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MAIN QUALITY PARAMETERS AND DIFFERENT FATS INCORPORATION IN COMMERCIAL PLANT-BASED MEAT ANALOGUES (PBMA): MAPPING THE PATH FOR PBMA FORMULATIONS

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ABSTRACT

Despite extensive efforts on the research of plant-based meat analogues (PBMA), little has been reported on the study of the incorporation of oils and fats, especially concerning the potential of palm oil in the plant-based meat industry. This study analysed the physicochemical properties and quality parameters of 17 commercially available PBMA, including nuggets, sausages, meatballs and mock meats. Analysis showed that mycoprotein-based nuggets had greatest texture hardness, while sausages fortified with konjac powder and mushrooms had the best cooking yield and moisture retention. Fat content was key to desired mouthfeel, with PBMA needing 8%-20% total fat (about 6% saturated fat), to optimise the texture. The other ideal ranges for main ingredients were 50%-70% water, protein content of 10%-30% (up to 39% for mycoprotein) and 50%-60% of mushroom for mushroom-based products. Correlation analysis demonstrated strong positive correlations for springiness, resilience and cohesiveness. Sausages and mock meats were tightly clustered, but nugget products showed more variability. Palm oil proved its worth as a versatile ingredient, doing well in a wide variety of product types and combinations. These findings provided the fundamental physicochemical parameters for the future formulation of PBMA products.

Keywords: meat substitutes, physicochemical properties, sustainable palm oil, vegan, vegetarian.

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INTRODUCTION

According to the projection of the United Nations (UN), the global population is estimated to reach 8.5 billion by 2030 and 9.8 billion by 2050 (United Nations, 2019). Therefore, there is a need for a substantial increase in food production. This rise in demand is accompanied by a shift towards plant-based (PB) alternatives, driven by concerns on environmental impact, animal welfare and health associated with conventional meat production (Ahmad *et al.*, 2022; Singh *et al.*, 2021). Plant-based meat analogues (PBMA) such as nuggets, meatballs, sausages and mock meat analogues mimicking chicken and beef, have emerged as viable substitutes for traditional meat products. PBMA are typically made from plant protein sources such as soy, wheat and pea. These analogues are processed to replicate the taste and texture of real meat, thus meeting consumer expectations while addressing sustainability concerns (Andreani *et al.*, 2023; Kyriakopoulou *et al.*, 2019).

In Asia, the market for PBMA is witnessing significant growth, with products serving as PB alternatives and essential proteins in the diet being introduced (Andreani *et al.*, 2023). While manufacturers commonly utilise ingredients such as pulse proteins, gluten and oilseed proteins to develop a range of PBMA products tailored to local tastes and preferences (Jahn *et al.*, 2021), incorporating palm oil could further enhance the sensory and nutritional qualities of these alternatives. Notably, PB alternatives, including those incorporating palm oil, often boast a favourable nutritional profile compared to animal-based processed meats, typically offering lower levels of total and saturated fats, less to zero *trans* fats and increased fibre content.

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The high solid fat content of palm oil fractions presents a promising opportunity for PBMA formulation. Its unique composition can contribute to a firmer texture and improved stability, essential characteristics for mimicking the texture of traditional meat products (Dian *et al.*, 2017). Furthermore, the utilisation of palm oil fractions is further enhanced by its abundance of tocotrienols, which may provide antioxidant benefits (Parveez *et al.*, 2024; Zainal *et al.*, 2022). Although these properties are advantageous, there is currently a scarcity of research on PBMA that incorporates palm oil, as other vegetable oils are frequently prioritised in current formulations (Singh *et al.*, 2021). Therefore, there is limited data available on PBMA made with the addition of palm oil, with other vegetable oils being more commonly used in their production. Hence, this study sought to analyse the composition and characteristics of commercial PBMA products in the local market to address the knowledge gap on underutilised PBMA, in order to guide future research and development of PBMA products.

MATERIALS AND METHODS

Materials

Seventeen commercially available PBMA samples were purchased from hypermarkets and vegetarian retailers (Kuala Lumpur & Selangor, Malaysia). The samples were stored at -20°C until analysis. Commercial PBMA samples (A-Q) were classified by diet (vegan and vegetarian) and oil/fat type (palm oil, palm fat, vegetable oils), as shown in *Figure 1*.

Product Assessment

The commercial PBMA samples' packaging label assessment was carried out by tabulating and evaluating the nutritional composition and details of ingredients used in the product formulations (per 100 g of each product respectively).

Cooking Loss

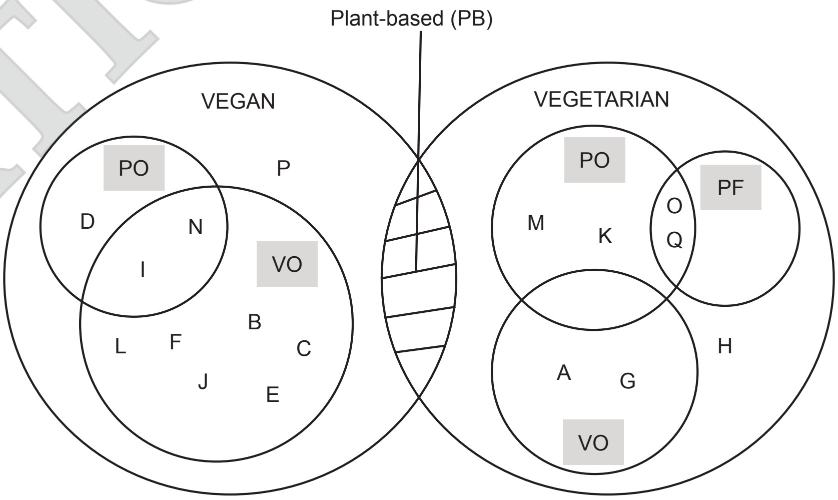
Cooking loss, the shrinkage of commercial PBMA samples during cooking, is a key indicator of meat analogue quality, particularly juiciness and yield. High cooking loss suggests product dryness and flavour concerns (McClements *et al.*, 2021). The percentage of cooking loss (%) of commercial PBMA samples was determined by calculating the percentage weight (g) difference of the commercial PBMA samples before (M_B) and after cooking (M_A) and multiplying the result by 100, using the following Equation (1).

$$\text{Cooking loss (\%)} = \frac{(M_B - M_A)}{M_B} \times 100 \quad (1)$$

Standardised cooking procedures were used. PBMA samples were cooled at room temperature for 30 min before analysis. Each sample was measured three times to ensure accuracy.

Cooking Yield

Cooking yield is a key parameter for assessing cooking efficiency, portion sizes and product characteristics including texture and moisture



Notes: A-E - PB nuggets; F-H - PB sausages; I-L - PB meatballs; M-Q - mock meats; PO - palm oil; VO - vegetable oils; PF - palm fat.

Figure 1. Classification of commercial PBMA based on dietary preferences and oil or fat compositions.

content. Manufacturers can use this information to optimise formulations and enhance product quality by adjusting ingredients or processing conditions based on the desired cooking yield. The percentage of cooking yield (%) of commercial PBMA samples was defined as the percentage of the original weight of the samples that was retained after cooking. It was calculated by dividing the weight of the cooked PBMA (M_A, after cooking) samples by the weight of the raw PBMA (M_B, before cooking) samples and multiplying the result by 100, using the following Equation (2) (Yadav *et al.*, 2016).

$$Cooking\ yield\ (\%) = \frac{M_A}{M_B} \times 100 \quad (2)$$

Standardised cooking procedures were followed, with each sample measured in triplicate to ensure accuracy.

Moisture, Water Activity, pH and Colour

The moisture content of commercial PBMA samples was determined gravimetrically by drying 2 g of the sample in a universal oven UFB 500 (Memmert, Schwabach, Germany) at 100°C-105°C until constant weight was achieved, typically after 4 hr. The water activity (a_w) was measured using a water activity meter (Novasina AG, Lachen, Switzerland) by levelling the sample prior to determination. Measuring water activity in commercial PBMA samples is crucial for assessing microbial safety. A total of 1 g of homogenised PBMA was mixed with 10 mL distilled water, vortexed for 1 min, allowed to settle for 5 min and then measured using a calibrated Testo206 digital pH meter (Testo AG, Lachen, Switzerland). The colour parameters, including L* (lightness), a* (red/green coordinate) and b* (yellow/blue coordinate), were recorded for the raw and cooked commercial PBMA samples using a chromameter CR-400 (Konica Minolta Sensing, Tokyo, Japan). The equipment was calibrated with a standard white calibration plate (Y = 93.5, X = 0.3132, y = 0.3198) to ensure accurate readings.

Texture Profile Analysis (TPA)

TPA was conducted on the commercial PBMA samples after removing any coatings and standardising the size of the PBMA samples within each batch. A texture analyser model TA.XTplus (Stable Microsystems, United Kingdom) was used to evaluate the commercial PBMA samples using a modified TPA method adapted from Echeverria *et al.* (2022). The samples were compressed twice to 50% original height at 2 mm s^{-1} crosshead speed with a P75 probe. Six replicate measurements per sample were recorded, yielding data on hardness, adhesiveness, cohesiveness, springiness, gumminess and chewiness to characterise the textural attributes.

Fatty Acid Composition (FAC)

FAC of commercial PBMA samples was determined as fatty acid methyl esters (FAME). Samples (0.05 g) were dissolved in 1 mL hexane, followed by 0.2 mL sodium methoxide (2 M) in anhydrous methanol. The mixture was vortexed for 1 min to facilitate transesterification. After sodium glycerolate sedimentation, 1 µL of clear supernatant was injected into an RTX 2330 fused silica capillary column (60 m × 0.25 mm × 0.25 µm) and analysed using a Bruker Gas Chromatography System Model 430-GC with FID and Galaxie Chromatography Data System. The injection and detection temperatures were 240°C, while the column was isothermal at 185°C. Helium was the carrier gas (1 mL min^{-1}). Peak identification was done by comparing the sample tested to the FAMEs standard, and the fatty acid profile was expressed as a percentage using area normalisation as in Equation (3):

$$FAC\ (\%) = \frac{Individual\ FAME\ area}{Total\ area} \times 100 \quad (3)$$

Statistical Analyses

All results were evaluated using one-way analysis of variance (ANOVA). The mean differences between groups were assessed using Tukey's post hoc test operating at a 5% level of significance ($p<0.05$). All statistical analyses were performed using the Minitab 21 statistical software (Minitab Inc., State College, PA, USA).

RESULTS AND DISCUSSION

Product Assessment Based on Label

The data presented in *Table 1* offer valuable insights into the source country and oils/fats composition of commercial PBMA products, thus providing an overview of their nutritional composition. Complementing this information, *Table 2* presents a detailed list of ingredients used in the formulation of the commercial PBMA products analysed in the current study. In general, vegan PBMA samples contain no animal-derived ingredients, while vegetarian PBMA samples may include animal-derived ingredients like eggs or dairy, but no meat. As shown in *Table 1* and 2, the trend observed in Malaysia highlights a notable prevalence of commercial vegan PBMA products over vegetarian alternatives, with soy protein (SP), in its various forms, such as isolate and textured, emerging as the primary protein source in PBMA formulations (Boukid, 2021). Despite the significance of SP, a gap in the utilisation of palm-based ingredients is evident, with the components varying from 2.2%-24.6% (total fat) across product categories. Palm oil, palm fats and blends are used in several PBMA products, but only seven out of 17 items directly incorporate them, indicating valuable prospects for further study and integration. Specifically, among vegan PBMA products, palm oil is utilised in various forms, including palm oil, palm fats and blends with other oils. These palm-based ingredients are primarily found in nuggets, meatballs and mock meats, highlighting their versatility in different product categories. In contrast, vegetarian PBMA products predominantly rely on other vegetable oils, such as sunflower, rapeseed and soybean with limited incorporation of palm-based ingredients. The study suggests that vegan PBMA manufacturers use palm oil more frequently than vegetarian ones.

Physicochemical Properties

Cooking loss, cooking yield, moisture, water activity, pH. *Figure 2* illustrates variations in cooking loss, cooking yield percentage, moisture content, water activity and pH among PBMA. Mock meats (samples M-Q) had the highest cooking loss (with Sample O showing approximately 27.29% and Sample P showing approximately 24.42%), followed by sausages (particularly Sample F at approximately 19.62%). Nuggets showed variable cooking losses, with some samples (B, C) having moderate losses around 16.31%-18.90%, while others (A, D and E) showed considerably lower losses (6.04%-10.46%). Meatballs generally demonstrated the lowest average value of cooking losses among the categories (5.00%-11.00%). These differences likely stem from variations in the composition and structure of the different PBMA types. Nuggets exhibited high cooking yield, with most samples (A-E) showing values above 80.00%. Sausages showed more variation, with Sample F having the lowest cooking yield among sausage samples, while Samples G and H exhibited significantly higher retention. Meatballs demonstrated consistently high cooking yield (Samples J and K), while Sample I had a slightly lower yield. Mock meats (M-Q) displayed a wider range, with Sample O having the lowest cooking yield, whereas Sample N achieved one of the highest values. The lower cooking loss and higher cooking yield in sausages may be attributed to dietary fibres from ingredients such as konjac powder and mushrooms, which improve water absorption, pH and lipid stability, enhancing emulsion stability (Mazumder *et al.*, 2023). The selection of oils and fats in PBMA formulations significantly impacts these properties. Overall, PBMA samples with palm oil and palm oil blends (Samples D, I and N) exhibited lower cooking loss and higher cooking yield among vegan options, suggesting better moisture retention and product integrity during cooking.

As shown *in Figure 2*e, the water activity (a_w) of PBMA ranged from 0.55-0.96. This indicates comparable susceptibility to microbial spoilage for both plant-based product types. Higher a_w values (above 0.6) increase spoilage risk, as they support the growth of various microorganisms. Bacteria typically require a_w >0.91, yeasts >0.88, and some moulds as low as 0.70 (Kabisch *et al.*, 2024). Consequently, higher a_w PBMA necessitate additional preservation methods like refrigeration to maintain shelf stability and safety.

Commercial PBMA exhibited pH values ranging from 6.09-7.59. This pH diversity likely stemmed from varied protein sources (*e.g.,* soy and mycoprotein) and additives. Notably, the oils and fats used in PBMA formulations, such as sunflower, rapeseed, and palm oils, generally had a neutral pH and exerted minimal direct impact on the product's overall pH. However, these lipids could indirectly influence pH stability and perception through their interactions with other ingredients. For instance, lipid oxidation products might have slightly lower pH over time, while fats could encapsulate acid-producing compounds, potentially buffering pH changes. Additionally, the emulsification of oils with proteins and stabilisers affected the distribution of charged molecules, subtly influencing the pH of the product. The type and quantity of oils used also impact the efficacy of pH-dependent additives and the overall protein functionality in the matrices (Kyriakopoulou *et al.*, 2021).

Colour. The colour analysis results in *Figure 3* show the variations in colour parameters (L*, a*, b*) between raw and cooked commercial PBMA samples across different categories and between raw and cooked states. These colour attributes are crucial for consumer acceptance and can be correlated with the diverse ingredients used in PBMA formulations. Raw PBMA exhibited a wide range of lightness (L* ~40-80), with nuggets generally being lighter. This variation likely stemmed from the different protein sources used, with soy-based products (*e.g.*, B, D, G) being lighter and those with vegetable blends or mycoprotein (*e.g.*, A, C) showing intermediate lightness. Cooking decreases L* values, indicating

TABLE 1. NUTRITIONAL COMPOSITION OF COMMERCIAL PLANT-BASED MEAT ANALOGUES

Samples	Nuggets					Sausages		
	A	B	C	D	E	F	G	H
Category	Vegetarian	Vegan	Vegan	Vegan	Vegan	Vegan	Vegetarian	Vegetarian
Source country	United States	Malaysia	South Africa	Singapore	Malaysia	Malaysia	Malaysia	Malaysia
Oils/Fats composition	Sunflower and rapeseed	Rapeseed	Sunflower	Palm	Soybean	Soybean	Soybean	-
Nutritional labelling								
Protein	9.4 g	11.80 g	10.5 g	12.50 g	14.3 g	15.8 g	7.7 g	21.6 g
Total fat	8.3 g	11.80 g	10.9 g	11.40 g	12.3 g	2.5 g	19.7 g	20.7 g
Saturated		0.80 g	1.3 g	3.80 g	9.6 g	0.65 g	0 g	
Monounsaturated	-	6.70 g	3.2 g	-	2.7 g	-	-	-
Polyunsaturated	-	2.70 g	5.8 g	-	0 g	-	-	-
Trans fat	-	0.10 g	-	0 g	0 g	0.0 g	-	-
Cholesterol	-	0.30 mg	-	0 mg	0 mg	0 mg	0.0 mg	-
Sodium	9.4 g	394 mg	735 mg	563 mg	80 mg	403.32 mg	61.3 mg	-
Total carbohydrate	17.0g	14.80 g	15.7 g	11.20 g	14.2 g	13.35 g	18.3 g	40 g
Dietary fibre	4.5 g	4.00 g	5.0 g	1.60 g	1.2 g	3.37 g	1.0 g	-
Sugar	0.6 g	1.00 g	-	0.90 g	2.7 g	0 g	4.9 g	-

Samples	Meatballs				Mock meats				
	I	J	K	L	M	N	O	P	Q
Category	Vegan	Vegan	Vegetarian	Vegan	Vegetarian	Vegan	Vegetarian	Vegan	Vegetarian
Source country	Malaysia	South Africa	Malaysia	Malaysia	Malaysia	Malaysia	Malaysia	Malaysia	Malaysia
Oils/Fats composition	Palm and canola	Sunflower	Palm	Coconut	Palm	Palm and sesame	Palm and palm fat	-	Palm and palm fat
Nutritional labelling									
Protein	17.3 g	7.7 g	21.6 g	11.5 g	13.0 g	15.0 g	17.3 g	15.8 g	17.5 g
Total fat	20.5 g	19.7 g	20.7 g	8.0 g	2.2 g	13.0 g	10.1 g	24.6 g	18.7 g
Saturated	2.1 g	0 g		6.0 g	1.0 g	5.8 g	5.2 g	14.0 g	9.9 g
Monounsaturated	12.8 g	-	-	1.9 g	-	-	-		
Polyunsaturated	5.6 g	-	-	0.1 g	-	-	-		
Trans fat	0 g	-	-	0 g	-	0 g	0.0 g	0 g	
Cholesterol	0 mg	0.0 mg	-	20 mg	0.0 mg	0 mg	0 mg	0 mg	0.0 mg
Sodium	260 mg	61.3 mg	-	576 mg	755.0 mg		545 mg	773.7 mg	967.8 mg
Total carbohydrate	7.5 g	18.3 g	40 g	7.5 g	15.2 g	22.0 g	6.9 g	24.6 g	6.7 g
Dietary fibre	8.4 g	1.0 g	-	3.3 g	3.5 g	-	4.5 g	15.8 g	3.5 g
Sugar	5.6 g	4.9 g	-	3.4 g	2.6 g	-	2.9 g	1.8 g	2.4 g

Note: A-E - PB nuggets; F-H - PB sausages; I-L - PB meatballs; M-Q - mock meats. In oils/fats composition, all are oils unless mentioned as fats.

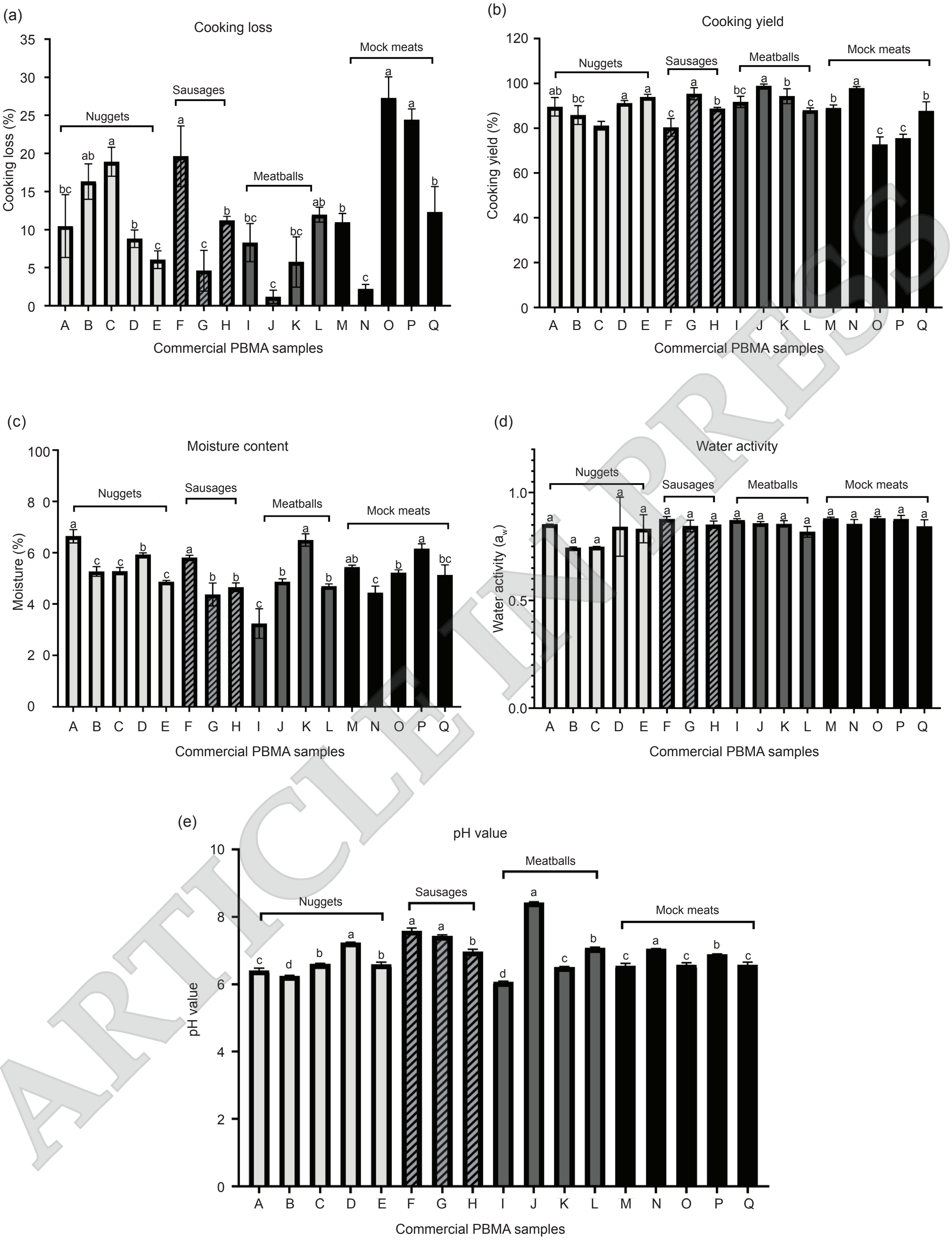
TABLE 2. LIST OF INGREDIENTS USED IN THE COMMERCIAL PLANT-BASED MEAT ANALOGUES

Products	Ingredients
Nuggets	
A	Mycoprotein (39%), water, rehydrated egg white, wheat flour, sunflower and rapeseed oils, salt, maize flour, starch, milk proteins, textured wheat protein (TWP), natural flavouring, tetrasodium diphosphate, sodium carbonate, pea fibre, calcium chloride, calcium acetate, wheat gluten, pectin, dextrose.
B	Soy protein (SP) 14.8%, crumbs, rapeseed oil, wheat flour (3.2%), starch, flavouring, vinegar, methyl cellulose, citrus fibre, salt, onion, garlic, guar gum.
C	Vegetable protein (11%), wheat flour, flavourings, maize starch, yeast, plant fibre, methyl cellulose, salt, herbs, mustard seeds, E551, garlic, wheat flour, vitamin C, sunflower seed oil.
D	Water, textured soy protein (TSP), palm oil, wheat flour, starch, rice flour, baking powder, sunflower oil, isolated soy protein (ISP), flavouring, sugar, salt, transglutaminase, yeast, L-alanine, salt, disodium succinate, E631, E627.
E	Tofu skin (54%), wheat flour, tapioca starch, soybean oil, yeast extract, spices (2%), salt, sugar, INS 500ii, flavouring, INS 160 ai.
Sausages	
F	ISP, soybean oil, water, salt, sugar, black pepper, and vegetarian meat seasoning.
G	SP, whey protein, ISP, soybean oil, water, soy sauce, salt, sugar, vegetarian bbq flavouring, E160a, yeast extract, water.
H	SP, ISP, barley cereals, konjac, starch, sugar, salt, albumens, vegetarian seasoning, spices.
Meatballs	
I	SP, water, palm and canola oils, wheat gluten, onion, methylcellulose, yeast extract, pepper, soybean sauce, flavouring, INS 150c, INS 330, INS331.
J	SP, sunflower seed oil, wheat flour, spices (contains sulphites), starches, flavourings, cellulose extract, salt, chillies, wheat fibre, mustard, caramel iv, garlic.
K	TSP (21%), shredded mushroom (6%), konjac powder, gluten, palm oil, modified starches, sugar, salt, white pepper, MSG.
L	Mushroom (64.9%), coconut oil, ISP, modified starch (INS1420), sugar, light soy sauce, salt, yeast, spices.
Mock meats	
M	Mushroom stem (53%), ISP (24%), palm oil (9%), albumen, starch, sugar, MSG, gluten, salt, sodium alginate, guar gum, sodium carboxymethyl cellulose, xanthan gum, polyglycerol polyricinoleate (PGPR, E476).
N	TSP, TWP, TSP, mushroom stem, salt, palm oil, sesame oil.
O	Hydrated TSP protein (75%), ISP, vegetable emulsion (21%) (water, palm oil), emulsified fat (water, RBD and hydrogenated RBD palm stearin, PGPR, sugar), albumen, MSG, salt.
P	ISP, modified starch, SP, vegetarian seasoning and spices, and ginger powder.
Q	Hydrated TSP (64%), ISP, vegetable emulsion (24%), emulsified fat (water, RBD and hydrogenated RBD palm stearin, PGPR, sugar), MSG, sugar, albumen, salt, spices, disodium 5′-inosinate, disodium 5′-guanylate, calcium phosphates, acesulfame potassium, disodium 5′-ribonucleotides, malic acid, processed seaweed.

Note: A-E - PB nuggets; F-H - PB sausages, I-L - PB meatballs; M-Q - mock meats; RBD - refined, bleached and deodorised.

darkening, likely due to Maillard reactions between reducing sugars and amino acids, similar to what occurs in animal-based meats (Lund *et al.*, 2011). Raw PBMA showed varying redness, with sausage analogues (H) having higher a* values. This could be attributed to colourants or natural ingredients like red beet powder (in H). Interestingly, cooking increases a* values for most products, possibly due to the formation of red-brown pigments during Maillard reactions. The extent of this increase varies, which may relate to the type and amount of reducing sugars and proteins in each formulation. The yellowness of raw PBMA varied considerably, with nugget products (B and E) showing high b* values. This could be due to the ingredients like turmeric, carotenoids or other yellow-hued additives (Ryu *et al.*, 2023). Cooking generally increases b* values, likely due to the formation of yellow-brown pigments during Maillard reactions and caramelisation of sugars.

The colour changes observed during cooking are influenced by the interactions between proteins, carbohydrates and fats in the PBMA matrix. For example, products with higher polyunsaturated oil content (*e.g.*, those using sunflower or rapeseed oils) may develop browning more quickly due to the higher oxidation rate of polyunsaturated fats during thermal processing (cooking). Additionally, the presence of antioxidants (like those naturally occurring in some vegetable proteins) could affect the rate and extent of browning reactions. It is noteworthy that while PBMA attempts to mimic the colour changes of animal-based meats during cooking, observable differences remain. This is likely due to the inherent differences in the chemical composition of PB ingredients compared to animal tissues.



Note: A-E - PB nuggets; F-H - PB sausages; I-L - PB meatballs; M-Q - mock meats. Samples with different superscripts across similar product categories are significantly different (p<0.05).

Figure 2. (a) Cooking loss, (b) cooking yield, (c) moisture content, (d) water activity and (e) pH of commercial plant-based meat analogues.

For instance, the lack of myoglobin in PBMA means that the characteristic colour changes associated with meat cooking (from red to brown) must be achieved through other means, such as carefully balanced formulations of proteins, sugars and additives.

The use of different vegetable oils in PBMA affected colour analysis, especially L* and b* values. In nuggets, Sample D (palm oil) had a higher L* value compared to Samples A, B, C and E, which used sunflower and rapeseed oils, suggesting that palm oil contributed to a lighter colour. In meatballs, Sample I (palm and canola oil blend) had a lower L* value than Samples J and L (sunflower and coconut oil), indicating the blend might result in a darker colour. The b* value varied depending on the vegetable oil used. In sausages, Sample F with soybean oil had a lower b* value than Sample G, which used soybean oil with whey protein and other ingredients, suggesting that additional components could influence yellowness. *Figure 3* does not conclusively show that PBMA with palm oil consistently resulted in superior colour attributes. While palm oil might contribute to lighter colour in nuggets and darker colour in meatballs, its impact on redness (a*) and yellowness (b*) varied depending on the product category. In mock meats, Samples N and Q (palm-based), exhibited variations in a* and b* values, indicating that palm oil alone did not determine these colour attributes.

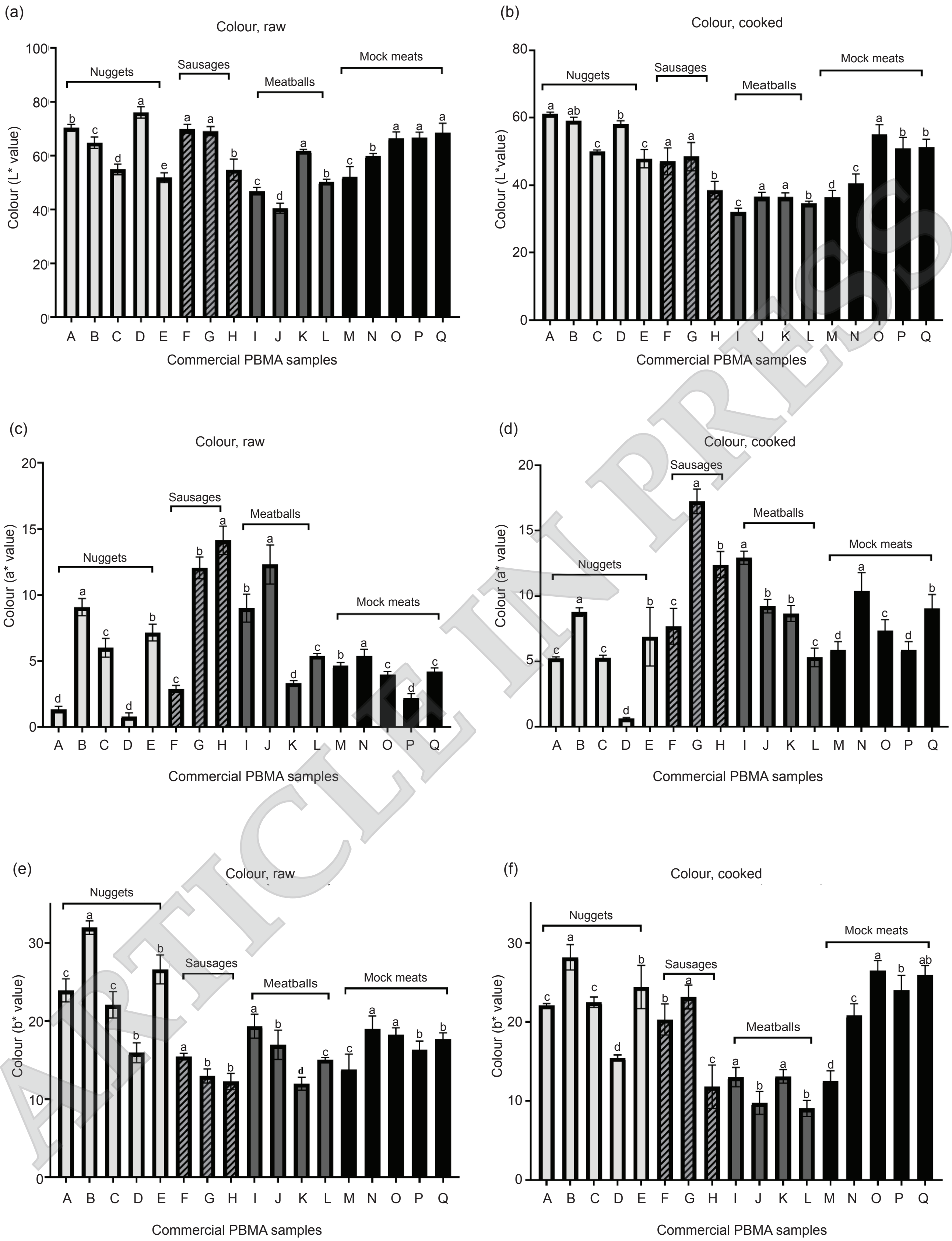
Texture analysis. Results of the texture analysis in *Figure 4* show significant variations in hardness and chewiness among commercial PBMA samples across different product categories. These textural attributes are critical for consumer acceptance and can be linked to the interaction of multiple major ingredients used in PBMA formulations, such as proteins, oils and fats, emulsifiers and starches. Nuggets demonstrated a wide range of hardness (2,047-13,410 g) and chewiness (553-4,334), with those primarily made from textured soy protein (TSP) showing considerable variation. Interestingly, the mycoprotein-based nugget (Sample A) exhibited the highest value of hardness (13,410 g), suggesting that mycoprotein could have contributed to a firmer texture compared to other protein sources in PB nuggets formulations (Finnigan *et al.*, 2017). Sausages, mainly composed of isolated soy protein (ISP), displayed softer textures than other types of PBMA with hardness ranging from 4,932-8,352 g and chewiness from 1,402-8,754. This softer profile could be attributed to the functional properties of ISP and its interaction with other ingredients in the sausage matrix. Meatballs exhibited the range of hardness (1,891-6,060 g) and chewiness (405-2,956), likely due to the diverse protein sources used, including TSP for plant-based options and beef for the meat-based variant. Mock meats, primarily utilising TSP and ISP, demonstrated the firmest textures specifically in Samples M and N, with hardness ranging from 9,338-10,129 g and chewiness from 3,376-4,819.

Palm oil significantly improved the structural profile of the vegan nugget (Sample D) compared to sunflower and rapeseed oils. Its tiny rod-like crystals (1-5 μ) had the ability to trap air within their structure giving them the potential to enhance plasticity (Devi & Khatkar, 2018). This structural characteristic likely contributed to the high springiness exhibited by Sample D, which referred to its ability to recover shape after being deformed. In addition, Sample D had the highest cohesiveness, chewiness and resilience, demonstrating powerful internal bonding and resistance to breakage. Palm oil has high solid fat content at room temperature which increases the stability of the protein-fat matrix, allowing for improved emulsification and structural integrity relative to the softer oils. Its dense crystalline structure improves emulsion stability and is most effective at low temperatures (Barbosa *et al.*, 2018). Comparing Sample K (vegetarian meatball) and vegan meatballs (Samples I, J and L) was not straightforward due to irregular compositions of various formulations. Sample M contains dairy and egg ingredients, enhanced water retention and texture, yielding the highest chewiness.

The observed textural differences among PBMA samples could be attributed to the interactions between multiple ingredients. While oils and fats are common in many PBMA samples, their impact on texture is influenced by other constituents too. For instance, emulsifiers influence fat and water distribution within the product, affecting overall texture (Echeverria *et al.*, 2022). Starches function as binders and fillers, modifying product density and mouthfeel. The protein source and its interactions with other ingredients significantly impact the final texture, as evidenced by the firm texture of the mycoprotein-based nugget, likely due to its fibrous nature (Finnigan *et al.*, 2017). Furthermore, processing methods of PBMA, such as extrusion also contribute to texture development (Kyriakopoulou *et al.*, 2019).

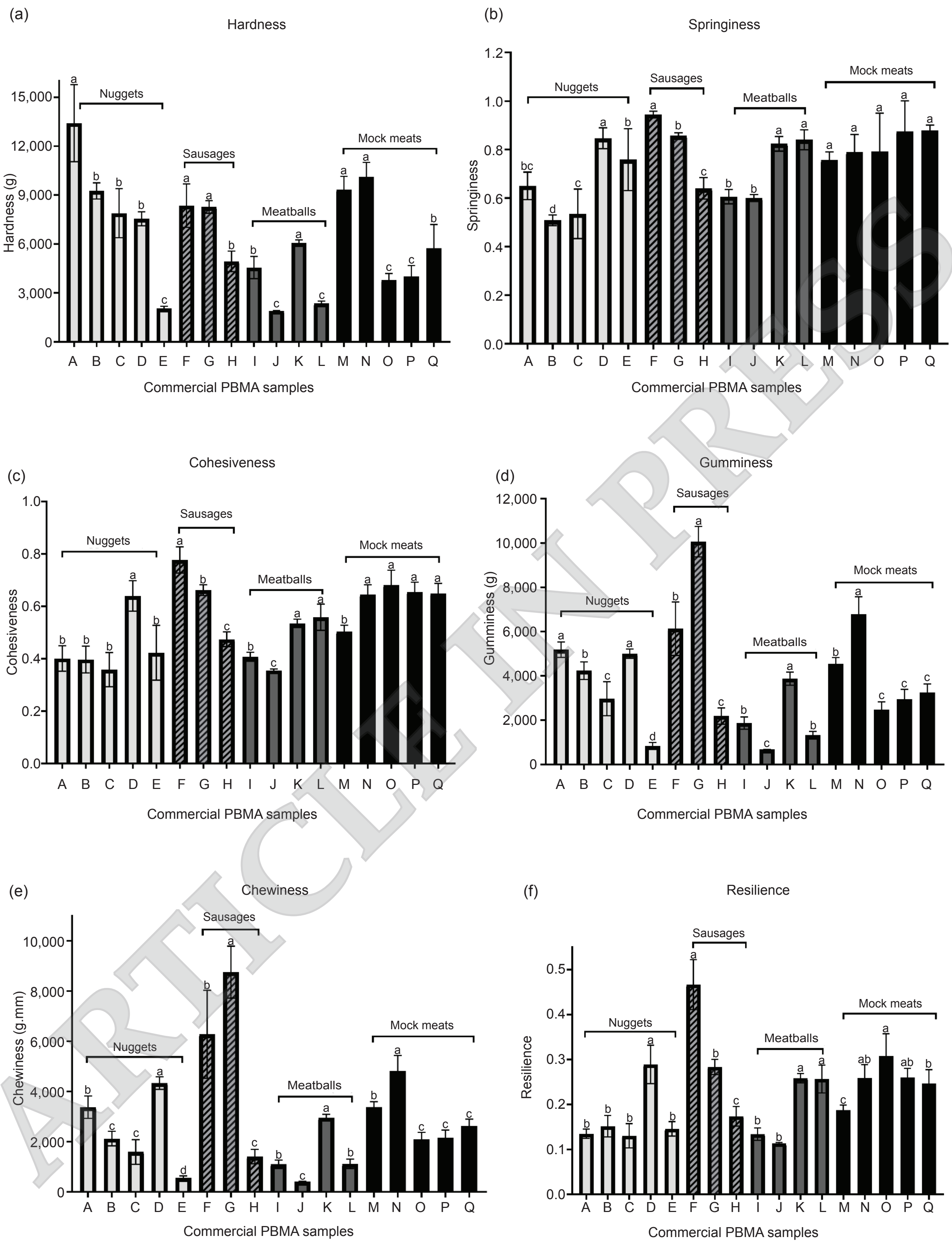
FAC. *Table 3* presents the FAC of commercial PBMA samples. Vegan PBMA with palm oil generally have SFA, especially palmitic acid (C16:0). This high SFA content is a characteristic feature of palm oil, which is widely used in the food industry for its functional properties and oxidative stability.

Vegan PBMA typically had lower SFA than vegetarian PBMA, likely due to the absence of eggs and dairy products. To provide context, eggs typically contain 30%-38% SFA of total fatty acids,



Note: A-E - PB nuggets; F-H - PB sausages; I-L - PB meatballs; M-Q - mock meats. Samples with different superscripts across similar product categories are significantly different ($p<0.05$).

Figure 3. Colour analysis (L, a* and b* values) of raw [(a), (c), (e)] and cooked [(b), (d), (f)] commercial plant-based meat analogues.*



Note: A-E - PB nuggets; F-H - PB sausages; I-L - PB meatballs; M-Q - mock meats. Samples with different superscripts across similar product categories are significantly different (p<0.05).

Figure 4. Texture analysis, (a) hardness, (b) springiness, (c) cohesiveness, (d) gumminess, (e) chewiness and (f) resilience of commercial plant-based meat analogues.

TABLE 3. FATTY ACID COMPOSITION (FAC) OF COMMERCIAL PLANT-BASED MEAT ANALOGUES

Sample	**Nuggets**					**Sausages**		
Label	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Category	**Vegetarian**	**Vegan**	**Vegan**	**Vegan**	**Vegan**	**Vegan**	**Vegetarian**	**Vegetarian**
Oils/Fats composition	**Sunflower and Rapeseed**	**Rapeseed**	**Sunflower**	**Palm**	**Soybean**	**Soybean**	**Soybean**	**-**
C8:0	-	-	-	1.58±0.04	-	-	-	-
C10:0	-	-	$0.11±0.00^{c}$	$1.05±0.01^{a}$	$0.21±0.06^{b}$	-	-	-
C12:0	-	-	$0.18±0.00^{ab}$	$0.53±0.32^{a}$	$0.11±0.01^{b}$	-	$0.21±0.03^{a}$	$0.20±0.02^{a}$
C14:0	$0.14±0.01^{c}$	$0.00±0.00^{d}$	$0.10±0.00^{c}$	$0.78±0.14^{a}$	$0.17±0.02^{b}$	-	$0.84±0.02^{b}$	$0.98±0.01^{a}$
C15:0	-	-	-	-	-	-	-	-
C16:0	$5.27±0.02^{d}$	$5.10±0.02^{d}$	$7.71±0.01^{c}$	$24.93±0.48^{a}$	$10.99±0.01^{b}$	$10.74±0.02^{c}$	$28.98±0.03^{b}$	$37.99±0.02^{a}$
C17:0	-	-	-	-	-	-	-	-
C18:0	$1.93±0.07^{d}$	$1.89±0.05^{d}$	$4.09±0.02^{b}$	$3.88±0.00^{c}$	$4.87±0.01^{a}$	$4.11±0.01^{ab}$	$4.05±0.05^{b}$	$4.13±0.02^{a}$
C20:0	$0.61±0.01^{a}$	$0.59±0.00^{a}$	$0.21±0.01^{c}$	$0.34±0.02^{b}$	$0.38±0.01^{b}$	$0.42±0.00^{a}$	$0.34±0.01^{c}$	$0.37±0.00^{b}$
C22:0	$0.30±0.03^{b}$	$0.00±0.00^{c}$	$0.63±0.09^{a}$	$0.37±0.03^{b}$	$0.30±0.11^{b}$	0.39±0.03	-	-
SFA	**$9.47±0.13^{d}$**	**$8.79±0.08^{d}$**	**$13.23±0.06^{c}$**	**$33.65±0.83^{a}$**	**$17.22±0.15^{b}$**	**$15.88±0.02^{c}$**	**$34.59±0.10^{b}$**	**$43.83±0.03^{a}$**
C16:1	$0.26±0.03^{a}$	$0.24±0.02^{a}$	$0.10±0.00^{c}$	$0.16±0.00^{b}$	$0.00±0.00^{d}$	-	$0.20±0.01^{b}$	$0.22±0.01^{b}$
C18:1	$64.83±0.10^{a}$	$63.32±0.10^{a}$	$31.51±0.06^{c}$	$36.02±0.11^{b}$	$23.64±0.04^{d}$	$26.30±0.02^{c}$	$38.49±0.02^{b}$	$44.47±0.05^{a}$
C20:1	$1.21±0.02^{a}$	$1.20±0.01^{a}$	$0.20±0.01^{b}$	$0.19±0.04^{b}$	$0.20±0.03^{b}$	$0.23±0.01^{a}$	$0.17±0.01^{b}$	$0.16±0.00^{b}$
MUFA	**$65.09±0.08^{a}$**	**$63.57±0.02^{b}$**	**$31.62±0.06^{d}$**	**$36.18±0.11^{c}$**	**$23.64±0.04^{e}$**	**$26.30±0.02^{c}$**	**$38.69±0.01^{b}$**	**$44.68±0.04^{a}$**
C18:2	$18.72±0.04^{d}$	$19.21±0.04^{d}$	$54.83±0.03^{a}$	$29.97±0.96^{c}$	$52.17±0.19^{b}$	$51.65±0.02^{a}$	$25.96±0.06^{b}$	$11.14±0.01^{c}$
C18:3	$6.72±0.05^{c}$	$8.45±0.02^{a}$	$0.25±0.00^{d}$	$0.20±0.02^{d}$	$6.97±0.02^{b}$	$6.17±0.01^{a}$	$0.76±0.03^{b}$	$0.34±0.01^{c}$
PUFA	**$25.44±0.07^{e}$**	**$27.65±0.06^{d}$**	**$55.08±0.03^{b}$**	**$30.17±0.93^{c}$**	**$59.13±0.18^{a}$**	**$57.82±0.02^{a}$**	**$26.72±0.09^{b}$**	**$11.49±0.02^{c}$**
C18:1T	$0.15±0.02^{a}$	$0.07±0.06^{b}$	$0.14±0.02^{a}$	$0.13±0.00^{a}$	$0.14±0.01^{a}$	-	-	-
C18:2T	$2.07±1.79^{a}$	$0.00±0.00^{b}$	$0.10±0.01^{ab}$	$0.13±0.01^{ab}$	$0.00±0.00^{b}$	$0.16±0.00^{a}$	$0.15±0.02^{a}$	$0.15±0.00^{a}$
TFA	**$2.20±1.73^{a}$**	**$0.06±0.01^{c}$**	**$0.24±0.06^{b}$**	**$0.20±0.00^{b}$**	**$0.10±0.00^{bc}$**	**$0.16±0.00^{a}$**	**$0.15±0.02^{a}$**	**$0.15±0.00^{a}$**

Note: A-E - PB nuggets; F-H - PB sausages; SFA - saturated fatty acids; MUFA - monounsaturated fatty acids; PUFA - polyunsaturated fatty acids; TFA - *trans* fatty acids. Samples with different superscripts across the rows of similar product categories are significantly different ($p<0.05$).

TABLE 3. FATTY ACID COMPOSITION (FAC) OF COMMERCIAL PLANT-BASED MEAT ANALOGUES (continued)

Sample	Meatballs				Mock Meats				
Label	I	J	K	L	M	N	O	P	Q
Category	Vegan	Vegan	Vegetarian	Vegan	Vegetarian	Vegan	Vegetarian	Vegan	Vegetarian
Oils/Fats Composition	Palm and Canola	Sunflower	Palm	Coconut	Palm	Palm and Sesame	Palm Oil and Palm Fat	-	Palm Oil and Palm Fat
C6:0	0.34±0.10^{b}	-	-	0.58±0.02^{a}	-	-	-	-	-
C8:0	0.23±0.08^{c}	1.94±0.01^{b}	1.26±0.04^{b}	5.96±0.24^{a}	-	-	-	-	-
C10:0	36.03±1.59^{a}	0.38±0.06^{c}	0.77±0.06^{c}	4.66±0.20^{b}	-	0.11±0.00^{a}	-	0.28±0.24^{a}	0.16±0.00^{a}
C12:0	1.14±0.26^{b}	0.51±0.07^{c}	0.19±0.00^{d}	36.03±1.59^{a}	0.33±0.00^{a}	0.26±0.00^{bc}	0.29±0.00^{ab}	0.22±0.04^{c}	0.31±0.01^{ab}
C14:0	-	-	0.93±0.01^{b}	14.89±0.65^{a}	1.06±0.00^{a}	1.02±0.01^{b}	1.02±0.00^{b}	1.00±0.01^{b}	1.05±0.00^{a}
C16:0	36.28±0.5^{a}	10.18±0.06^{b}	36.19±0.17^{a}	9.31±0.06^{b}	39.63±0.05^{a}	37.84±0.01^{c}	38.97±0.05^{b}	38.85±0.10^{b}	39.48±0.01^{a}
C17:0	-	-	-	-	-	-	-	-	-
C18:0	4.05±0.02^{b}	6.88±0.03^{a}	4.21±0.07^{b}	3.11±0.04^{c}	4.53±0.00^{a}	4.12±0.02^{d}	4.39±0.00^{c}	4.11±0.03^{d}	4.46±0.02^{b}
C20:0	0.42±0.03^{a}	0.23±0.02^{b}	0.40±0.01^{a}	0.17±0.01^{c}	0.38±0.00^{ab}	0.39±0.02^{a}	0.39±0.00^{a}	0.36±0.00^{b}	0.37±0.01^{ab}
C22:0	-	0.62±0.02	-	-	0.37±0.02	-	-	-	-
SAFA	**43.45±0.60^{b}**	**21.22±0.21^{c}**	**44.12±0.02^{b}**	**74.71±2.57^{a}**	**46.07±0.07^{a}**	**43.91±0.01^{c}**	**45.23±0.06^{b}**	**44.98±0.19^{b}**	**45.99±0.01^{a}**
C16:1	0.22±0.00^{a}	0.22±0.01^{a}	-	-	0.20±0.00^{bc}	0.26±0.01^{a}	0.19±0.00^{c}	0.21±0.00^{b}	0.21±0.01^{bc}
C18:1	43.67±0.65^{a}	44.47±0.04^{a}	43.54±0.15^{a}	11.52±0.67^{b}	41.79±0.06^{d}	44.67±0.01^{a}	43.20±0.08^{c}	44.04±0.17^{b}	41.45±0.02^{e}
C20:1	0.24±0.02^{a}	0.16±0.00^{ab}	0.17±0.01^{ab}	0.00±0.00^{b}	0.19±0.03^{a}	0.18±0.00^{a}	0.17±0.02^{a}	0.15±0.01^{a}	0.14±0.01^{a}
MUFA	**43.89±0.65^{ab}**	**45.02±0.03^{a}**	**43.53±0.15^{b}**	**11.52±0.67^{c}**	**41.99±0.05^{d}**	**44.93±0.01^{a}**	**43.40±0.09^{c}**	**44.24±0.17^{b}**	**41.65±0.01^{e}**
C18:2	11.76±0.04^{b}	33.47±0.23^{a}	11.75±0.11^{b}	12.46±1.69^{b}	11.67±0.01^{b}	10.83±0.01^{d}	11.08±0.00^{c}	10.51±0.03^{e}	12.07±0.01^{a}
C18:3	0.90±0.02^{b}	0.29±0.03^{d}	0.46±0.03^{c}	1.31±0.21^{a}	0.27±0.00^{bc}	0.34±0.01^{a}	0.27±0.00b^{c}	0.26±0.00^{c}	0.28±0.01^{b}
PUFA	**12.66±0.06^{b}**	**33.76±0.17^{a}**	**12.21±0.13^{b}**	**13.77±1.90^{b}**	**11.94±0.01^{b}**	**11.16±0.02^{d}**	**11.35±0.00^{c}**	**10.77±0.03^{e}**	**12.36±0.00^{a}**
C18:1T	-	0.60±0.30^{a}	0.09±0.01^{b}	-	-	0.08±0.00^{a}	-	0.02±0.03^{c}	0.06±0.00^{b}
C18:2T	0.15±0.01^{b}	0.60±0.00^{a}	0.17±0.00^{b}	0.16±0.02^{b}	0.19±0.04^{a}	0.18±0.00^{a}	0.15±0.02^{ab}	0.11±0.00^{b}	0.15±0.00^{ab}
TFA	**0.15±0.01^{c}**	**1.20±0.01^{a}**	**0.26±0.01^{b}**	**0.16±0.02^{c}**	**0.19±0.05^{abc}**	**0.25±0.00^{a}**	**0.15±0.02^{bc}**	**0.13±0.03^{c}**	**0.21±0.00^{ab}**

Note: I-L - PB meatballs; M-Q - mock meats; SAFA - saturated fatty acids; MUFA - monounsaturated fatty acids; PUFA - polyunsaturated fatty acids; TFA - *trans* fatty acids. Samples with different superscripts across the row of similar product categories are significantly different ($p<0.05$).

with palmitic acid (C16:0) and stearic acid (C18:0) being predominant (Tomaszewska *et al.*, 2021). Dairy products exhibit even higher SFA content, ranging from 60%-70% of total fatty acids in whole milk and cheese, including a significant portion of short- and medium-chain fatty acids unique to dairy fat (Markey *et al.*, 2017). Vegan PBMA samples made with sunflower or rapeseed oil (Samples B, C and L) showed a higher proportion of unsaturated fatty acids (UFA), including oleic acid (C18:1) and linoleic acid (C18:2), which might have resulted in a softer texture and different flavour profiles. Vegetarian PBMA samples also showed variations in FAC depending on the type of oil used, implying that the oil greatly affected their fatty acid profile and nutritional and sensory qualities.

Additionally, the analysis of *trans* fatty acids (TFA) in commercial PBMA samples showed ranges between 0.06%-2.20% of TFA. Although Codex recommends a maximum of 2 g TFA per 100 g of total fat, and many countries are considering a similar limit, current regulations often do not require TFA declaration if the amount per serving is below a certain threshold (Karupaiah *et al.*, 2014).

Correlation analysis by Principal Component Analysis (PCA). PCA of PBMA products (*Figure 5*) aids in predicting future developments. PC1 (73.97%) and PC2 (9.84%) explained 83.81% of total variation, highlighting texture (springiness, resilience, cohesiveness) as the key characteristic. Control of hardness was also critical to achieve the desired balance. These results indicate that

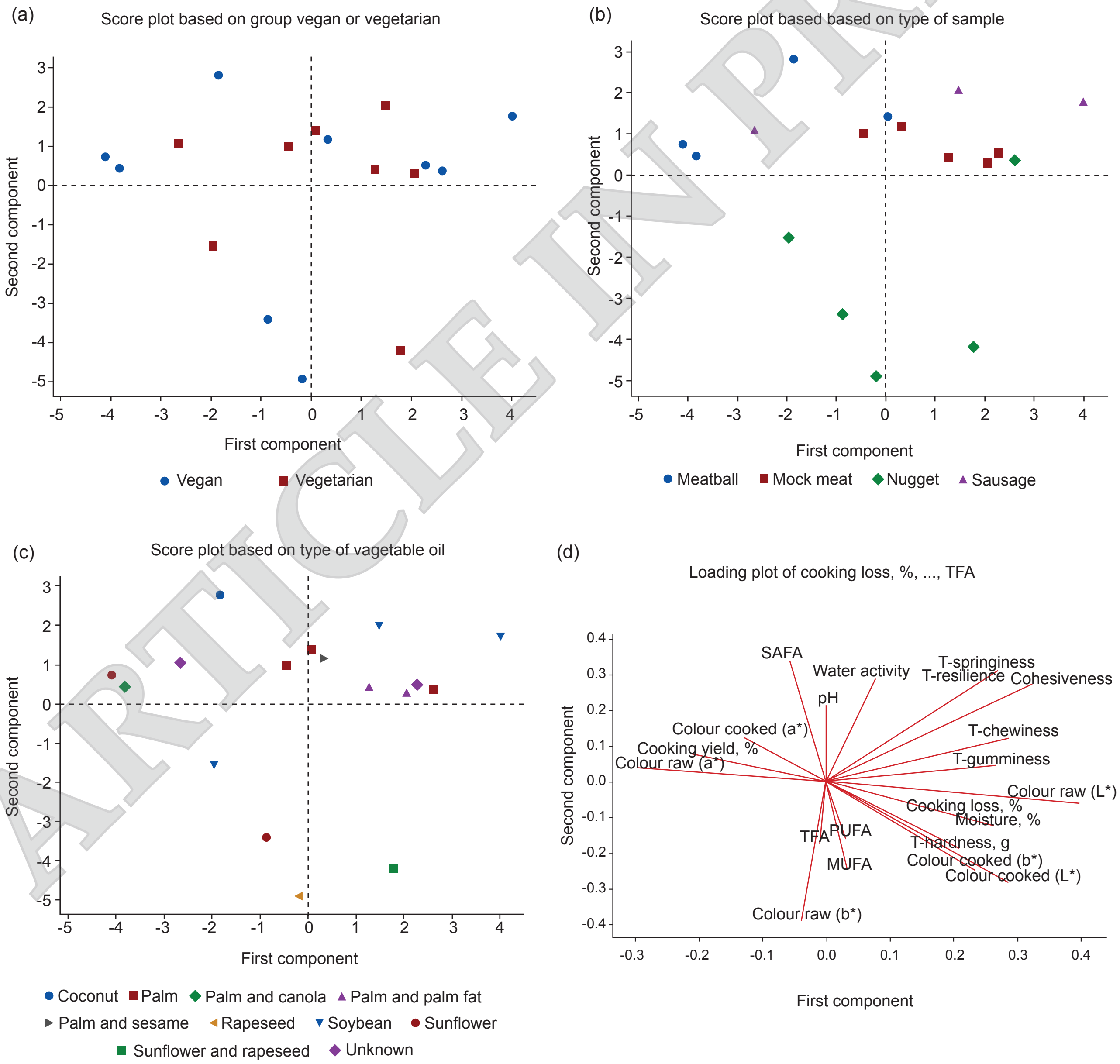


Figure 5. PCA analysis, score plot based on (a) group, (b) type of sample, (c) type of oil and (d) loading plot of PCA analysis for plant-based meat analogues products.

targeting certain textural features demands more attention when formulating. Notably, L* value was among the most prominent parameters in the PCA, suggesting significant lightness is observed in other plant-based products such as nuggets, meatballs and meat substitutes, which could explain the strong association. Moisture-related attributes demonstrated the inverse relationship between moisture content and cooking loss. Reducing cooking loss increased moisture retention, contributing to the stability and juiciness of the product. Therefore, balance must be obtained in formulations. Within product categories, there was clustering, with sausages and mock meats well-optimised, and nuggets showing scattered results, particularly in moisture properties that require standardisation. Palm oil proves to be a versatile fat source. Alone or in combination with canola/sesame oil, palm oil enables products to achieve desirable textural and moisture properties which indicates functional and textural goals are attained without compromising key characteristics. The flexibility makes it valuable in diverse plant-based meat formulations.

CONCLUSION

Commercial PBMA products showed SP dominance and a growing preference for vegan alternatives. However, the underutilisation of palm-based products provides a potential for future innovation. Palm oil, with its unique composition and functional qualities, has the potential to improve the sensory and nutritional profiles of PBMA, especially in vegan formulations. Palm-based PBMA, especially in vegan formulations, reduced cooking loss and improved cooking yield, thus improving moisture retention and product quality. Palm-based PBMA samples may also have desired textural properties and fatty acid profiles closer to those of animal-based meats, but with zero *trans* fats and lower saturated fats than animal-based processed meat products. Future research should investigate the correlation between current findings with microstructure and sensory attributes to optimise formulations.

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