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ORIGINAL PAPER

Chemical composition, antioxidant profile and physicochemical properties of commercial non-cocoa- and cocoa-flavoured plant-based milk alternatives

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Abstract

In recent years, there has been a significant rise in the popularity of plant-based milk alternatives (PBMAs). This work examined the nutritional value, antioxidant profile and physicochemical characteristics of commercial non-cocoa- and cocoa-flavoured PBMAs. The examined products were either nut or oat-based ones. In the absence of protein fortification, the products' protein content was found to be low. Fat content was also low, whereas carbohydrate and sugar contents were related to sugar addition. Oleic, linoleic and α-linolenic acids were the primary unsaturated fatty acids. PBMAs have low Atherogenicity (AI) and Thrombogenicity (TI) indices and high hypocholesterolaemic:hypercholesterolaemic fatty acid ratio (h/H). The antioxidant profile significantly differed ($P < 0.001$) between non-cocoa- and cocoa-flavoured PBMAs. The antioxidant profile of cocoa-flavoured PMBAs improved due to the polyphenols present in cocoa beans. The physicochemical characteristics of the analysed PBMAs demonstrated great versatility. The nutritional profile of PBMAs also showed considerable variability, influenced by factors, such as product type and ingredient formulation. Additionally, differences in the nutritional composition and physicochemical properties were observed between non-cocoa and cocoa-based PBMAs.

Keywords Plant-based milk alternatives · Cocoa · Chemical composition · Fatty acid composition · Physico-chemical characteristics · Antioxidants

Introduction

Plant-based milk alternatives (PBMAs) are becoming increasingly popular in recent years [1]. According to the Market and Research Report from Fortune Business Inside (2022) [2], the global dairy alternatives market was valued at USD 22.25 billion in 2021. The market is expected to grow from USD 25.19 billion in 2022 to USD 61.43 billion by 2029 at a CAGR (Compound Annual Growth Rate) with a CAGR of 13.58% during the forecast period, driven mainly by the growing demand for plant-based milk alternatives. Lactose intolerance, allergies to cow milk, the prevalence of hypercholesterolemia, lifestyles, such as veganism and flexitarianism, sustainability as related to greenhouse emissions, animal welfare and calorie concern are the principal factors that led to the development of plant-based milk alternatives [3–7].

PBMAs are extracts of plant material dissolved in water, imitating cow milk in consistency and appearance [8, 9]. Homogenisation and thermal treatment are employed to improve plant-derived beverages' suspension and microbial stability. PBMAs can be classified into the following five categories (a) cereal-based, such as oat, rice, corn and spelt milk, (b) legume-based, such as soya, peanut, lupin and cowpea milk, (c) nut-based, such as almond, coconut, hazelnut, pistachio and walnut milk (d) seed-based, such as sesame, flax, hemp and sunflower milk and (e) pseudo-cereal-based, such as quinoa, teff and amaranth milk [9]. The nutritional properties of PBMAs are affected by the plant

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source, processing conditions and fortification with minerals and/or vitamins and the presence of other ingredients, such as sweeteners and oil [10]. Most commercially available products have considerably low protein content, and only soy-based products, with protein contents ranging from 2.6 to 3.7%, have values comparable with cow's milk [8, 10]. PBMAs have low-fat content that positively appeals to consumers towards product purchase [11]. The sugar content is variable depending on the plant source and product formulation. Rice- or oat-based products have a naturally high carbohydrate and sugar contents, whereas flavoured beverages contain 2 to 8 times more sugar than non-flavoured ones [12, 13]. Compared to bovine milk, plant-based beverages generally have lower levels of minerals and vitamins, such as calcium, magnesium and vitamin D, whilst exhibiting higher salt content [12]. Despite this nutritional imbalance [9], PBMAs contain functionally active components with health-promoting properties, captivating the attention of health-conscious consumers. Amongst these components, the antioxidant levels of PBMAs have garnered considerable interest as they distinguish them from dairy milk. Finally, the physicochemical characteristics affect the sensory characteristics and consumer acceptability of plant-based beverages [14], and plant-based milk substitutes should ideally have similar physicochemical and sensory characteristics as bovine milk [15].

Despite the increasing popularity of PBMAs and the constant introduction of new products based on various cereals, nuts, legumes, and seeds, there is limited research on the nutritional quality and physicochemical characteristics of commercially available products. The main objective of the current study was to provide a comprehensive analysis of commercially available PBMAs, both cocoa unflavoured and flavoured, with respect to their nutritional value, adherence to nutritional labelling, antioxidant profile, and physicochemical characteristics. A secondary goal was to compare the characteristics mentioned above between non-cocoa-flavoured and cocoa-flavoured PBMAs, as well as to compare them with cow milk.

Materials and methods

Sampling

Samples of PBMAs ($n=22$) were purchased from November 2021 to April 2022 from major supermarket retailers located in Northern Greece. There was no selection regarding number and type of samples included in the study. All available brands that were sold in supermarket retailers were included in the study. There were 14 non-cocoa-flavoured samples, and the remaining 8 samples were cocoa-flavoured. Furthermore, selected samples had to meet the following criteria (a) to be widely available in food stores, (b) to be produced in Greece and (c) to be stored under refrigerated conditions during purchase. On arrival at the laboratory, the samples were thoroughly mixed and decanted into 15-ml Falcon tubes stored at − 20 °C before analysis. The declared nutrient composition of each sample was noted.

Compositional analysis

Gross composition, in terms of moisture (total solids), ash, protein, lipid, edible fibres, sugar and carbohydrate contents, was determined by the application of standard methods routinely applied in the analysis of fluid milk samples. In detail, total solids, ash, protein and edible fibres were determined by the AOAC 925.23, 945.46, 991.20 and 2009.01 methods, respectively [16, 17]. Fat content was determined with the Gerber method. The total sugar content was estimated using the Lane and Eynon method. Carbohydrate content was calculated by deducting the percentages of ash, protein and fat from the percentage of total solids.

Fatty acid composition

The fatty acid composition was determined according to the method of Bligh and Dyer [18], as described by Kasapidou et al. [19]. Fatty acid methyl esters were prepared from the extracted lipids by base-catalysed methanolysis of the glycerides using KOH in methanol, according to the method ISO-IDF 15884 [20] of the International Organization for Standardization. Fatty acid methyl ester analysis was performed on an Agilent Technologies 6890N GC (Agilent Technologies, Inc., USA) equipped with a flame ionisation detector (FID) and a 60 m × 0.25 mm i.d., 0.25 μm film thickness DB-23 (50% Cyanopropyl 50% dimethyl polysiloxane) capillary column (Model Number: Agilent 122 2362). The injector temperature was set at 250 °C. The oven temperature was programmed from 110 °C (held for 6 min), to 165 °C at 1 °C/min (held for 13 min), to 195 °C at 15 °C/min (held for 22 min) and to 230 °C at 7 °C/min (hold for 7 min). The carrier gas was helium at 0.7 ml/min, the injection volume was 3 μl, and the split ratio was 1:50. The injection was performed using an Agilent 7683 Series auto-sampler. Fatty acids were identified using standard commercial mixtures: (a) 37-component FAME mix (Supelco, 47885-U), (b) PUFA-2, and (b) a mixture of cis- and trans-9,11- and

-10,12-octadecadienoic acid methyl esters (Sigma, O5632-250MG) as reference standards. Fatty acids were quantified by peak area measurement, and the results are expressed as per cent (%) of the total peak areas for all quantified acids.

Nutritional indices of fatty acids

Nutritional indices were employed to assess the fatty acid composition and its relation to healthy fat consumption. The following indices, reported in the recent study of Chen and Liu [21] related to plant oil were used:

$$\text{Polyunsaturated fatty acid (PUFA)/saturated fatty acid ratio (SFA)} = \sum \text{PUFA} / \sum \text{SFA}$$

$$\text{Atherogenicity Index (AI)} = [\text{C12}:0 + (4 \times \text{C14}:0) + \text{C16}:0] / \sum \text{UFA}$$

$$\text{Thrombogenicity Index (TI)} = (\text{C14}:0 + \text{C16}:0 + \text{C18}:0) / [(0.5 \times \sum \text{MUFA}) + (0.5 \times \sum \text{n-6PUFA}) + (3 \times \sum \text{n-3PUFA}) + (\text{n-3/n-6})]$$

$$\text{Hypocholesterolaemic : hypercholesterolaemic fatty acid ratio (h/H)} = (\text{C18}:1\text{n-9 cis} + \sum \text{PUFA}) / (\text{C12}:0 + \text{C14}:0 + \text{C16}:0)$$

where UFA (unsaturated fatty acids) and MUFA (monounsaturated fatty acids).

Total phenolic and flavonoids content, and antioxidant profile

For the total phenolic content (TPC) determination of the samples, the Folin–Ciocalteau method was applied [22]. The results are expressed as milligrammes of gallic acid equivalents (GAE) per mL of sample. The total flavonoid content was determined with the $AlCl_3$ solution method described by Bhaigyabati et al. [23], using rutin as a standard for the calibration curve. The results are expressed as mg of rutin equivalents per mL of sample. Free radical scavenging activity was measured with the DPPH (2,2-diphenyl-1-picrylhydrazyl) method as described by Sanchez-Moreno et al. [24] with slight modifications. The results are expressed as µM of Trolox (a water-soluble analogue of vitamin E: (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) equivalents per mL of sample. The reducing power activity of the samples was measured with the FRAP (Ferric Reducing Antioxidant Power) method, as reported by Pulido et al. [25], with minor modifications. The results are expressed as µM of Trolox equivalents per mL of sample.

Physicochemical properties

Before analysis, samples were thoroughly mixed by multiple gentle inversions of the sample container whilst avoiding froth formation. Sample pH, electrical conductivity, Brix and refractive index values were determined as described by Kasapidou et al. [26]. A Crison GLP 21 pH-metre (Barcelona, Spain) equipped with a glass electrode with an integrated temperature sensor (5014 T electrode, Crison, Barcelona, Spain), was used to measure sample pH following calibration. Electrical conductivity (20 °C) was determined using a GLP 31 conductometer (Crison Instruments, Barcelona, Spain) with a Sodium Ion-Selective Electrode 5070 (Crison Instruments, Barcelona, Spain) after calibration. Soluble content, referred to as refractive index and Brix values, was determined using a digital refractometer (DR6000-T, Krüss, Hamburg, Germany) set at 20 °C. Colour was assessed with instrumental colour measurements (L* luminosity; a* redness and b* yellowness) using a Minolta Chroma Meter (model CR-410, Minolta Camera Co, Osaka, Japan) with a 10-mm measuring area (aperture) and illuminant source C. The instrument was calibrated using the white calibration plate (Y = 93.66, x = 0.3150, y = 0.3217). The sample (50 ml) was placed in a black container, and the colorimeter-supplied optically inactive glass aperture cover was used to avoid external light interference during measurement. Chroma value was calculated as follows; $\text{Chroma} = (a^{*2} + b^{*2})^{0.5}$

The Whiteness index (WI) for the non-cocoa beverages was determined according to Jeske et al. [8] as follows; $\text{WI} = 100 - ((100 - L^*)^2 + a^{*2} + b^{*2})^{0.5}$

The viscosity of the samples was measured at 20 °C using Viscometer Visco Star plus (FUNGILAB, S. A., Barcelona, Spain) with stainless steel spindle R2 at a steering rate of 100 rpm according to manufacturer's guidelines for spindle selection. Measurements were made for 1 min at 20 °C, and results are expressed in millipascal-second (mPa·s) units.

Statistical analysis

Results are presented as mean values for the duplicate analyses for each sample. Differences between non-cocoa- and cocoa-flavoured PBMAs were assessed using independent samples t-test and were considered significant if $P \leq 0.05$. All data for each group are presented as mean values. SPSS software (version 28.0, SPSS Inc., Chicago, IL, USA) was used for data analysis. Principal component analysis (PCA) was performed with the R software (ver. 4.2.1, R Foundation for Statistical Computing, Vienna, Austria), using the "factoextra" R package (version 1.0.7).

Results and discussion

Characteristics of the PBMAs

Most PBMAs were nut (almond, peanut, hazelnut and walnut)-based (Table 1). Almond-based samples accounted for almost 57% of the non-cocoa-flavoured beverages and 37.5% of the cocoa-flavoured samples. Additionally, most of the non-cocoa-flavoured samples (57%) had no added sugar, whereas all cocoa-flavoured samples contained sugar. Furthermore, cocoa content ranged from 1 to 1.7% in the latter sample type. Moreover, a small number of the samples were enriched in protein, calcium, and vitamins. Finally, although data is not presented, PBMAs were mainly produced by two major manufacturers of dairy products in Greece. In detail, the first company produced 12 out of the 22 samples (≈ 54%), whereas the second manufacturer produced 7 out of the 22 samples (≈ 32%). Almond- and oat-based milk are highly preferred in the USA, Ukraine and Canada [11, 27, 28]. The above findings explain that either almond- or oat-based milk alternatives dominated the PBMAs market in Greece.

Concerning the average declared composition, there were no statistically significant differences ($P > 0.05$) in all reported nutrients except carbohydrates and sugars, and high statistically significant ($P < 0.001$) differences were observed. The latter is because all the cocoa-flavoured samples contained sugar, whereas most non-flavoured beverages had no added sugar (Table 2).

Proximate analysis

The average composition (g/100 g) for each product category is as follows: (A) Non-cocoa-flavoured PBMAs: moisture 91.48, ash 0.65, fat 1.40, protein 1.63, carbohydrate 4.85, sugars 3.43, and edible fibre 0.59. (B) Cocoa-flavoured PBMAs: moisture 85.98, ash 0.74, fat 1.15, protein 1.25, carbohydrate 10.87, sugars 7.26, and edible fibre 0.93. Highly significant differences ($P < 0.001$) were observed in moisture, carbohydrate and sugar content between non-cocoa-flavoured and cocoa-flavoured products. The content of all examined components was very versatile, and there was no pattern related to product type, whether it was nut-based or cereal-based. The composition of PBMAs is influenced by various factors, including the raw materials used, processing conditions, fortification with nutrients, and the inclusion of additional ingredients, such as sweeteners and oil [10]. Nevertheless, the proximate composition of the analysed samples aligns with the findings of previous review studies conducted by Aydar et al. [29] and Fructuoso et al. [30], which investigated the nutritional composition of retail and experimental samples of PBMAs from different countries. In relation to the nutritional value of the PBMAs as compared to the widely consumed cow milk, protein content ranged from 0.23 to 1.44 g/100 g and from 0.69 to 0.92 g/100 g for the non-protein-fortified non-cocoa-flavoured and cocoa-flavoured PBMAs, respectively. The average protein content for the protein-fortified products was approximately 3.3 g/100 g. The lowest protein content was observed in the coconut-based product, and the highest protein content in one of the almond-based beverages. For cocoa-flavoured PBMAs, the highest protein content was found in the oat and carob, and hazelnut beverages, whereas the lowest was in an almond-based product. Fat content ranged from 0.93 to 2.20 g/100 g in non-flavoured beverages. The lowest value was again found in the coconut-based product and the highest in a protein-enriched almond-based product. For the flavoured products, the lowest content was observed in the oat and carob products, whereas the highest was in an almond-based beverage. Carbohydrate content ranged from 0.82 to 9.53 g/100 g in the non-cocoa PBMAs, whereas 50% of the examined samples had similar higher carbohydrate content in relation to cow milk expressed as lactose. Cocoa-flavoured PBMAs had a carbohydrate content ranging from 9.46 to 12.92 g/100 g. Retail cow milk contains 3.27 g/100 g of protein, 3.49 g/100 g of fat, and 4.52 g/100 g of carbohydrates [31]. In comparison, protein-enriched PBMAs have a similar protein content to cow milk. Furthermore, the average fat content in PBMAs is similar to that of low-fat milk, whilst the average carbohydrate content of non-flavoured PBMAs is comparable to that of cow milk.

A comparison of declared and determined values was conducted to identify which products were within or beyond tolerance limits. Results showed that the carbohydrate content was outside the acceptable range in six samples, whilst one sample had fat content beyond the established tolerance limits [32]. Approximately 27.3% of all samples showed deviations in at least one nutrient (Table 3). Nutrient values declared on the label and values determined in the laboratory are presented in Fig. 1. Finally, Principal Component Analysis (PCA) showed that the two groups of PBMAs are not clearly separated although the 2 principal components cumulatively explain 81% of the entire data set variability (Fig. 2).

Fatty acid composition and nutritional indices

The fatty acid composition of PBMAs is presented in Table 4. Palmitic acid (C16:0) is the major saturated fatty acid, followed by myristic (C14:0) and stearic (C18:0) acid in all examined products except coconut-based PBMA that contained high levels of the short-chain saturated caprylic

Table 1 Product characteristics and declared nutritional composition of the samples (g/100 ml)

Sample no.	Type	Product characteristics	Protein	Fat	SFA	Carbohydrate	Sugars	Edible fibre	Sodium chloride
Non-cocoa-flavoured plant-based milk alternative									
1	Almond (3%)	Gluten-free No added sugar	0.7	1.7	0.1	0.5	0.5	1.8	0.10
2	Almond (2.5%)	Gluten-free	0.7	1.5	0.1	2.8	2.8	1.0	0.10
3	Almond (4.5%)	Gluten-free Preservative-free	1.3	2.9	0.2	3.4	3.2	< 0.5	< 0.01
4	Almond (3.5%)	Gluten-free No added sugar	1.0	2.2	0.2	< 0.5	< 0.5	< 0.5	0.08
5	Almond (3%)	Gluten-free Enriched with calcium and vitamins	0.7	1.7	0.1	4.4	3.6	0.4	0.10
6	Almond (3%)	Gluten-free No added sugar Enriched with calcium and vitamins	0.7	1.7	0.1	3.0	2.0	0.4	0.10
7	Almond (2.5%)	Gluten-free Increased protein	3.2	1.7	0.1	2.9	2.9	1.3	0.10
8	Almond (2.5%)	Gluten-free Increased protein	3.2	2.0	0.2	5.2	4.0	1.3	0.11
9	Oat (12%)	No added sugar	1.2	1.5	0.3	8.0	4.9	1.7	0.11
10	Oat (12%)	Increased protein	3.2	1.5	0.2	8.4	6.2	2.0	0.11
11	Oat (8%) & Seeds (Sesame 0.5%, sunflower 1%, pumpkin 0.5%)	No added sugar Enriched with calcium and vitamins	0.3	0.8	0.1	2.7	1.6	0.2	0.10
12	Oat (8%) & Hazelnut (2.5%)	No added sugar	1.2	2.2	0.2	5.6	3.5	1.7	0.11
13	Rice (5.1%) & Coconut (1.5%)	Gluten-free No added sugar Enriched with calcium and vitamins	0.2	1.5	1.0	5.0	2.7	0.2	0.10
14	Peanut (3%)	Gluten-free No added sugar	0.7	1.7	0.2	0.5	0.5	1.8	0.10
Cocoa-flavoured plant-based milk alternative									
1	Almond (2.5%)	Cocoa (1%)/ Enriched with calcium and vitamins	0.7	1.4	0.2	8.1	6.5	0.4	0.15
2	Almond (2.5%)	Cocoa (1.7%) Gluten-free	0.7	1.7	0.3	7.4	7.4	1	0.10
3	Almond (2.5%)	Cocoa (1.6%) Gluten-Free Increased protein	3.2	1.9	0.3	7.2	7.2	1.9	0.10
4	Oat (8%)	Cocoa (1.5%)	0.9	1.5	0.3	10.3	8.3	1.9	0.11
5	Oat (12.5%) & Carob (5%)	Cocoa (1.5%)	1.4	1.0	0.3	10.8	7.6	1.4	0.11
6	Rice (16%) & Hazelnut (2.5%)	Cocoa (1%) Enriched with calcium and vitamins	1.0	2.5	0.4	12.3	4.8	0.5	0.20
7	Hazelnut (2.5%)	Cocoa (1.7%)	0.4	1.9	0.3	7.4	7.4	1.6	0.10
8	Walnut (4.5%)	Cocoa (1.7%) Gluten-Free	0.7	3.0	0.4	7.3	7.3	1.9	0.10
Plant-based milk alternative category average									
Non-cocoa-flavoured			1.31	1.76	0.22	4.03	2.95	1.15	0.10
Cocoa-flavoured			1.19	1.93	0.33	8.96	7.14	1.54	0.12
Significance			NS	NS	NS	***	***	NS	NS

SFA saturated fatty acids, *NS* non-significant

***$P < 0.001$

Table 2 Determined proximate composition of plant-based milk alternatives (g/100 g)

Sample no.	Type	Moisture	Ash	Protein	Fat	Carbohydrate	Sugars	Edible fibre
Non-cocoa-flavoured plant-based milk alternative								
1	Almond	94.93	0.59	0.83	1.45	2.20	0.89	0.40
2	Almond	94.10	0.61	0.75	1.40	3.14	2.93	0.50
3	Almond	93.75	0.32	1.44	2.10	2.39	1.21	0.40
4	Almond	96.56	0.29	0.93	1.40	0.82	0.50	0.40
5	Almond	91.82	0.61	0.74	2.00	4.83	3.94	0.40
6	Almond	93.90	0.59	0.79	2.00	2.72	2.48	0.40
7	Almond	90.08	0.78	3.30	2.20	3.64	2.94	1.80
8	Almond	87.14	1.25	3.35	2.00	6.26	5.65	0.70
9	Oat	88.45	0.63	1.19	1.45	8.28	5.64	0.40
10	Oat	84.17	1.26	3.29	1.75	9.53	8.85	1.00
11	Oat and seeds	88.83	0.58	0.85	1.10	8.64	3.47	0.60
12	Oat and hazelnut	90.16	0.57	1.17	1.80	6.30	5.15	0.50
13	Coconut	91.71	0.41	0.23	0.93	6.72	2.86	0.40
14	Peanut	95.12	0.59	0.73	1.20	2.36	1.56	0.40
Cocoa-flavoured plant-based milk alternative								
1	Almond	88.10	0.55	0.69	1.20	9.46	8.08	0.40
2	Almond	87.37	0.76	0.86	0.70	10.31	7.27	0.90
3	Almond	82.21	0.72	3.33	2.20	11.54	6.77	1.30
4	Oat	83.78	0.79	0.81	1.70	12.92	8.55	0.40
5	Oat and carob	87.07	0.97	0.92	0.10	10.94	7.66	0.40
6	Hazelnut	85.31	0.66	0.92	1.30	11.81	5.42	1.20
7	Hazelnut	87.36	0.71	0.80	1.45	9.68	7.02	1.40
8	Walnut	86.63	0.79	0.85	1.40	10.33	7.34	1.40
Plant-based milk alternative category average								
Non-cocoa-flavoured		91.48	0.65	1.40	1.63	4.85	3.43	0.59
Cocoa-flavoured		85.98	0.74	1.15	1.26	10.87	7.26	0.93
Significance		***	NS	NS	NS	***	***	NS

NS non-significant

***$P < 0.001$

acid (C8:0) and capric (C10:0) acid. Coconut-based PBMA also contained high levels of lauric acid (C12:0). Although lauric acid is a saturated fatty acid, it provides various health benefits, such as enhancing the immune system and increasing the elasticity of blood vessels. Furthermore, lauric acid possesses antimicrobial, antibacterial, and antiviral properties and exhibits anticarcinogenic effects [9, 33]. Oleic (C18:1 *cis* n-9) and α-linolenic (C18:3 n-3) acids were the major MUFA and PUFA in all types of examined PBMAs. The fatty acid profile agrees with that reported in the review study of Aydar et al. [29]. Martínez-Padilla et al. [1] reported higher levels of palmitic and stearic acids and lower levels of oleic and α-linolenic acids in commercial almond-based beverages. In the same study, oat-based products had a similar profile, whereas coconut-based products contained higher levels of lauric acid. For non-cocoa PBMAs, differences in the content of the major fatty acids, i.e. palmitic, stearic, oleic and α-linolenic between the nut and oat-based products, were noted. However, this pattern was not observed in cocoa-flavoured PBMAs as differences in the fatty acid profile were even evident within the same type of nut. Highly significant differences ($P < 0.001$–0.01) were found in the levels of stearic, α-linolenic and arachidic (C20:0) acids between non-cocoa- and cocoa-flavoured PBMAs. The differences are attributed to the fatty acid profile of cocoa beans and various nuts. Stearic acid is the major saturated fatty acid in cocoa beans [34], whereas walnut contains high levels of α-linolenic acid in comparison to almonds and hazelnuts [35] (Table 5).

Dietary guidelines recommend reducing the intake of SFA and replacing them with unsaturated fats like PUFA and MUFA to promote healthy food-based dietary patterns [36]. Distinctive differences were observed between the nut and oat-based samples. Nut-based samples had a higher MUFA content in comparison to oat-based products. SFA and PUFA contents were higher in oat-based

Table 3 Compliance with European Union tolerance limits [32]

Sample no.	Type	Protein	Fat	Carbohydrate	Sugars	Edible fibre
Non-cocoa-flavoured plant-based milk alternative						
1	Almond	0.14	0.23	1.73	0.40	1.39
2	Almond	0.07	0.08	0.39	0.17	0.49
3	Almond	0.16	0.77	0.98	1.97	0.09
4	Almond	0.07	0.78	0.33	0.01	0.09
5	Almond	0.06	0.33	0.50	0.40	0.01
6	Almond	0.10	0.33	0.24	0.52	0.01
7	Almond	0.20	0.53	0.79	0.08	0.53
8	Almond	0.29	0.03	1.15	1.73	0.59
9	Oat	0.04	0.03	0.40	0.82	1.29
10	Oat	0.27	0.28	1.27	2.78	0.99
11	Oat and seeds	0.58	0.32	**6.07**	1.92	0.41
12	Oat and hazelnut	0.01	0.37	0.79	1.73	1.19
13	Coconut	0.04	0.56	1.82	0.20	0.21
14	Peanut	0.04	0.48	1.89	1.08	1.39
Cocoa-flavoured plant-based milk alternative						
1	Almond	0.03	0.18	1.50	1.70	0.01
2	Almond	0.21	0.99	**3.06**	0.02	0.69
3	Almond	0.29	0.33	**4.51**	0.33	0.58
4	Oat	0.05	0.22	**2.81**	0.37	1.49
5	Oat and carob	0.42	0.95	0.36	0.17	0.99
6	Hazelnut	0.03	1.18	0.31	0.70	0.72
7	Hazelnut	0.44	0.43	**2.42**	0.28	0.18
8	Walnut	0.19	**1.58**	**3.18**	0.15	0.48

Bold numbers indicate nutrients exceeding tolerance limits

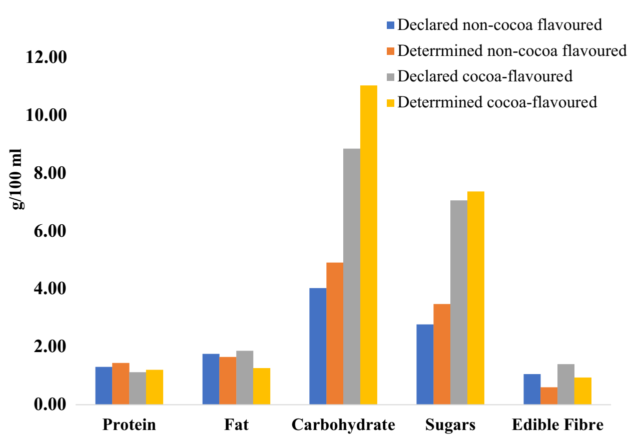


Fig. 1 Declared and determined nutrient composition of non-cocoa- and cocoa-flavoured plant-based milk alternatives. Determined values were converted to g/100 ml using density values—data not shown

products. A similar composition was reported by Martínez-Padilla et al. [1] for commercial almond-, oat- and hazelnut-based products. The major fatty acids found in PBMAs were SFA, such as palmitic acid (C16:0) and stearic acid (C18:0), as well as UFA, such as oleic acid (C18:1 cis-9), linoleic acid (C18:2 n-6), and α-linolenic acid (C18:3 n-3).

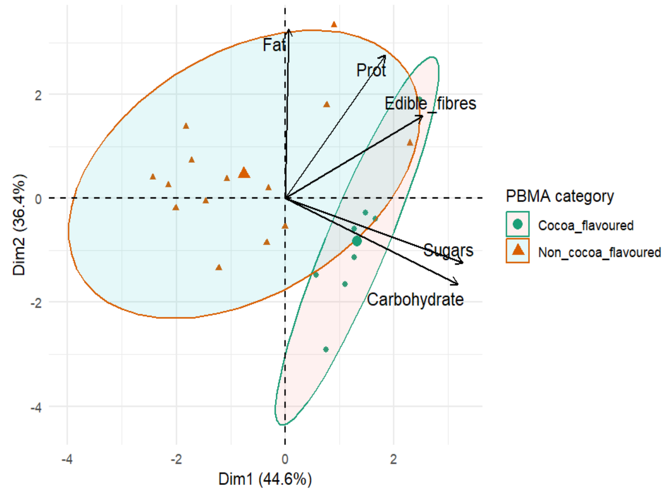
The PUFA/SFA ratio is commonly used to evaluate the impact of the diet on cardiovascular health as it hypothesises that PUFA can depress low-density lipoprotein cholesterol and reduce the levels of serum cholesterol, whereas SFA contributes to high levels of serum cholesterol [21]. Guidelines recommend a PUFA/SFA ratio above 0.45 [37], as found in both categories of PBMAs overall. The high content of SFA in the coconut-based beverage leads to an extremely low value of the PUFA/SFA index. The PUFA/SFA ratio was very variable amongst the different types of PBMAs and within the same type of PBMA, such as almonds.

Atherogenicity and thrombogenicity indices were low in all types of examined PBMAs, except for the coconut-based beverage that the higher AI and TI values are related to its high content of saturated fatty acids. Low values and preferably <3 of both indices are beneficial for human health [38].

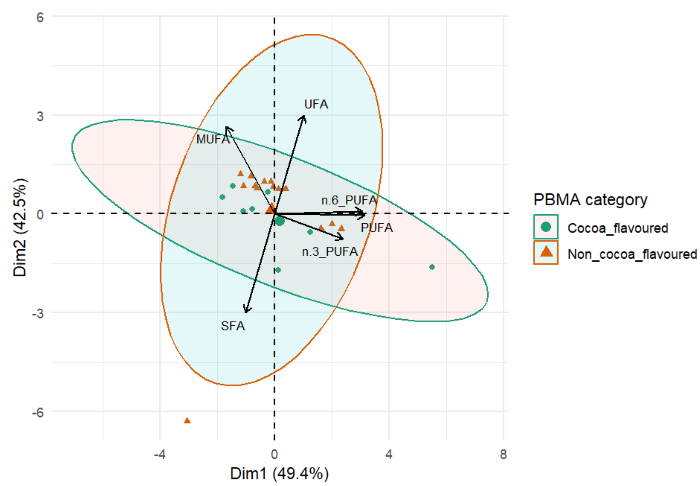
Regarding the h/H ratio, high values are desirable because it describes the relationship between the hypocholesterolemic and the hypercholesterolemic fatty acids. Lower h/H values were observed in oat-based products, whereas nut-based products had higher values. Similarly, the exceptionally high content of saturated fatty acids in the coconut-based sample negatively affected the h/H ratio.

Health-related indices did not differ ($P > 0.05$) between the non-cocoa- and cocoa-flavoured PBMAs. However, the

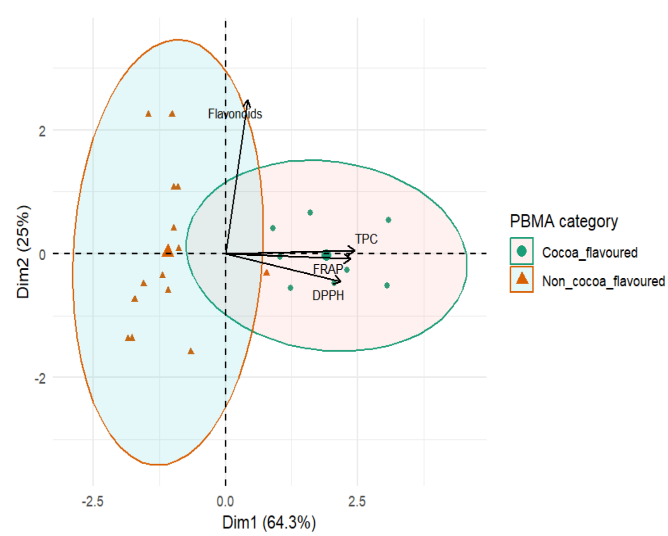
Fig. 2 Principal component analysis for **a** the chemical composition, **b** the fatty acid composition and **c** the antioxidant profile



(a) Principal Component analysis for the determined chemical composition



(b) Principal Component analysis for the fatty acid composition (lipid classes)



(c) Principal Component analysis for the antioxidant profile

Table 4 Fatty acid composition of plant-based milk alternatives

Sample no.	Type	Fatty acid												
		C8:0	C10:0	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1 *cis* n-9	C18:2 *cis* n-6	C18:3 n-3	C20:0	C21:0	C20:5
Non-cocoa-flavoured plant-based milk alternative														
1	Almond	nd	nd	nd	2.79	6.13	0.37	2.17	66.21	22.32	nd	nd	nd	nd
2	Almond	nd	nd	nd	2.19	6.19	0.46	2.61	70.65	17.90	nd	nd	nd	nd
3	Almond	nd	nd	nd	1.67	7.30	0.49	3.75	67.04	19.43	nd	0.18	0.14	nd
4	Almond	nd	nd	nd	1.80	7.14	0.36	4.45	66.01	20.12	nd	0.11	nd	nd
5	Almond	nd	nd	nd	1.50	6.99	0.38	2.71	59.17	29.25	nd	nd	nd	nd
6	Almond	nd	nd	nd	1.70	6.37	0.28	2.22	64.92	23.97	0.10	nd	0.16	0.27
7	Almond	nd	nd	nd	1.69	6.91	0.36	2.70	64.05	23.33	0.72	0.11	0.12	nd
8	Almond	nd	nd	nd	1.33	7.60	0.33	2.56	61.69	25.68	0.52	0.18	0.11	nd
9	Oat	nd	nd	nd	2.69	11.26	nd	3.79	40.93	40.10	0.45	0.21	0.34	0.22
10	Oat	nd	nd	nd	1.84	10.17	0.16	3.91	36.96	44.94	1.06	0.29	0.30	0.38
11	Oat and seeds	nd	nd	nd	1.85	9.77	nd	4.21	39.14	44.17	0.20	0.26	0.19	0.21
12	Oat and hazelnut	nd	nd	nd	1.81	6.96	0.14	2.20	74.37	14.03	0.19	0.11	0.20	nd
13	Coconut	7.73	7.66	37.67	15.04	9.52	nd	3.04	17.53	1.80	nd	nd	nd	nd
14	Peanut	nd	nd	nd	1.64	9.87	0.81	2.21	69.68	15.22	0.18	0.16	0.24	nd
Cocoa-flavoured plant-based milk alternative														
1	Almond	nd	nd	nd	2.24	7.35	0.39	3.92	62.47	23.63	nd	nd	nd	nd
2	Almond	nd	nd	nd	1.97	10.13	0.39	8.74	62.99	15.62	0.16	nd	nd	nd
3	Almond	nd	nd	nd	1.34	10.08	0.37	7.52	62.07	17.91	0.36	0.28	0.08	nd
4	Oat	nd	nd	nd	2.20	10.99	0.21	6.42	41.80	37.20	0.24	0.34	0.24	0.35
5	Oat & Carob	nd	nd	nd	5.20	17.69	nd	9.16	40.25	25.93	0.99	0.35	0.43	nd
6	Hazelnut	nd	nd	nd	1.78	8.12	0.23	5.22	72.32	12.33	nd	nd	nd	nd
7	Hazelnut	nd	nd	nd	1.60	8.69	0.15	8.44	71.74	9.12	nd	0.26	nd	nd
8	Walnut	nd	nd	nd	1.19	8.42	0.07	6.73	21.07	52.39	9.76	0.27	0.11	nd
Plant-based milk alternative category average														
Non-cocoa-flavoured		7.73	7.66	37.67	2.82	8.01	0.38	3.04	57.03	24.61	0.43	0.18	0.20	0.27
Cocoa-flavoured		nd	nd	nd	2.19	10.18	0.26	7.02	54.34	24.27	2.30	0.30	0.22	0.35
Significance		–	–	–	NS	NS	NS	***	NS	NS	***	**	NS	–

nd not detected, *NS* non-significant

**$P < 0.01$; ***$P < 0.001$

Table 5 Nutritional indices of fatty acid composition of plant-based milk alternatives

Sample no.	Type	Nutritional index						
		SFA	MUFA	PUFA	PUFA/SFA	AI	TI	h/H
Non-cocoa-flavoured plant-based milk alternative								
1	Almond	11.10	66.58	22.32	2.01	0.19	0.25	9.43
2	Almond	10.99	71.10	17.90	1.63	0.17	0.25	10.75
3	Almond	13.04	67.53	19.43	1.49	0.16	0.29	9.72
4	Almond	13.51	66.37	20.12	1.49	0.17	0.31	10.65
5	Almond	11.20	59.55	29.25	2.61	0.15	0.25	9.84
6	Almond	10.46	65.20	24.34	2.33	0.15	0.23	11.02
7	Almond	11.54	64.41	24.06	2.08	0.15	0.25	10.49
8	Almond	11.77	62.02	26.20	2.23	0.15	0.25	11.47
9	Oat	18.30	40.93	40.77	2.23	0.27	0.42	6.26
10	Oat	16.51	37.12	46.37	2.81	0.21	0.36	6.79
11	Oat and seeds	16.28	39.14	44.58	2.74	0.21	0.37	4.59
12	Oat and hazelnut	11.27	74.51	14.21	1.26	0.16	0.24	8.69
13	Coconut	80.66	17.53	1.80	0.02	5.55	2.85	0.53
14	Peanut	14.12	70.48	15.40	1.09	0.19	0.32	8.11
Cocoa-flavoured plant-based milk alternative								
1	Almond	13.51	62.86	23.63	1.75	0.19	0.31	8.16
2	Almond	20.83	63.38	15.78	0.76	0.23	0.52	6.72
3	Almond	19.29	62.44	18.27	0.95	0.19	0.46	8.74
4	Oat	20.19	42.02	37.79	1.87	0.25	0.49	5.21
5	Oat and carob	32.83	40.25	26.92	0.82	0.57	0.89	2.30
6	Hazelnut	15.12	72.55	12.33	0.82	0.18	0.36	8.23
7	Hazelnut	18.99	71.89	9.12	0.48	0.19	0.46	13.01
8	Walnut	16.72	21.14	62.15	3.72	0.16	0.25	13.01
Plant-based milk alternative category average								
Non-cocoa-flavoured		17.91	57.32	24.77	1.86	0.56	0.48	8.45
Cocoa-flavoured		19.69	54.57	25.75	1.39	0.24	0.47	6.82
Significance		NS	NS	NS	NS	NS	NS	NS

SFA saturated fatty acids, *MUFA* monounsaturated fatty acids, *PUFA* polyunsaturated fatty acids, *PUFA/SFA* polyunsaturated fatty acid/saturated fatty acid ratio, *AI* Atherogenicity Index, *TI* Thrombogenicity Index, *h/H* hypocholesterolaemic: hypercholesterolaemic Index, *NS* non-significant

higher content of cocoa beans in palmitic (C16:0), stearic (C18:0) and oleic (C18:1 cis-9) acids [34] has affected the nutritional indices of cocoa-flavoured PBMAs. When the coconut-based sample was excluded from the statistical analysis, significant differences were observed in the content of SFA ($P < 0.01$) and the index TI ($P < 0.01$).

When compared to retail cow milk, differences in the content of lipid classes are observed, where SFA accounted for 68.8%, MUFA for 27.3%, and PUFA for 3.97%. Additionally, the average AI and TI indices are lower than those of full-fat milk (2.60 and 3.13, respectively), whereas the PUFA/SFA and h/H ratios were significantly higher than those of the retail milk (0.06 and 0.50, respectively) [31]. In general, the nutritional indices of PBMAs were better in comparison to those reported in the scientific literature on ruminant milk [21].

A direct comparison of the nutritional profile of fat in PBMAs with that of cow milk may not be suitable, as milk fat is considered the most complex amongst natural fats due to its composition, which consists of approximately 400 different fatty acids [39]. Additionally, PBMAs contain vegetable oils such as sunflower oil that provide a smooth mouthfeel and a silky aspect [1, 29]. Thus, the fatty acid profile is not only related to the plant material of the PBMAs. Finally, nutritional indices are based on the overall food intake rather than individual components or specific foods. This distinction is particularly relevant in PBMAs as their lipid content is typically less than 2 g per 100 ml, resulting in a minimal contribution to daily fat intake. The Principal Component Analysis (PCA) revealed that the two principal components collectively account for over 90% of the total variability in the data set, even though the groups are not distinctly separated (Fig. 2).

Antioxidant profile

TPC content differed between the examined samples ranging from 0.19–0.53 to 0.72–1.13 GAE/mL for non-cocoa and cocoa-flavoured PBMAs (Table 6). Oat-based non-cocoa PBMAs had a higher TPC than nut-based products, whereas the combination of oat and seeds or nuts increased the TPC. The lowest TPC content was found in the coconut-based beverage, whereas TPC was variable within the almond-based products. Silva et al. [40] reported higher TPC for oat-based samples and variable TPC for almond and coconut-based products. Moreover, higher TPC and flavonoid contents have been reported by Aly et al. [41] in oat-based products compared to nut-based products. When cocoa-flavoured PBMAs are examined, no pattern is found between oat and nut-based products, and in contrast to the non-cocoa-flavoured PBMAs, higher TPC was observed in almond-based products in comparison to oat-based on average. With regard to flavonoid content, a subclass of polyphenols, no consistent pattern was observed between the nut and almond-based products in both categories of PBMAs. The flavonoid content was variable within the same category of PMBAs, and greater variability was observed in non-cocoa PBMAs rather than the cocoa-flavoured products. The average flavonoid content was lower in nut-based products than

Table 6 Antioxidant profile of plant-based milk alternatives

Sample no.	Type	TPC[1] (mg GAE/mL)	Flavonoids[2] (mg RE/mL)	DPPH[3] (µM TE/mL)	FRAP[4] (µM TE/mL)
Non-cocoa-flavoured plant-based milk alternative					
1	Almond	0.28	0.04	nd	0.10
2	Almond	0.24	0.04	nd	0.08
3	Almond	0.28	0.08	0.07	0.51
4	Almond	0.24	0.20	nd	0.13
5	Almond	0.36	0.08	0.42	0.33
6	Almond	0.31	0.09	0.40	0.27
7	Almond	0.43	0.20	0.05	0.32
8	Almond	0.41	0.11	0.45	0.39
9	Oat	0.43	0.15	0.19	0.52
10	Oat	0.46	0.15	0.19	0.61
11	Oat and seeds	0.53	0.11	1.76	1.88
12	Oat and hazelnut	0.50	0.12	0.13	0.39
13	Coconut	0.19	0.07	0.14	0.26
14	Peanut	0.39	0.04	0.71	1.83
Cocoa-flavoured plant-based milk alternative					
1	Almond	1.10	0.10	1.58	4.51
2	Almond	1.13	0.10	1.55	11.74
3	Almond	1.13	0.10	0.72	11.85
4	Oat	0.75	0.09	0.93	8.15
5	Oat and carob	0.92	0.14	0.65	9.52
6	Hazelnut	0.74	0.11	0.80	7.42
7	Hazelnut	0.72	0.13	0.79	6.46
8	Walnut	0.98	0.15	1.76	11.83
Plant-based milk alternative category average					
Non-cocoa-flavoured		0.36	0.11	0.41	0.54
Cocoa-flavoured		0.93	0.11	1.10	8.93
Significance		***	NS	***	***

nd not detected, *NS* non-significant

***$P < 0.001$

[1]Total phenolic content (TPC) expressed in mg of gallic acid equivalents (GAE)/mL; [2]Flavonoid content expressed as mg of rutin equivalents (RE)/mL

[3]Free radical scavenging activity expressed as µM of Trolox equivalents (TE)/mL

[4]Ferric reducing antioxidant power) expressed as µM of Trolox equivalents (TE)/mL

the cereal-based ones. According to Yang et al. [42], walnuts contain the highest TPC and flavonoid content, followed by peanuts, hazelnuts and almonds. However, this pattern was only partially observed in both categories of PBMAs of the present study.

With regard to the antioxidant activity, examined either as free radical scavenging activity (DPPH) or as ferric reducing antioxidant power (FRAP), variations were observed in both non-cocoa- and cocoa-flavoured PBMAs. The antioxidant capacity (DPPH) ranged from 0.07–1.76 to 0.65–1.76 μM TE/mL for the non-cocoa- and cocoa-flavoured PBMAs. Similarly, the antioxidant capacity (FRAP) ranged from 0.08–1.88 to 4.51–11.85 μM TE/mL for the non-cocoa- and cocoa-flavoured PBMAs. Antioxidant activity (DPPH) was not detected in the three almond-based samples. Silva et al. [40] could not detect antioxidant activity in some rice, peanut and oat samples. The latter authors also reported variability in the antioxidant activity within the same type of PBMA (almond, oat and coconut). Aly et al. [41] also reported lower FRAP values in coconut-based PBMAs in comparison to oat-based PBMAs. The antioxidant activity examined as DPPH and FRAP were not expressed to the same degree within the same sample as each assay employs different mechanisms. Specifically, DPPH is based on single electron transfer, whilst FRAP is based on hydrogen atom transfer [43]. Highly significant differences ($P < 0.001$) between non-cocoa and cocoa PBMAs were observed in TPC, free radical scavenging activity and FRAP, whereas no differences ($P > 0.05$) were found in the content of flavonoids (Fig. 3). Although cocoa, nuts and cereals contain compounds with antioxidant function parameters, such as origin, variety, processing conditions, and interaction with other ingredients, could affect their polyphenol content and profile and subsequently the antioxidant activity [40, 44]. Limited research has been conducted to extensively study the antioxidant profile of PBMAs.

In cow milk, the published DPPH and FRAP values are 0.0709 and 0.0489 μM TE/mL, respectively [45]. Furthermore, there is considerable variation in the reported TPC values of cow milk, ranging from 0.0489 to 0.69 mg GAE/mL [40, 45]. The wide range makes it difficult to conclude on differences in TPC between PBMAs and cow milk.

The Principal Component Analysis (PCA) demonstrated that the two groups of PBMAs are not distinctly separated despite the fact that the two principal components together account for nearly 90% of the overall variability in the data set (Fig. 2).

Physicochemical properties

The pH of PBMAs was high, far above the pH of cow milk (6.65) in most of the examined samples. However, the oat and carob cocoa-flavoured sample had lower pH in relation to cow milk (Table 7). Barišić et al. [46] reported that the pH of cocoa-based beverages is affected by the type of cocoa used. Beverages made with alkalized cocoa will have a higher pH and darker colour compared to non-alkalized cocoa beverages, which typically have a lower pH. The oat and the carob cocoa-flavoured product exhibited the lowest colour saturation values in relation to the other cocoa-flavoured PBMAs. The oat and the carob cocoa-flavoured products were produced by a small local manufacturer that might have followed a different production procedure in relation to the other samples produced by leading dairy companies. The pH values are higher than those reported for almond, oat, and peanut PBMAs [14, 47]. Non-cocoa-flavoured PBMAs had significantly higher ($P < 0.05$) pH than the cocoa-flavoured ones.

The Brix and the refractive index values exhibited significant variability in non-cocoa-flavoured PBMAs, ranging from 1.80–18.05 to 1.0302–1.3770, respectively. However, in cocoa-flavoured PBMAs, the range was narrower, with values ranging from 11.40 to 17.60 for Brix and 1.3504–1.3576 for refractive index. Frühauf et al. [14] reported that the soluble solid values (Brix) could be attributed to various factors, such as the botanical origin of the plant material, the degree of extraction of soluble solids from the type of plant material, and the beverage formulation, which typically includes multiple types of salts, minerals, and sugars. Significant differences ($P < 0.01$) in the Brix values were found between non-cocoa and cocoa-flavoured PBMAs, whereas there were no differences in the refractive index between the two categories of PBMAs. The higher Brix values for the cocoa-flavoured PBMAs are attributed to the cocoa content and to the fact that all these products contain sugar. The lack of significant difference between the two categories of PBMAs in the refractive index is related to the fact that Brix values measure sucrose, whereas the refractive index measures sucrose and other sugars. The refractive index of reduced-fat (1–2%) cow milk ranges from 1.465 to 1.460 [48].

Similarly to Brix and refractive index values, electrical conductivity values were not consistent ranging from 0.91 to 6.77 mS/cm in the non-cocoa-flavoured PBMAs. However, no significant differences ($P > 0.05$) were found between non-cocoa- and cocoa-flavoured PBMAs. The electrical conductivity of semi-skimmed cow milk (fat content 1.61%) is 5.23 mS/cm [49].

The viscosity of both non-cocoa- and cocoa-flavoured PBMAs demonstrated substantial variation, ranging from 16.67–36.70 to 10.32–66.70 mPa·s, respectively. These values were higher compared to skim milk and whole-fat milk (2.2 mPa and 2.6 mPa, respectively), and consistent with findings from other studies [8, 14]. No significant differences ($P > 0.05$) were found between con-cocoa- and cocoa-flavoured PBMAs, and the higher viscosity values

Table 7 Physico-chemical characteristics of plant-based milk alternatives

Sample no.	Type	pH	Brix	Refractive Index (nD)	Electrical conductivity (mS/cm)	Viscosity (mPa·s)	Colour				
							L*	a*	b*	Chroma	Whiteness Index
Non-cocoa-flavoured plant-based milk alternative											
1	Almond	7.59	3.30	1.3770	3.66	24.68	85.98	− 3.75	2.03	4.26	85.35
2	Almond	7.70	5.10	1.3408	3.50	25.20	83.66	− 3.54	2.67	4.43	83.07
3	Almond	7.26	7.80	1.3509	1.01	26.84	85.23	− 3.45	1.56	3.79	84.75
4	Almond	7.50	1.80	1.3350	0.91	36.70	85.98	− 3.21	2.27	3.93	85.44
5	Almond	7.73	8.60	1.3459	2.33	21.56	83.96	− 3.17	2.57	4.08	83.45
6	Almond	7.60	7.60	1.3443	2.53	22.40	83.10	− 3.18	2.10	3.81	82.68
7	Almond	8.62	12.35	1.3513	4.82	16.67	77.45	− 2.30	3.39	4.10	77.08
8	Almond	7.40	14.10	1.3542	6.77	35.16	70.33	− 1.20	2.70	2.95	70.18
9	Oat	8.28	12.00	1.3508	3.57	20.87	74.64	− 4.68	8.03	9.29	72.99
10	Oat	8.63	18.05	1.3605	4.66	21.34	68.83	− 1.64	3.87	4.20	68.55
11	Oat and seeds	7.01	11.60	1.0374	2.70	22.88	77.47	− 1.59	1.84	2.43	77.34
12	Oat and hazelnut	8.40	11.35	1.0302	3.60	18.81	81.11	− 3.77	4.48	5.86	80.22
13	Coconut	7.80	6.90	1.3431	2.60	24.31	88.77	− 1.88	− 6.27	6.55	87.00
14	Peanut	7.56	4.50	1.3393	3.82	27.90	65.63	0.94	6.98	7.04	64.92
Cocoa-flavoured plant-based milk alternative											
1	Almond	7.04	12.80	1.3517	3.45	19.27	48.68	7.86	4.99	9.31	–
2	Almond	7.59	12.10	1.3520	4.41	27.11	41.51	7.65	2.56	8.06	–
3	Almond	7.65	16.70	1.3572	4.52	37.54	35.38	6.20	− 0.40	6.21	–
4	Oat	7.53	16.00	1.3576	4.39	27.56	31.92	6.12	− 1.55	6.31	–
5	Oat and carob	6.23	12.10	1.3517	3.12	10.32	39.38	5.57	− 0.65	5.60	–
6	Hazelnut	6.90	14.00	1.3569	4.03	32.79	37.93	7.70	5.41	9.41	–
7	Hazelnut	7.57	11.40	1.3504	4.11	66.70	38.28	7.95	2.40	8.30	–
8	Walnut	7.51	13.00	1.3522	4.12	65.70	43.64	9.66	5.59	11.15	–
Plant-based milk alternative category average											
Non-cocoa-flavoured		7.79	8.93	1.3043	3.32	24.67	79.44	− 2.60	2.73	4.77	78.79
Cocoa-flavoured		7.25	13.51	1.3537	4.02	35.87	39.59	7.34	2.29	8.04	–
Significance		*	**	NS	NS	NS	***	***	NS	***	–

NS non-significant; $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

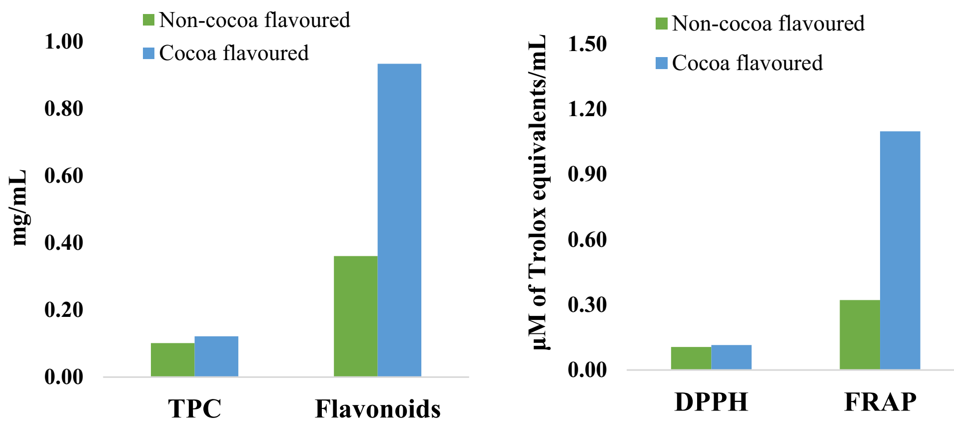


Fig. 3 Total phenolic (mg gallic acid equivalents/mL) and flavonoids (mg rutin equivalents/mL) content. Antioxidant activity by DPPH and FRAP (µM Trolox equivalents/mL) in non-cocoa- and cocoa-flavoured plant-based milk alternatives

of cocoa-flavoured PBMAs are related to the higher solid contents. All products contained gellan gum as a thickening agent that increases viscosity, but no pattern was observed within products of the same type regarding plant origin. Jeske et al. [8] also reported variable viscosity values in PBMAs of the same plant origin, i.e. almond. According to McClements [15], the amount of oil bodies, fat droplets, other colloidal matter and the presence of thickening agents affect the rheological properties of PBMAs.

Colour data shows that the non-flavoured almond and coconut PBMAs had high luminosity (L*) values indicating a higher light reflectance for the chromaticity parameters (a* and b*), a phenomenon specific for white substances. All non-cocoa-flavoured samples had luminosity values greater than 50, which is considered the threshold value for the characterisation of white samples [14]. The negative a* values observed in non-flavoured PBMAs indicate a tendency towards a greener colour, whilst the negative b* values found in both categories of PBMAs are associated with bluer colour. Chroma (saturation) values are affected by the chromaticity parameters (a* and b*) describing the perceived colour intensity of the samples. Greater saturation values are associated with a higher perception of colour intensity. All colour parameters (L*, a*, b* and chroma) were very variable in both categories of PBMAs. McClements et al. [15] also reported high variability in the colour coordinates of PBMAs and attributed these differences to the size and concentration of the present particles, as well as the types and levels of the chromophores. There was a highly significant difference ($P < 0.001$) between non-cocoa and cocoa-flavoured samples in the L*, a* and chroma values.

According to Vogelsang-O'Dwyer et al. [50], the Whiteness Index is a useful tool for evaluating the colour of milk alternatives, aiming to simulate the characteristic white colour of cow milk and enhance consumer appeal. The reported Whiteness Index for full and reduced-fat cow milk is 81.89 and 89.10 [8, 50]. The lowest Whiteness Index was observed in the peanut milk alternative, whereas the highest was found in coconut milk. The Whiteness Index is related to the plant material and processing conditions. The average Whiteness Index for almond-based alternatives was 81.50, making these products comparable to full-fat cow milk. For oat-based products, the Whiteness Index was far below the reported values for cow milk enabling distinction from cow milk. In the study conducted by Moss et al. [28], which explored consumer perceptions and attitudes towards PBMAs, it was found that the white colour associated with almond milk was positively regarded and increased consumer preference. On the other hand, the yellow colour associated with oat milk was negatively correlated with consumer liking. Jeske et al. [8] reported lower Whiteness Index values in all types of examined commercial products compared to the present study. Additionally, the latter workers noted significant variability in the Whiteness Index amongst various types of PBMAs.

Conclusions

The present work aimed to study the nutritional properties and physicochemical characteristics of commercial PBMAs sold under refrigerated conditions. To our knowledge, this is the first study also examining the properties of commercially available cocoa-flavoured PBMAs. The results have shown that the nutritional profile of PBMAs is very versatile with its composition being influenced by factors, such as product type and formulation of ingredients. Therefore, consumers should study the declared composition to enable them to choose products suitable to their personal nutritional requirements in relation to growth stage and health. Similarly, antioxidant profile and physicochemical characteristics differ between products and are affected by the product matrix. Differences in the nutritional value and physicochemical characteristics were found between non-cocoa- and cocoa-based PBMAs. However, a limitation of the study is that the product composition of non-cocoa- and cocoa-flavoured PBMAs differs in terms of product ingredients, and this variation is not solely due to the addition of cocoa. As a result, making a direct comparison between the two types of PBMAs may be inapplicable. However, it provides a general insight into the differences in various qualitative characteristics of non-cocoa- and cocoa-based PBMAs widely available in the Greek market.

Finally, future research on PBMAs should be intensified given the continuous expansion of the commercial range of PBMAs. In addition, mineral and vitamin contents and anti-nutrient factors should be determined to ensure a comprehensive assessment of the nutritional value of PBMAs.

Author contributions EK: conceptualization, writing-original draft preparation, writing-reviewing and editing. ZB: methodology, formal analysis. VP: methodology, investigation. GP: Data curation, writing—reviewing and editing. IN: investigation. P-AN: investigation. ET: investigation. PM: supervision, methodology, project administration.

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Data availability The data presented in this study is contained within the article.

Declarations

Conflict of interest The authors declare no conflict of interest.

Compliance with ethics requirements This study does not contain any studies with human participants or animal performed of any of the authors.

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