBMA and CMP with the Recommended Daily Allowances (RDA) for each macronutrient, expressed as a percentage of RDA per 100g of each product.

Figure 1. Comparison of protein content (per 100g) of food products against the RDA (%)

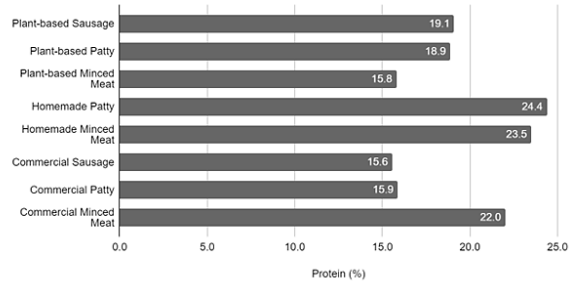


Figure 2. Comparison of carbohydrates content (per 100g) of food products against the RDA (%)

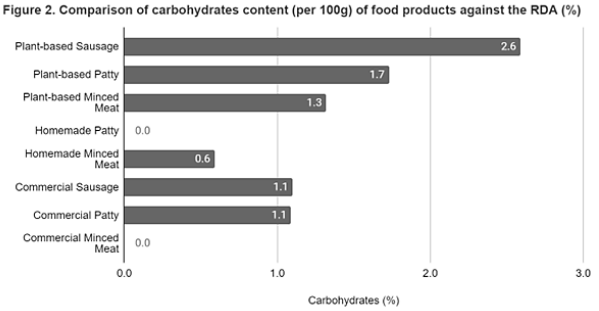


Figure 5. Comparison of sodium content (per 100g) of food products against RDA (%)

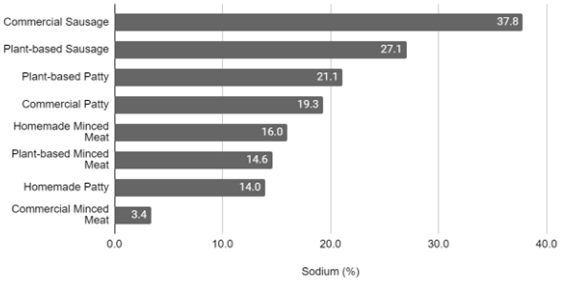


Figure 3. Comparison of fat content (per 100g) of food products against the RDA (%)

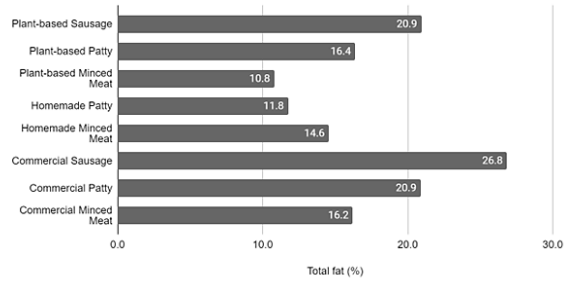
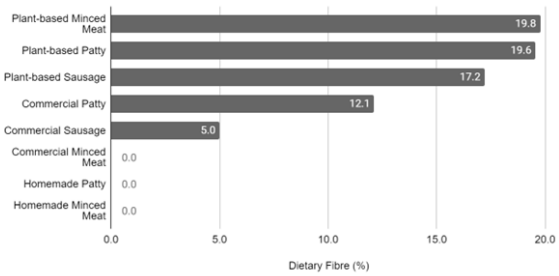


Figure 4. Comparison of dietary fibre content (per 100g) of food products against RDA (%)



The top three products with the highest protein content were home-made patty (24.4% of RDA), home-made minced meat (23.5% of RDA), and commercial minced meat (22.0% of RDA). Plant-based sausages contained the most carbohydrates (2.6% of RDA) while homemade meat patty did not. Total fat content was the highest among commercial sausages (26.8% of RDA), commercial patty (20.9% of RDA) and plant-based sausages (20.9% of RDA). The saturated fat content also follows the same trend; commercial sausage (30.3% of RDA), commercial patties (27.9% of RDA), and PBMA sausages (22.8% of RDA) (data not shown). Dietary fibre was not found in homemade or commercial minced meat products, but in all PBMAs. For sodium, products with the highest sodium levels were commercial sausages (37.8% RDA), PBMA sausages (27.1% RDA), and PBMA patties (21.1% RDA).

Table 2. Perceived Acceptability of PBMAs

Participants' Perception of PBMAs (n=52)	n	%
I think it is important to eat healthily		
Strongly agree / Agree	52	100.0
PBMAs are healthier than meat products		
Strongly agree / Agree	10	19.2
Neutral	19	36.5
Strongly disagree / Disagree	17	34.6
Unsure	6	11.5
PBMAs are high in proteins		
Strongly agree / Agree	9	17.3
Neutral	24	46.2
Strongly disagree / Disagree	13	25.0
Unsure	6	11.5
PBMAs have equivalent amounts of salt as meat and meat products	21	40.4
Strongly agree / Agree	19	36.5
Neutral	6	11.5
Strongly disagree / Disagree	6	11.5
Unsure		
PBMAs are high in dietary fibre		
Strongly agree / Agree	5	9.6
Neutral	20	38.5
Strongly disagree / Disagree	21	40.4
Unsure	6	11.5
The production of PBMAs emits lesser greenhouse gases compared to meat and meat products		
Strongly agree / Agree	5	9.6
Neutral	13	25.0
Strongly disagree / Disagree	24	46.2
Unsure	10	19.2
PBMAs are ultra-processed foods		
Strongly agree / Agree	2	3.8
Neutral	11	21.2
Strongly disagree / Disagree	33	63.5
Unsure	6	11.5
Do you eat PBMAs?		
Yes, on a regular basis	3	5.8
I have tried plant-based meat alternatives, but do not eat them on a regular basis	41	78.8
No	8	15.4
If you eat PBMAs regularly, what are the reasons for eating them? [Multi-select] (n = 3)		
Environment reasons		
Animal welfare	1	1.0
Health reasons	3	3.0
I like the taste	2	2.0
Accessible	2	2.0

Participants' Perception of PBMAs (n=52)	n	%
It tastes authentic to real meat	1	1.0
	1	1.0
If you do not eat PBMAs regularly, what is the likelihood of you trying them? (n = 49)		
Not likely at all	6	12.2
Somewhat likely	16	32.7
Moderately likely	17	34.7
Very likely	9	18.4
Extremely likely	1	2.0
If you do not eat PBMAs regularly, what are the reasons for not eating them regularly? [Multi-select] (n = 49)		
Unhealthy	4	4.6
Too processed	15	17.2
I do not like the taste of meat alternatives	18	20.7
I do not like to try new foods	1	1.1
Meat alternatives are for vegans and vegetarians only	1	1.1
Too expensive	25	28.7
Inaccessible	18	20.7
Others	5	5.7
What is the likelihood of you purchasing PBMAs regularly?		
Not likely at all	25	48.1
Somewhat likely	13	25.0
Moderately likely	11	21.2
Very likely	1	1.9
Extremely likely	0	0.0
Already purchasing	2	3.8
What is the likelihood of you replacing conventional meat with PBMAs?		
Not likely at all	28	53.8
Somewhat likely	13	25.0
Moderately likely	7	13.5
Very likely	2	3.8
Extremely likely	0	0.0
Already replacing	2	3.8

Perceived Acceptability of PBMAs

Table 2 illustrates the perceived acceptability of PBMAs. All 52 respondents agreed that healthy eating is important. Respondents were mostly ambivalent towards the notion that PBMAs are healthier than meat products (36.5%) and are high in proteins (46.2%). The largest proportion of respondents perceived PBMAs to have the same amount of salt as meat and meat products (40.4%), disagree that PBMAs are high in dietary fibre (40.4%), and emit less greenhouse gases during its production (46.2%). Interestingly, almost two-thirds of the respondents did not view PBMAs as ultra-processed foods (63.5%).

Amongst all respondents, only three respondents consumed PBMAs regularly (5.8%), with their top motivating factors including animal welfare, health reasons, and liking the taste of PBMAs. For the remaining 49 respondents who do not regularly eat PBMAs, their main barriers included PBMAs being too expensive (28.7%), disliking the taste of PBMAs (20.7%), and inaccessibility (20.7%). Most respondents were unlikely to purchase PBMAs regularly (48.1%) or replace conventional meat with PBMAs in their diets (53.8%).

Table 3. Regression analysis to investigate demographic and dietary habits associated with intent of purchase and replacement of PBMA. (N=52)

	Likelihood of Purchase		Likelihood of Replacement	
	OR	*P-value*	OR	*P-value*
Demographics				
Age (years)				
21 - 30	*Reference*	*NA*	*Reference*	*NA*
31 - 40	8.75	*0.056*	14.00	*0.021*
41 - 50	0.75	*0.728*	1.20	*0.827*
51 - 60	1.56	*0.565*	2.50	*0.243*
Gender				
Female	*Reference*	*NA*	*Reference*	*NA*
Male	4.25	*0.015*	3.60	*0.029*
BMI				
Normal	*Reference*	*NA*	*Reference*	*NA*
Underweight	0.42	*0.464*	0.50	*0.563*
Overweight	3.75	*0.072*	3.20	*0.104*
Obese	6.67	*0.034*	4.67	*0.059*
Ethnicity				
Chinese	*Reference*	*NA*	*Reference*	*NA*
Non-Chinese1	2.10	*0.337*	0.52	*0.401*
Income				
Low	*Reference*	*NA*	*Reference*	*NA*
Middle	0.86	*0.815*	0.61	*0.472*
High	2.20	*0.260*	2.69	*0.163*
Diet Type				
Omnivore	*Reference*	*NA*	*Reference*	*NA*
Others2	2.61	*0.279*	3.42	*0.167*
Perception				
I think it is important to eat healthy	5.08	*0.007*	3.24	*0.046*
PBMAs are healthier than meat products	2.65	*0.018*	2.49	*0.022*
PBMAs are high in proteins	0.76	*0.469*	0.84	*0.655*
PBMAs have equal salt as meat and meat products	0.42	*0.025*	0.57	*0.110*
PBMAs are high in dietary fibre	0.81	*0.571*	1.01	*0.988*
PBMA production emits lesser greenhouse gasses	0.84	*0.559*	0.95	*0.845*
PBMA are ultra-processed foods	1.13	*0.737*	1.17	*0.666*

1 Non-Chinese includes Malay, Indians and Eurasians

2 Others is defined as vegetarian, pescatarian, flexitarian.

Statistical differences under a logistic regression model, where *P<0.05* are indicated in bold.

Table 4. Mean participant sensory perceptions between commercial meat products (CMP), homemade (HMP), and plant-based meat alternative (PMBA) food products (N=21)

Food Products	Nugget				Fish finger				Minced meat				Beef patty			
	CMP	HMP	PBMA	P-valued	CMP	HMP	PBMA	P-valued	CMP	HMP	PBMA	P-valued	CMP	HMP	PBMA	P-valued
Taste	1.24a,b	2.33a	2.43a	*<0.001*	2.00	2.19	1.81	*0.467*	2.14	2.14	1.71	*0.276*	1.57a	2.24a	2.19	*0.055*
Texture	1.52a,b	2.24a	2.24a	*0.028*	1.76	2.24	2.00	*0.304*	1.86	2.10	2.05	*0.717*	2.10	1.86	2.05	*0.717*
Colour	1.91	2.52a	1.57b	*<0.001*	1.43b	2.24a	2.33a	*0.006*	2.24	2.10	1.67	*0.156*	2.00	2.00	2.00	*1.00*
Saltiness	1.38b	2.67a	1.95c	*<0.001*	1.81a	2.62b	1.57a	*0.002*	2.10a	2.62a	1.29b	*<0.001*	1.57a	2.52b	1.91a	*0.007*
Fat	1.57a	2.52b	1.91a	*0.007*	1.33b	2.71a	1.95b	*<0.001*	2.24	2.05	1.71	*0.229*	2.00	1.95	2.05	*0.953*

Abbreviations: CMP = Commercial Meat Products, HMP = Homemade Meat Products, PBMA = Plant-based Meat Alternatives.

Mean values within a column with unlike superscript letters were significantly different (P<0.05)

d Friedman's Two-way ANOVA were used.

(1- Most tasty/salty/fatty, 2 – moderately tasty/salty/fatty, 3 – least tasty/salty/fatty; 1- most appealing colour/texture, 2 – moderately appealing colour/texture, 3- least appealing colour/texture

Predictors Of PBMAs Purchase And Replacement Intent

From Table 3, male gender (OR 4.25, P=0.015), obese BMI classification (OR 6.67, P=0.034), a positive perception towards healthy eating (OR 5.08, P=0.007) and the perception that PBMAs are healthier than meat products (OR 2.65, P=0.018) are significant predictors of the likelihood to purchase PBMAs. The likelihood to replace existing meat consumption with PBMAs are significantly determined by age range of 31-40 years (OR 14.0, P=0.021), male gender (OR 3.60, P=0.029), a positive perception towards healthy eating (OR 3.24, P=0.046) and the perception that PBMAs are healthier than meat products (OR 2.49, P=0.022).

ensory Evaluation

Table 4 shows the participants' sensory perceptions between plant-based meat alternatives (PBMA), commercial meat products (CBP) and homemade meat products (HMP). For nuggets, significant differences were observed across all sensory attributes (P<0.05). PBMA nuggets were the least preferred in terms of taste compared to CMP and HMP nuggets (P<0.001). Texture preferences for PBMA and HMP nuggets were similar, but both were found to be less appealing than CMP nuggets (P=0.028). In terms of colour, HMP nuggets have the most appealing colour, followed by CMP and PBMA nuggets (P<0.001). Significant differences in saltiness were noted, with HMP nugget perceived as the least salty compared to the CMP and PBMA nuggets (P<0.001). CMP nuggets were considered the fattiest, followed by PBMA and HMP nuggets (P=0.007).

For fish fingers, no significant differences were found in perceived taste and texture. However, significant differences were noted for colour (P=0.006), saltiness (P=0.002) and fat content (P<0.001). PBMA fingers were rated the lowest for colour, homemade fish fingers rated the lowest for saltiness and fattiness. In the minced meat category, PBMA was perceived as the saltiest compared to CMP and HMP (P<0.001). For beef patty, CMP and PBMA were perceived as saltier than HMP (P=0.007).

DISCUSSION

The findings of this study provide valuable insights into the nutritional quality, perceptions, and sensory evaluation of plant-based meat alternatives (PBMAs) compared to conventional meat products and homemade meat equivalents. Our results indicate that while PBMAs offer a viable alternative to meat products, there are significant differences in their nutritional profiles and sensory attributes that warrant consideration.

Our study revealed that while PBMAs contained the highest fibre content, they had lower protein content compared to homemade meat products. Additionally, the highest levels of saturated fat and sodium were found in plant-based sausages and commercial meat products such as sausages and patties. These findings are consistent with existing literature. Firstly, PBMAs have been reported to have higher fibre and sodium content compared to meat products 26. Secondly, both PBMAs and commercial meat products are generally associated with higher saturated fat and sodium content due to their ultra-processed nature 11,27. Lastly, in line with our study, PBMAs have generally been shown to have a lower protein content 28. In contrast, homemade meat products contained the highest protein levels but the lowest sodium and saturated fat content.

Nutritionally, reducing the consumption of red and processed meat and partially replacing it with PBMAs has been shown to improve the intake of unsaturated fatty acids and dietary fibre 29,30. Generally, PBMA products contain fewer calories, less total and saturated fat, and more dietary fibre than their meat counterparts 16. However, the production PBMAs often results in products with high levels of sodium, sugar, saturated fat, and added flavourings and additives 11. Additionally, PBMAs may lack essential micronutrients like iron, zinc, and vitamin B_{12}12. PBMA products with low nutritional quality and elevated sodium levels poses health risks such as chronic kidney disease 31.

Iron, zinc, and vitamin B_{12} are challenging to obtain in a meat-free diet, and their bioavailability in meat substitutes can be limited by factors like phytate content 32. Vitamin B_{12}, which is absent in plants, presents an additional challenge, potentially causing deficiencies, especially among vegetarians, vegans, pregnant women, or females in their reproductive years 33. Reducing sodium content through natural seasonings, improved processing techniques, fortifying PBMAs, and advocating for nutrient-rich plant foods can mitigate these challenges 28,34. Therefore, there is a critical need for education and guidelines centred on plant-based nutrition and fortification strategies to enhance the nutritional profile of PBMAs, positioning them as part of a healthy and sustainable diet.

The knowledge, attitudes, and behaviours (KAB) survey indicated that while there is a growing interest in PBMAs, several misconceptions persist among consumers. A significant proportion of respondents did not consider PBMAs to be ultra-processed and were ambivalent about the health benefits of PBMAs. These findings could be attributed to the lack of familiarity and knowledge deficit regarding PBMAs and highlight the need for better consumer education on the nutritional quality of PBMAs. Our study identified several demographic and attitudinal factors that significantly predict the likelihood of purchasing PBMAs and replacing meat products with them. The key predictors of PBMA purchase included male gender, an obese body mass index, positive attitudes towards healthy eating, and regular PBMA consumption. Interestingly, previous studies have reported a higher propensity for females to buy PBMAs, with some even identifying no significant gender differences 23,35,36. Although the relationship between males and the increased likelihood of purchasing PBMAs is not well-explored in previous research, several suggested reasons for this finding could be attributed to the rise in number of males expressing personal health and environmental goals - goals that could potentially be attained by decreasing red meat consumption or increasing PBMAs intake 37. Our findings showed that an obese BMI classification is a predictor of PBMAs' purchase intent. This aligns with a recent study, which found that a higher BMI status was associated with a higher purchase intent for beef patties 38. However, this correlation was not observed for plant-based patties. Moreover, the current literature is limited regarding the correlation between BMI classifications and the purchase intent of PBMAs, indicating a need for further studies to better establish this relationship.

Our findings also suggest that positive attitudes towards healthy eating influence the decision to purchase PBMAs, likely due to the perceived health benefits of plant-based diets 39. However, positive attitudes toward healthy eating do not necessarily correlate with PBMA purchase intent, possibly due to the perceived overly-processed nature of PBMAs 40,41. Additionally, consumers have limited access to reliable scientific publications or the ability to evaluate robust scientific data 11. Knowledge of PBMAs depends on claims made by manufacturers and internet searches, which generally do not provide clear, validated evidence for specific features. Therefore, there is a need to inform consumers about the nutritional quality of PBMAs to enable them to make informed purchasing decisions.

The intent to replace meat consumption with PBMAs is primarily driven by individuals aged 31-40 years and those with a positive perception towards PBMAs. Studies on factors affecting PBMA replacement intent are rarely examined 42. Nonetheless, our results provide more insights into the habits of those replacing meat with PBMAs, thereby contributing to the current literature. Despite these predictors, consumers' food decisions are influenced by a multitude of other factors 11,43,44. Although our findings showed that only a small number of participants consume PBMAs regularly, this is consistent with other studies 45. The top facilitators for these individuals were animal welfare and health reasons. For the majority, costs, taste preferences, and the perception that PBMAs as overly processed were the key barriers to consumption. These results align with many existing studies, reiterating that animal welfare and health reasons are enablers to

purchasing and replacing meat with PBMAs, while price, taste, and perceived unnaturalness are common barriers 27,44,46. Additionally, individuals with strong attachments to meat and habitual meat intake are reported to be less likely to purchase and regularly replace meat with PBMAs 36,46.

The study found that plant-based meat alternatives (PBMAs) were generally less preferred compared to commercial meat products (CMP) and homemade meat products (HMP) across various sensory parameters. Specifically, PBMA nuggets were rated lower for taste and texture while PBMA fish fingers were less favoured in terms of colour. In the minced meat category, PBMAs were perceived as the saltiest. The overall appearance of a product is important for priming consumers and developing expectations prior to consumption 17. Disconfirmation of expectations occurs when the perceived liking after consumption is below the expected liking, which may happen when the visual cues misrepresent the taste, odour, and flavour of the product 17. One processing limitation of using plant proteins is that the colour of PBMAs may fade when exposed to light or oxygen, leading to an unappetizing product 47, as observed with nuggets and fish fingers in our study. Certain ingredients can affect the colour and appearance of PBMAs. For example, changing the ratio of chickpea flour to texturized vegetable protein in meatless nuggets improved colour and appearance scores 48. However, the presence of carotenoids in chickpea flour contributed to a yellow colour, which was unappealing to the participants. In our study, homemade nuggets had the most appealing colour, followed by commercial and PBMA nuggets. This suggests that the colour profile can be optimized in homemade nuggets, especially when using healthy ingredients (lean chicken, chopped vegetables) and healthy cooking methods (air-frying, grilling).

Saltiness is a marker of sodium content in the product. Our results showed that PBMA minced meat and beef patties were perceived as the saltiest compared to commercial and homemade meat products. This aligns with findings from a study comparing PBMA beef patties to their meat equivalent, which showed that maintaining a high sodium level in PBMAs is important for consumer acceptance in terms of flavour 49. In contrast, homemade nuggets were perceived as the least salty, indicating that commercial products are usually formulated with high sodium levels to enhance flavour, which in turn lowers the nutritional quality of the final product.

Another challenge for PBMAs is recreating the unique texture, mouthfeel, and juiciness of traditional meat products 50. In our study, the texture of commercial nuggets was more appealing than that of PBMA and homemade nuggets, suggesting consumer familiarity with the texture of commercial nuggets, which are high in saturated fat and sodium. These heterogenous findings highlight the sensory challenges PBMAs face in gaining consumer acceptance compared to traditional meat products. While PBMAs show potential, particularly in texture for certain products, they need improvement in taste, texture and colour profiles. Addressing these sensory attributes, in addition to the nutritional quality, could enhance the appeal of PBMAs and support their adoption as viable alternatives to conventional meat products.

The strength of our study lies in its comprehensive assessment of the nutritional quality of PBMAs in Singapore. Additionally, our findings provide valuable insights into consumers' perception of PBMAs, examining their knowledge, attitudes, & behaviours through sensory profiling. However, the demographics in this study was not representative of the Singapore population. Our participants were mostly of Chinese ethnicity and from a younger age group, which may have limited purchasing ability. Future studies should consider using a larger sample size, a wider age group and including other ethnicities to explore potential differences with respect to ethnicities, age groups and socio-economic stratifications.

CONCLUSIONS

The variety of novel protein alternatives on the market is increasing, with many new product innovations potentially prompting consumers to change their dietary habits. Plant-based meat alternatives (PBMAs) may replace and complement meat- and animal-derived products in the human diet, potentially reducing the environmental impact of food consumption.

Our results suggest differences in the nutritional quality of PBMAs compared to their meat counterparts. Homemade meats have better nutritional quality compared to PBMAs and commercial meat products. However, it is important to highlight that the nutritional quality of foods still depends on the ingredients used during the preparation and cooking. Additionally, the nutritional advantages of plant-based diets cannot be directly extrapolated to diets that include PBMA. Although completely substituting meat with PBMAs does not necessarily equate to an improved or healthier diet, partially replacing meat or including PBMAs in one's diet is unlikely to result in adverse nutritional status.

The increasing popularity of PBMAs presents both opportunities and challenges for public health nutrition and dietetics practice. The knowledge, attitudes, and behaviors (KAB) survey indicated that while there is a growing interest in PBMAs, several misconceptions persist among consumers. A significant proportion of respondents did not consider PBMAs to be ultra-processed and were ambivalent about the health benefits of PBMAs. These findings highlight the need for improved consumer education regarding the nutritional quality and health benefits of PBMAs. Dietitians and nutritionists can play a pivotal role in dispelling misconceptions and promoting informed food choices. As the PBMA market continues to grow and evolve, valuable insights from this study can be channeled towards nutrition education and the development of evidence-based guidelines for PBMAs to allow the public to make better-informed food choices.

In conclusion, our study highlights the importance of considering both nutritional quality and consumer perceptions when evaluating PBMAs as substitutes for meat. By addressing the identified nutritional challenges and improving consumer education, PBMAs have the potential to significantly contribute healthier and more sustainable dietary patterns.

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