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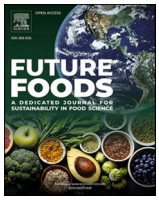
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# The Rise of Plant-Based Yoghurts: Market Dynamics and Product Characterization in Relation to Dairy

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ABSTRACT

In the context of increasing global efforts to promote sustainable food systems and shift away from animal-based products, plant-based yoghurts have emerged as a promising alternative to dairy. Aligned with the United Nations 2030 Agenda for Sustainable Development, particularly Goal 2 - Zero Hunger, these products aim to support both human and planetary health by offering nutritionally adequate and environmentally conscious solutions. This study explores the global plant-based yoghurt market by analysing current trends and evaluating the physicochemical properties of eight commercial products available on the Irish market, in comparison to traditional dairy yoghurts. The results from the market research highlight a diverse range of base ingredients, primarily soy (41%) and coconut (26%), followed by oat (13%), almond (8%), cashew (6%), chickpea (4%), and fungi (2%). Blended formulations were also prevalent, with 40 out of 145 products combining different plant bases such as oat with faba bean or chickpea with cashew. Analysis of the commercial yoghurts showed that the protein content of the soy-based products (3.3% to 5.1%) was the most comparable to the dairy ones (3.8% and 4.7%). Coconut-based yoghurts were the most similar in colour to dairy, with whiteness index values of 79.69% and 80.93% determined, closely matching those of dairy yoghurts (82.82% and 81.52%). Regarding rheological behaviour, the damping factor obtained from the frequency sweep test indicated that soy-based samples (0.20 to 0.27) were comparable to dairy yoghurts (0.24 to 0.25). The differences in rheological and textural properties observed in the other plant-based yoghurts were most likely due to the addition of various starches and pectins used as stabilisers and thickening agents. The results obtained in this study provide a clear overview of the current market landscape for plant-based yoghurt and highlight the link between product formulation and the resulting physicochemical and rheological properties.

## 1. Introduction

Yoghurt is widely recognised and consumed around the world, from developed and underdeveloped countries (Chandan, 2006). Traditionally made from fermented animal milk, yoghurt has long been associated with positive effects on gut health, metabolic activity, and the balance of intestinal microflora (Shah, 2017). Among these health benefits, yoghurt is known to have a positive impact on gastrointestinal infections, reduction of serum cholesterol and cardiovascular disease and anticancer effects (Chandan, 2006). However, as global priorities shift toward more sustainable and equitable food systems, attention is increasingly focusing on plant-based alternatives that can offer similar nutritional benefits with a lower environmental impact. In line with the 2030 Agenda for Sustainable Development, particularly Goal 2 - Zero Hunger, which aims to ensure food security and promote sustainable agriculture, reducing dependence on animal-based products is a key objective (Goal 2: Zero Hunger). In this context, the development of high-protein alternatives that do not rely on animal-derived ingredients has become increasingly important to support both environmental sustainability and global nutrition goals. Such innovations not only support better human nutrition but also contribute to the reduction of greenhouse gas emissions (Jaeger et al., 2023b).

In this evolving landscape, the plant-based yoghurt sector has gained substantial expansion, largely due to increasing consumer demand for nutritious, environmentally friendly, and allergen-conscious alternatives (Types of Consumers for Targeted Marketing, 2023). Organizations

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such as The Good Food Institute support the growing role of plant-based and alternative proteins in balanced diets around the world. They also welcome the Codex Alimentarius Commission's focus on these innovative food sources and production methods as a positive step forward (Motarjemi, 1991). To meet these demands, plant-based yoghurts are currently developed from a wide array of plant sources, including seeds, nuts, legumes, cereals, pseudo-cereals, and fruit pulps, offering diverse nutritional profiles and sensory characteristics that can appeal to a broad range of consumers (Montemurro et al., 2021).

The global market of plant-based yoghurt was estimated at USD 3.82 billion in 2024 and is predicted to grow at a compound annual growth rate (CAGR) of 19.7% from 2025 to 2030 (Vegan Yogurt Market Size & Share, 2025). However, growth remains modest compared to the dairy yoghurt market, valued at approximately USD 135 billion in 2025, with non-dairy alternatives representing only 1-4% of global yoghurt sales by value (Yogurt Market Size, Share, 2025). Retail data from mature European markets such as Germany and France indicate flat or minimal volume growth for plant-based yoghurts, whereas increases are mainly observed in Spain, the Netherlands, and the UK, suggesting signs of market saturation in some regions (European plant-based sales data - GFI Europe 2025). Despite this, the growth of plant-based yoghurts is driven by the rise of plant-based diets, which have been gaining popularity, particularly among flexitarians and vegans. These individuals are looking to replace the use of animal and dairy products, including yoghurts. Euromonitor International conducted a Lifestyle Survey, which found that nearly 50% of global consumers follow this type of diet (Euromonitor). As reported by Statista (Plant-based yogurt, cheese, and eggs worldwide, 2023), in Europe, consumers who reduce meat consumption tend to eat more often plant-based yoghurt. In 2023, plant-based yoghurt was the second-most frequently consumed plant-based food product among flexitarians in selected European countries, with 33% of respondents reporting regular consumption, following plant-based milk at 36%. While the plant-based yoghurt market is rapidly expanding due to growing consumer demand for dairy alternatives, several limitations still prevent them from fully matching traditional dairy yoghurts. In terms of nutrition, many plant-based options contain significantly less protein and often lack a complete amino acid profile, unless fortified or blended (D'Andrea et al., 2023). From a sensory perspective, undesirable off-flavours, particularly the "beany" notes in soy and pulse-based products, can negatively affect consumer acceptance (Jaeger et al., 2023a). Additionally, plant-based yoghurts tend to have weaker gel structures and rely more heavily on stabilisers to achieve acceptable texture and water retention, which can impact overall functionality and shelf stability (Marlapati et al., 2024; Montemurro et al., 2021). These challenges highlight the need for further innovation in formulation and processing to bridge the gap with dairy products.

As part of the current study, an online search was performed to obtain an overview of commercially available plant-based yoghurts produced through fermentation (see supplementary material). 145 plant-based yoghurts were identified, with the key producers being USA and UK, with these findings consistent with data reported in several market research publications (D'Andrea et al., 2023; (Plant-based yogurt, cheese, and eggs worldwide, 2023).). The most widely used base ingredient is soy (41% of products), followed by coconut (26%), with raw materials such as chickpea and fungi also gaining traction, highlighting the diversity and level of innovation characterising this sector. Also, many commercial plant-based yoghurts combine different plant ingredients to closely resemble the flavour, texture, and nutritional qualities of conventional dairy yoghurt. 83% were flavoured, reflecting a common strategy to improve the sensory profile, particularly those made from legumes, which often exhibit "beany" notes, as well as other bases that may display "nutty" nuances, bitterness, astringency, or grassy attributes that are generally unappealing to consumers. Market data highlights that dietary and allergen-related claims, such as "Vegan", "Dairy Free", and "Gluten Free", are the dominant marketing strategies in this category, complemented by nutritional claims like "source of protein" or "source of calcium", reflecting an industry-wide effort to meet consumer expectations for both functionality and nutritional quality. Despite this, achieving protein levels comparable to dairy yoghurt remains a key technological challenge, with most commercial plant-based yoghurts falling below the protein contents typically found in regular or Greek dairy yoghurt.

In this study, the physicochemical and rheological properties of eight plant-based yoghurts, available in the Irish market, in comparison with two dairy yoghurts were analysed. Preliminary market insights were also integrated, providing a comprehensive characterization of commercially available plant-based yoghurts. This research helps to understand the quality, texture, and consumer-relevant properties of plant-based alternatives, guiding both product development and informed consumer choices in a rapidly growing market.

## 2. Materials & Methods

### 2.1. Commercial Yoghurts

Eight commercial plant-based yoghurts were purchased based on their regional availability. Additionally, two styles of dairy yoghurts (regular and Greek) were chosen as benchmarks, to cover the wide range of viscosities, structural characteristics and product types represented within the plant-based yoghurts. All samples were declared as fermented yoghurts. The commercial names and brands are not shown, and the samples are presented under alternative identifiers. The list of ingredients and nutritional composition of each sample is reported in Table 1. Allergens are listed in bold. All information was sourced from the official websites of the manufacturers or from retailers, including supermarkets and online platforms.

### 2.2. pH and Total Titratable Acidity (TTA)

pH and TTA were measured according to Jaeger et al. (Jaeger et al., 2024) by weighing 10 g of the sample into a beaker, and adding 95 mL of water and 5 mL of acetone. The mixture was stirred with a stirring bar. The pH was recorded using a pH meter (Mettler Toledo, Columbus, OH, USA), and the TTA was evaluated through titration with 0.1 M NaOH, continuing until a pH of 8.5 was reached, followed by a 3-minute readjustment period. TTA values are reported as mL of 0.1 M NaOH required per 10 g of sample.

### 2.3. Water Activity and Water Holding Capacity (WHC)

An Aqua Lab water activity meter (AQUA LAB GmbH & Co.KG, Höhr-Grenzhausen, Germany) was used to measure the water activity.

The method described by Grasso et al. (Grasso et al., 2020) was used for analysing Water Holding Capacity (WHC), with minor modifications. To summarise, 40 g of commercial yoghurt was placed in a 50 mL tube (Thermo Fisher Scientific, Waltham, MA, USA) and centrifuged at 640 × g for 20 minutes at 4 °C using a Sorvall RC 5C Plus centrifuge, which had a Sorvall SS-34 rotor (Du Pont Instruments, Wilmington, DE, USA). After centrifugation, the supernatant was collected and weighed. WHC was calculated according to Equation (1):

$$WHC\ (\%) = \left(1 - \frac{weight\ of\ supernatant}{weight\ of\ sample}\right) \times\ 100 \quad (1)$$

### 2.4. Colour and Whiteness Index (WI)

The colour of the samples was assessed using a Chroma Meter (Minolta CR-300, Osaka, Japan) operating in the CIE Lab* colour space. Prior to measurement, the device was calibrated with a standard white tile. In this colour space, values are represented on Cartesian coordinates: the L* value indicates lightness, the a* value denotes the red

**Table 1**
List of ingredients of commercial yoghurts.

| Yoghurt | Ingredients |
|---|---|
| Dairy<br>*Regular plain yoghurt* | Skim **milk**, Ultrafiltered skim **milk**, Cream, Skim **milk** powder, Active probiotic culture (*Bifidobacterium lactis* CNCM I-2494), and active bacterial cultures. |
| Dairy-G<br>*Plain Greek yoghurt* | Irish Whole **Milk** (76%), Irish Cream (**Milk**) (16%), Skimmed **Milk** Powder, Live Yoghurt Cultures |
| Soy-1<br>*Plain soy yoghurt* | **Soya** base (Water, Hulled **soya beans** (10.7%)), Sugar, Calcium (Tri-calcium citrate), Stabiliser (Pectins), Acidity regulators (Sodium citrates, Citric acid), Flavouring, Sea salt, Antioxidants (Tocopherol-rich extract, Fatty acid esters of ascorbic acid), Vitamins (B12, D2), Yoghurt cultures (*S. thermophilus, L. bulgaricus*). |
| Soy-2<br>*Plain soy yoghurt* | Water, **soya beans** (13%), Sugar, Modified Maize Starch, Potato Starch, Calcium Phosphates, Sea Salt, Acidity Regulator: Citric Acid; Vitamin D2, Vitamin B12, Flavouring, Lactic Acid Cultures. |
| Soy-3<br>*Greek-style soy yoghurt* | **Soya** juice* 99% (water, **soya beans*** 11,9%), thickener: pectin, selected live cultures. |
| Oat<br>*Greek-style oat yoghurt* | Water, oats 11%, rapeseed oil, potato starch, potato protein, acids (malic acid, lactic acid), stabiliser (pectin), minerals (calcium carbonate, calcium phosphate, potassium iodide), salt, vitamins (D2, B12). |
| Coconut-1<br>*Plain coconut yoghurt* | Water, Coconut Milk (20%), Modified Maize Starch, Dextrose, Natural Flavourings, Calcium Phosphates, Salt, Thickener (Pectins), Colour (Carotenes), Live Dairy Free Cultures (*S. thermophilus, L. bulgaricus*), Vitamin D2, Vitamin B12. |
| Coconut-2<br>*High viscosity coconut yoghurt* | Coconut Milk (67%), Coconut Water (28%), Corn Flour, Corn Fibre, Potato Flour, Fruit Pectin, Cultures (*S. thermophilus + L. bulgaricus, Lactobacillus acidophilus, Bifidobacterium lactis*). |
| Soy-Faba<br>*High protein, high viscosity soy yoghurt* | **Soya** base (85%) (Water, Hulled **soya beans** (9.8%)), Sugar, **Soya** protein isolate, Strawberry-red currant-raspberry mix (2%) (Strawberry (0.8%), Red currant (0.8%), Raspberry (0.4%)), Faba bean protein, Calcium (Tri-calciumcitrate), Stabiliser (Pectins), Natural flavourings, Modified starch, Black carrot concentrate, Acidity regulators (Citric acid, Sodium citrates), Vitamins B12, D2, Live cultures (*S. thermophilus, L. bulgaricus*). |
| Oat-Faba<br>*High viscosity blend yoghurt* | Water, Sugar, Fully Hydrogenated Coconut Oil, Gluten-Free Oat Flour (4%), Coconut Milk (4%), Faba Bean Protein, Rapeseed Oil, Flavourings, Modified Starch, Salt, Emulsifiers (E472e, E471), Calcium, Vitamins (Riboflavin (B2), B12, D2), Iodine, Starter Culture: Lactobacillus acidophilus, Bifidobacterium Sp. |

(positive) to green (negative) axis, and the b* value corresponds to the yellow (positive) to blue (negative) axis. The Whiteness Index (Boeck et al., 2021) of the samples was calculated based on Equation (2):

$$WI = 100 - \sqrt{((100 - L^*)^2 + a^{*2} + b^{*2})} \quad (2)$$

### 2.5. Protein content

Protein content was determined using the Kjeldahl method (AACC Method 46-12), using a nitrogen-to-protein conversion factor of 6.25.

### 2.6. Rheological properties

The rheological properties of the commercial yoghurts were evaluated using a controlled-stress rheometer (MCR301, Anton Paar GmbH, Graz, Austria) fitted with a concentric cylinder measuring system (C-CC27-T200/SS, Anton Paar) (Boeck et al., 2022).Two rheological tests were performed: a frequency sweep test and a three-interval thixotropy test. Frequency sweeps were conducted over a range of 0.01 to 15 Hz at a constant strain of 0.1%. To assess gel-like behaviour, the slopes of G′, G″, and $|\eta^*|$ versus angular frequency ($\omega = 2\pi f$) were determined using log–log plots. The three-interval thixotropy test (Boeck et al., 2021) consisted of an initial oscillatory interval (0.1% strain at 1 Hz frequency for 120 seconds), followed by a second interval (steady shear at 200 $s^{-1}$ for 120 seconds) and a third interval (0.1% strain at 1 Hz frequency for 300 seconds). Structural breakdown due to high shear was quantified as follows (3) (Boeck et al., 2021):

$$\Delta G'[\%] = 100\% - (G'_{end} \times 100\%)/G'_{start}) \quad (3)$$

$$\Delta G''[\%] = 100\% - (G''_{end} \times 100\%)/G''_{start})$$

### 2.7. Textural properties

The textural properties of the samples were assessed using a penetration and back-extrusion test. A TA-XT2i Texture Analyzer (Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell and a 35 mm diameter extrusion disc was used to perform the test. The probe operated at a speed of 1 mm/s, with a penetration depth of 20 mm and a trigger force of 0.05 N (Silva and O'Mahony, 2018). All yoghurt samples were stored under refrigerated conditions (4 °C) and were opened immediately before the texture analysis was performed. The following parameters were recorded: firmness (maximum positive force), consistency (positive area under the curve), cohesiveness (maximum negative force), and viscosity index (negative area under the curve).

### 2.8. Statistical Analysis

All analyses were performed in triplicate. The data were first assessed for normality. For datasets that met the assumption of normal distribution, a one-way ANOVA was conducted to evaluate the homogeneity of variances. If variances were homogeneous, Tukey's post hoc test was applied; otherwise, Welch's ANOVA followed by the Games-Howell test was used. For non-normally distributed data, the non-parametric Kruskal-Wallis test was performed. All statistical analyses were conducted using IBM SPSS Statistics version 26 (Armonk, NY, USA), with a significance level set at $p < 0.05$. Statistically significant differences were determined among all sample groups.

## 3. Results and discussion

### 3.1. Nutritional composition

The nutritional values of the purchased commercial yoghurts, as per their labels, are reported in Table 2. All the nutrients are standardised per 100g. The total energy in Kcal was between 50 and 189 Kcal/100g, with oat-based yoghurts having the highest level. The labelled protein content of the plant-based yoghurts analysed ranged from 0.6 to 7.5g/100g, while the dairy products fell in the middle range, containing between 3.9 and 5.1g/100g. However, plant-based products with high protein content typically contain added protein sources other than the base ingredient (soya-faba, oat-faba, oat). Among the products without added proteins, soy-based yoghurts showed higher protein contents than coconut-based products. Dairy yoghurt generally had more protein than most plant-based alternatives, except for Soy-3, which was a Greek-style yoghurt. Coconut-1 and Coconut-2 yoghurts had the lowest protein contents, at 0.6 g/100g and 1.2 g/100g, respectively.

A similar study with comparable results was conducted by Grasso et al., (2020) who evaluated the nutritional composition of six commercial plant-based yoghurts and compared with dairy products. The soy yoghurt and dairy yoghurts had the simplest formulations, with no added hydrocolloids. While coconut yoghurt had the highest saturated fat content (4.2 g/g fat) and the lowest protein content, soy yoghurt showed a relatively high protein content (up to 4.6 g/100 g) and minimal additives (Grasso et al., 2020).

The nutritional values across product categories show significant differences in carbohydrate and fat content per 100g. Among the legume-based soy yoghurts, Soy-3 has the lowest carbohydrate content at 1.4 g, while Soy-Faba, a blend of two legumes, contains 7 g. On the

**Table 2**
Nutritional Information of commercial Plant-Based Yoghurts analysed. Products marked with "*" contain added protein; "**" Greek-style yoghurts.

| Categories | Per 100g | Energy [kcal] | Carbohydrates [g] | Sugars [g] | Total Fibre [g] | Protein [g] | Fat [g] | Saturated Fat [g] | Sodium [g] |
|---|---|---|---|---|---|---|---|---|---|
| Dairy | Dairy | 65 | 4.7 | 4.7 | - | 3.9 | 3.4 | 2.2 | 0.13 |
| | Dairy-G** | 135 | 7.5 | 6.1 | 0.5 | 5.1 | 9.4 | 6.3 | 0.15 |
| Legume-based | Soy-1 | 79 | 2.1 | 2.1 | 1 | 4 | 2.3 | 0.4 | 0.25 |
| | Soy-2 | 50 | 3.3 | 1.8 | 0.6 | 4 | 2.2 | 0.3 | 0.18 |
| | Soy-3** | 53 | 1.4 | 0 | - | 5.7 | 3.3 | 0.5 | 0.11 |
| Cereal-based | Oat** | 145 | 10 | 4.1 | 0.9 | 3.3 | 10 | 0.8 | 0.11 |
| Fruit-based | Coconut-1 | 79 | 8 | 4.3 | 0.2 | 0.6 | 4.9 | 4.2 | 0.35 |
| | Coconut-2 | 120 | 5.9 | 1.6 | 1 | 1.2 | 10 | 9 | 0.04 |
| Blend 1 Legumes | Soy-Faba* | 81 | 7 | 6.8 | 1.1 | 7.5 | 2.2 | 0.4 | 0.18 |
| Blend 2 Cereal-Legume | Oat-Faba* | 189 | 17 | 14 | - | 3 | 12 | 8.6 | 0.18 |

other hand, the cereal-based option, Oat, and the cereal-legume blend, Oat-Faba, are the highest in carbohydrates, with 10 g and 17g, respectively. This marks a maximum carbohydrate difference of 15.6 g between Soy-3 and Oat-Faba.

In terms of fat content, the lowest values are found in Soy-2 and Soy-Faba, each with 2.2 g/100g. The highest fat content is again in Oat-Faba (12 g), followed by Coconut-2 (10 g) and Oat (10 g). This results in a fat difference of 9.8 g between Soy-2/Soy-Faba and Oat-Faba.

Overall, soy-based legume yoghurts stand out as the lowest in both carbohydrates and fat, making them nutritionally more valuable. In contrast, blended products, particularly those combining cereal and legumes, tend to be more energy-dense and contain significantly higher levels of macronutrients.

### 3.2. Measured protein content

In this study, protein content of the commercial plant-based yoghurts was determined and compared to that declared on the product label (Figure 1). In 2021, the Food Safety Authority of Ireland found that, out of 200 commercial yoghurts available on the Irish market, most had lower nutrient content than declared when laboratory measurements were compared to labelled values (FSAI, 2025). A similar discrepancy was reported by Jeske et al., who observed differences between measured and labelled protein content in plant-based milk (Jeske et al., 2017). The same trend was observed in the current study. The results are consistent across all products with most of them showing measured values that are slightly lower than those declared on the label. For instance, soy-1 had a measured protein content of 3.7% compared to the labelled 4%, soy-2 measured 3.3% versus 4%, oat measured 2.8% compared to 3.3%, and coconut-2 showed a significant gap, with 0.6% measured versus 1.2% declared. A different measurement method may be responsible for these differences. The Kjeldahl method involves chemical digestion, distillation, and titration. It determines organic nitrogen and ammonia (but not total nitrogen) by converting protein nitrogen into ammonium ions through boiling in sulfuric acid with a catalyst. In contrast, the Dumas method relies on high-temperature combustion and directly measures the total nitrogen content of the sample (Thompson et al., 2002). Several studies suggest that the Dumas method typically gives higher protein values than those obtained with the Kjeldahl method (Jung et al., 2003).

### 3.3. pH and Total Titratable Acidity (TTA)

The pH and TTA values are reported in Table 3. The pH values varied between 4 and 4.8 across the samples. Among the samples tested, the oat-based yoghurt had the lowest pH, which was not significantly different from the pH observed in the dairy Greek yoghurt control (Dairy-G). Coconut-based yoghurt (Coconut-2) exhibited the highest pH value (4.80), which aligns with findings reported by Daszkiewicz et. al.

**Table 3**
pH and TTA values of commercial plant-based and dairy yoghurts. Data are presented as mean ± standard of triplicate measurements. Values within the same column which share a lowercase letter do not differ significantly.

| Sample | pH | TTA [ml 0.1M NaOH/10g sample] |
|---|---|---|
| Dairy | $4.46\pm0.023^{ab}$ | $10.53\pm0.029^{a}$ |
| Dairy-G | $4.38\pm0.006a^{b}$ | $14.58\pm0.076^{b}$ |
| Soy-1 | $4.65\pm0.001^{abc}$ | $7.77\pm0.029^{c}$ |
| Soy-2 | $4.77\pm0.010^{cd}$ | $5.97\pm0.029^{g}$ |
| Soy-3 | $4.87\pm0.015^{cd}$ | $5.72\pm0.104^{e}$ |
| Oat | $4.14\pm0.006^{b}$ | $6.77\pm0.076^{h}$ |
| Coconut-1 | $4.58\pm0.005^{abd}$ | $4.65\pm0.050^{f}$ |
| Coconut-2 | $4.80\pm0.124^{cd}$ | $2.42\pm0.161^{i}$ |
| Soy-Faba | $4.76\pm0.015^{cd}$ | $10.23\pm0.056^{d}$ |
| Oat-Faba | $4.64\pm0.010^{abc}$ | $5.57\pm0.076^{e}$ |

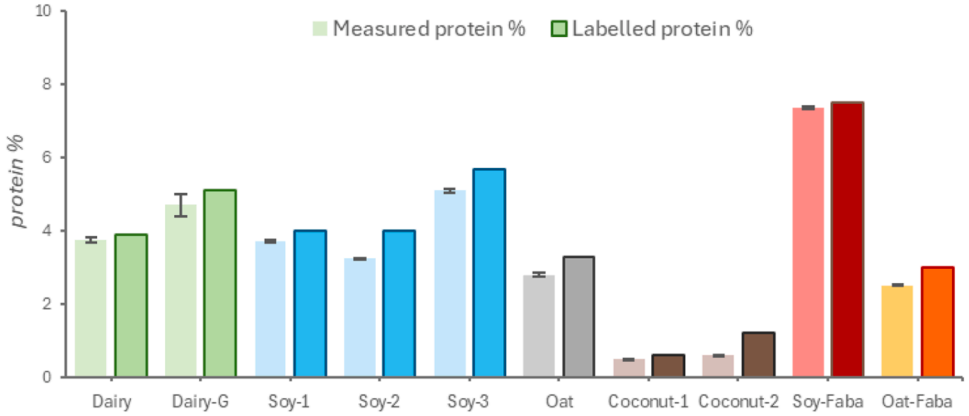



**Figure 1.** Protein content of the commercial plant-based and dairy yoghurts as declared on the product label and measured with Kjeldahl method.

(2024), who observed that fermented products made from coconut milk had higher pH values compared to those made exclusively from cow milk (Daszkiewicz et al., 2024).

The titratable acidity (TTA) results for the yoghurt samples significantly differed for most samples. These differences could be attributed to the addition of acids during yoghurt formulation to achieve the optimal pH for fermentation, as well as to the use of acidity regulators such as citric acid, malic acid, lactic acid, and sodium citrate (Grasso et al., 2020). Among the commercial products analysed, Soy-1, Soy-2, Oat, and Soy-Faba contained added acids used as acidity regulators. Moreover, the microorganisms commonly used for the fermentation of plant-based products are lactic acid bacteria, particularly *Streptococcus thermophilus, Lactobacillus bulgaricus, Lactobacillus acidophilus*, and, in some cases, *Bifidobacterium lactis*, a strain more frequently used in dairy yoghurts. These types of LAB are classified as homofermentative, as they primarily produce lactic acid during fermentation, contributing to the acidification of the yoghurt (Harper et al., 2022). Across the analysed samples, these yoghurt cultures were the most frequently listed on product labels. The TTA value was higher in dairy yoghurts, primarily because of their elevated concentration of total solids, particularly organic acids, salts, and proteins. These components contribute to a greater buffering capacity, which enhances the product's resistance to changes in pH and explains the observed differences in acidity between dairy and plant-based samples (Daszkiewicz et al., 2024).

Lactose in dairy milk also allows lactic acid bacteria to generate additional lactic acid, which increases the TTA further (Ahansaz et al., 2023).

### 3.4. Water Activity and Water Holding Capacity (WHC)

There was no significant difference in water activity among the products (Table 4). Overall, the samples demonstrated effective WHC with no phase separation, except for Soy-2 and Soy-3, which exhibited a low degree of syneresis. Syneresis is a significant defect in fermented gels and results in the release of liquid on the gel surface, leading to an undesirable mouthfeel and reduced consumer appeal (Arab et al., 2023). This can occur in plant-based yoghurts due to the fermentation process and acidification kinetics that destabilise plant protein structures, potentially weakening the product matrix and causing phase separation during storage (Montemurro et al., 2021). Dairy yoghurts can retain water more effectively, due to the strong gel formed from casein and whey proteins, which trap water in their structure (Kneifel and Seiler, n. d.). In the production of Greek-style dairy yoghurt, a significant proportion of whey is removed, resulting in a higher total solids content and a thicker consistency that reduces the likelihood of syneresis (Dairy-G, 99.9% WHC). In comparison, plant-based fermented products often need the incorporation of modified starches or other starch-based additives to enhance water-holding capacity, functioning as thickeners or stabilisers to replicate the texture and structural stability of dairy yoghurts (Arab et al., 2023; Daszkiewicz et al., 2024).

**Table 4**
Mean and standard deviation of Water Activity (Aw) and Water Holding Capacity (WHC) of yoghurts. Values within the same column which share a lowercase letter do not differ significantly.

| Sample | Aw | WHC [%] |
|---|---|---|
| Dairy | $0.96\pm0.01^{a}$ | $97.1\pm0.14^{a}$ |
| Dairy-G | $0.97\pm0.00^{a}$ | $99.9\pm0.02^{b}$ |
| Soy-1 | $0.98\pm0.00^{a}$ | $99.3\pm0.06^{c}$ |
| Soy-2 | $0.96\pm0.014^{a}$ | $95.1\pm0.40^{d}$ |
| Soy-3 | $0.96\pm0.01^{a}$ | $97.5\pm0.63^{abcd}$ |
| Oat | $0.96\pm0.005^{a}$ | $99.9\pm0.01^{b}$ |
| Coconut-1 | $0.95\pm0.01^{a}$ | $99.6\pm0.07^{bc}$ |
| Coconut-2 | $0.97\pm0.01^{a}$ | $98.3\pm0.75^{abcd}$ |
| Soy-Faba | $0.97\pm0.01^{a}$ | $99.8\pm0.05^{b}$ |
| Oat-Faba | $0.97\pm0.01^{a}$ | $99.9\pm0.01^{b}$ |

### 3.5. Colour and Whiteness Index (WI)

The results from colour analysis are shown in Table 5. There was no significant difference in brightness (L*) between dairy yoghurts, Oat and Coconut-2. Dairy yoghurts had the highest L* and the lowest a* values, indicating a cold white colour. Soy yoghurts had the highest b* values, corresponding to a more pronounced yellow colouration, while Coconut-based products had the lowest value, indicating a less yellow tone compared to the other samples. Comparable outcomes were noted in the study of Malparlati et. al. (2024). Coconut-2, Soy-3, and Oat had L* values that were statistically similar to those of the dairy sample. For dairy products, whiteness is a critical quality attribute that strongly influences consumer perception and acceptance (Cadwallader, 2010). Pictures of the samples are reported in Figure 2. Achieving a similar colour in plant-based yoghurt alternatives is notably more challenging as these products are expected to look similar to cow's milk, with a consistent, milky white appearance. From the WI reported in Table 5, it can be said that the Coconut-based yoghurts (80.93 and 83.05) are closer to dairy in terms of whiteness (82.82 and 81.52), followed by Oat and Soy-based products.

### 3.6. Rheological properties

To gain a better understanding of their gel internal structure and enable comparison with dairy yoghurts, rheological tests were performed. The frequency sweep test assesses the time-dependent behaviour of yoghurt within its non-destructive deformation range. Higher frequencies simulate faster movements, such as those that may happen during transportation or handling, while lower frequencies represent slow movements over longer periods or at rest, like when the yoghurt is sitting on a shelf ("Frequency sweeps, Anton Paar Wiki"). From the results obtained ($d\log G'/d\log\omega$, $d\log G''/d\log\omega$, $d\log|\eta^*|/d\log\omega$) in Table 6, it emerges that both the elastic G' and viscous G'' moduli increase slightly with frequency for all products, a behaviour typical of weak gel structures with a stable and flexible internal network. This was also noted in the study of Morell et. al. (2015), where the viscoelastic properties of yoghurts were analysed. Furthermore, the complex viscosities were slightly greater than -1, indicating that the samples do not behave as ideal gels but rather as weak or semi-solid gels (Klost and Drusch, 2019). Such behaviour is characteristic of yoghurt and yoghurt-like products, where the internal matrix provides stability while still allowing some flow under shear. In the graphs presented below, the storage modulus ($G'$), loss modulus ($G''$), and complex viscosity ($|\eta^*|$) are plotted as a function of frequency. The products have been divided into two groups based on their viscosities. Figure 3 shows yoghurts with

**Table 5**
Mean and standard deviation of colour analysis. CIE L*a*b* colour space, with L*=brightness (0=black, 100=white); a*= green (-500) to red (+500); b*= blue (-200); and WI (white index). Values with different superscript letters are significantly different.

| Sample | L* | a* | b* | WI |
|---|---|---|---|---|
| Dairy | $85.81\pm1.02^{ef}$ | $-2.79\pm0.06^{a}$ | $7.86\pm0.07^{abc}$ | $82.82\pm2.26^{a}$ |
| Dairy-G | $85.86\pm0.60^{ef}$ | $-2.79\pm0.02^{a}$ | $11.56\pm0.06^{de}$ | $81.52\pm0.42^{ab}$ |
| Soy-1 | $81.61\pm0.49^{cd}$ | $-2.41\pm0.04^{b}$ | $12.50\pm0.09^{ef}$ | $77.70\pm0.31^{bcd}$ |
| Soy-2 | $79.73\pm0.11^{abc}$ | $-1.65\pm0.02^{f}$ | $11.20\pm0.03^{cd}$ | $76.78\pm0.08^{cd}$ |
| Soy-3 | $82.07\pm0.43^{de}$ | $-0.81\pm0.04abe^{f}$ | $9.23\pm0.06^{bc}$ | $79.82\pm0.36a^{bcd}$ |
| Oat | $81.48\pm0.41^{f}$ | $-0.81\pm0.01^{a}$ | $8.31\pm0.03^{cd}$ | $79.69\pm0.37^{abcd}$ |
| Coconut-1 | $81.22\pm0.06^{bcd}$ | $-1.05\pm0.01^{e}$ | $3.16\pm0.01^{a}$ | $80.93\pm0.05^{abc}$ |
| Coconut-2 | $83.57\pm0.64^{de}$ | $-0.47\pm0.03^{ab}$ | $4.15\pm0.03^{def}$ | $83.05\pm0.61^{a}$ |
| Soy-Faba | $71.51\pm0.31^{a}$ | $5.31\pm0.04^{c}$ | $5.94\pm0.04^{ab}$ | $70.42\pm0.29^{d}$ |
| Oat-Faba | $74.21\pm1.00^{ab}$ | $1.00\pm0.03^{d}$ | $14.33\pm0.12^{f}$ | $70.47\pm0.82^{d}$ |

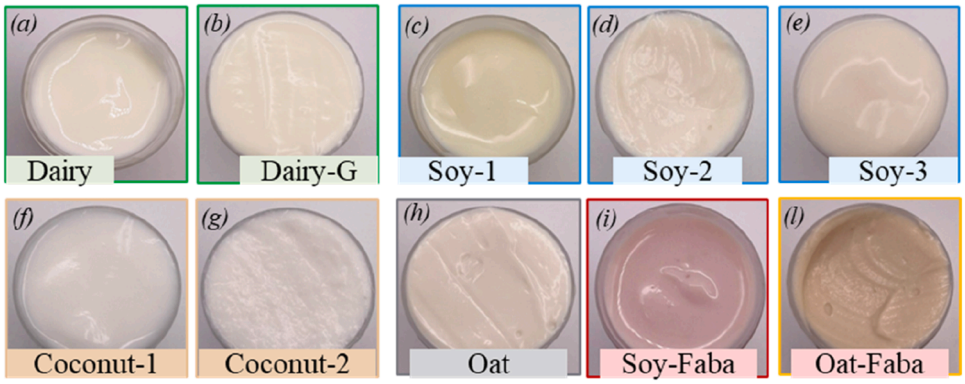



**Figure 2.** Pictures of commercial plant-based yoghurts analysed.

**Table 6**
Results of the thixotropy test (ΔG′ [%] and ΔG″ [%]) and the frequency sweep (dlog G′/dlogω, dlog G″/dlogω, dlog|η*|/dlogω) are presented. Values within the columns marked by different superscript letters show significant differences ($p \leq 0.05$).

| Sample | Dlog (G″)/ Dlog(ω) | Dlog(G′)/Dlog (ω) | Dlog(\|η *\|)/Dlog (ω) | ΔG″ % | ΔG′ % |
|---|---|---|---|---|---|
| Dairy | 0.178 ±0.010$^{cd}$ | 0.141 ±0.004$^{abc}$ | -0.857 ±0.003$^{bc}$ | 46.12 ± 4.98$^{a}$ | 49.01 ± 4.21$^{a}$ |
| Dairy-G | 0.150 ±0.008$^{bc}$ | 0.146 ±0.001$^{abc}$ | -0.854 ±0.001$^{bc}$ | 77.72 ±1.10$^{b}$ | 77.83 ±1.26$^{d}$ |
| Soy-1 | 0.266 ±0.005$^{g}$ | 0.131 ±0.005$^{ab}$ | -0.861 ±0.004$^{b}$ | 24.45 ± 1.18$^{a}$ | 26.7 ± 0.95$^{b}$ |
| Soy-2 | 0.217 ±0.004$^{ef}$ | 0.104±0.007$^{a}$ | -0.893 ±0.006$^{e}$ | 27.17 ±2.98$^{a}$ | 29.75 ±2.78$^{b}$ |
| Soy-3 | 0.213 ±0.012$^{ef}$ | 0.158 ±0.004$^{cde}$ | -0.839 ±0.004$^{ad}$ | 24.21 ±0.83$^{a}$ | 29.14 ±1.37$^{abcdef}$ |
| Oat | 0.110 ±0.010$^{a}$ | 0.075±0.002$^{h}$ | -0.924 ±0.002$^{e}$ | 89.09 ±0.63$^{c}$ | 87.54 ±0.34$^{c}$ |
| Coconut-1 | 0.336 ±0.019$^{h}$ | 0.099 ±0.032$^{abcdefgh}$ | -0.894 ±0.030$^{abce}$ | 4.97 ±1.18$^{d}$ | 7.84±0.58$^{e}$ |
| Coconut-2 | 0.239 ±0.012$^{fg}$ | 0.084±0.008$^{h}$ | -0.912 ±0.008$^{e}$ | 78.98 ±1.91$^{b}$ | 79.74 ±2.26$^{cd}$ |
| Soy-Faba | 0.204 ±0.07$^{de}$ | 0.171 ±0.001$^{de}$ | -0.827 ±0.000$^{cd}$ | 35.67 ± 9.62$^{abcd}$ | 37.33 ± 10.25$^{abcdef}$ |
| Oat-Faba | 0.136 ±0.009$^{ab}$ | 0.176 ±0.007$^{efg}$ | -0.826 ±0.007$^{cd}$ | 83.98 ± 2.42$^{bc}$ | 85.69 ± 1.88$^{c}$ |

lower viscosities than Dairy (regular plain yoghurt), while Figure 4 displays yoghurts with higher viscosities than Dairy-G (Greek-style yoghurt). In general, G' is 4–5 times greater than G'', indicating that all yoghurts predominantly exhibit an elastic or solid-like behaviour. This applies to both dairy and plant-based varieties, with damping factors (tan δ) of 0.25 (Dairy) and 0.24 (Dairy-G), which are very similar to those of the soy-based samples (ranging from 0.20 to 0.27). A tan δ value of less than one confirms the elastic properties over the viscous ones (Morell et al., 2015). Oat and Coconut-2, which present a more compact structure, are characterised by a storage modulus 6–9 times greater than their loss modulus. Under high-frequency oscillatory shear or mechanical agitation, this gel network is disrupted, causing G' to diminish and G″ to increase. Consequently, the yoghurt evolves toward a more viscous-like liquid, and its complex viscosity becomes more strongly dependent on frequency. This observation is further supported by the thixotropy test, where the reduction in G' is very pronounced for Oat (G' drops by 89%) and G″ by 87%), Coconut-3 (G' drops by 78% and G″ by 79%) and Oat-Faba (G' drops by 83% and G″ by 85%), values that are similar to those for Dairy-G (G' drops by 77% and G″ by 77%), reflecting their comparable consistency. In contrast, dairy shows a lower reduction (G' drops by 46% and G″ by 49%) and the soy samples exhibit an even smaller change (G' drops from 24% to 27% and G″ from 27% to 29%) under shear, indicating higher resistance to mechanical stress.

These rheological behaviours may be attributed to the use of structuring agents and emulsifiers in the formulation of commercial plant-based yoghurts (Dhakal et al., 2023). It is well known that stabilisers and emulsifiers are used to improve plant-based yoghurt texture, creaminess, and to mimic dairy gel microstructure. The most commonly used ingredients for this purpose include pectin, various types of starch, gelatin and gums (Baskar et al., 2022). In the list of ingredients of the products analysed (Table 1), pectin and modified starch are predominantly used. Pectin, classified as a food additive (E 440i) from the European Food Safety Authority (EFSA), is a complex polysaccharide that occurs naturally in fruits and vegetables (Mortensen et al., 2017). It is a hydrocolloid utilised for its capacity to form a gel (Arab et al., 2023; Demarinis et al., 2023; Jaeger et al., 2023a).

Modified starch is widely used to improve texture and viscosity in yoghurt formulations (Morell et al., 2015). Starch is a plant-based polysaccharide that enhances texture and prolongs shelf life, making it a valuable ingredient in food applications. Acting as a stabiliser, it forms a gel-like structure that thickens and stabilises food products (Rashwan et al., 2024). Heat-induced gelatinisation causes the irreversible swelling of starch granules, leading to a significant increase in viscosity. Additionally, fermentation has been shown to improve the cohesiveness of the starch gel, likely due to pH-induced denaturation of proteins entrapped within the gelatinised matrix (Montemurro et al., 2021).

### 3.7. Textural properties

Textural properties are critical indicators of both structure and quality in dairy and plant-based yoghurts (Mehta et al., 2023). The results obtained from the back-extrusion method used to analyse the textural properties of the commercial products are presented in Figure 5. This test is used to assess the flow behaviour of yoghurt using a cylindrical probe that is driven into the sample and subsequently retracted at constant speed, while the force is recorded (Extrusion Testing | Texture Analyser). From the resulting curve, key textural parameters such as firmness, viscosity index, and consistency were calculated. Among the plant-based samples, soy- and coconut-based yoghurts most closely mimicked the textural properties of dairy products. For example, dairy yoghurt showed a firmness of 0.438 N, compared to 0.344 N for Soy-2 and 0.436 N for Coconut-1. In terms of consistency, dairy yoghurt measured 5.643 N·s, while Soy-1 and Soy-2 reached 5.910 and 5.823 N·s, respectively. The viscosity index of dairy yoghurt was -5.452, closely matched by Soy-3 at -5.660 and Coconut-1 at -2.806, compared to -2.783 for dairy. In contrast, the Oat and Oat-Faba samples, which were thicker and more structured, presented the highest values across all textural parameters. A statistically significant difference was observed only in firmness, with Oat-Faba showing a markedly higher value. This is most likely due to the addition of starch in the formulation, as well as emulsifiers such as E472e and E471, which can strengthen the gel matrix

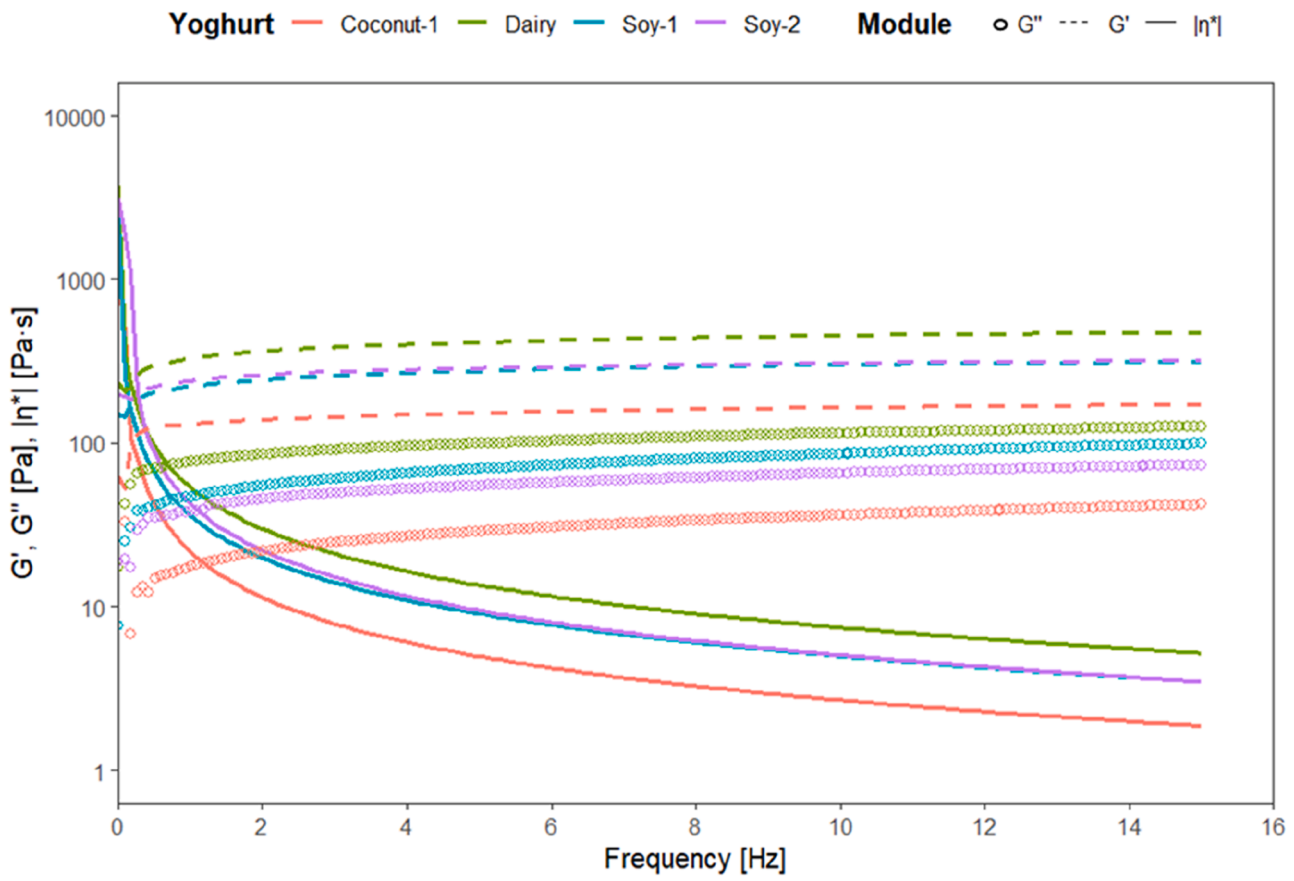



**Figure 3.** Results of frequency sweep test: dependence of storage modulus G′, loss modulus G″ and complex viscosity |η* | on frequency of low viscosity yoghurts.

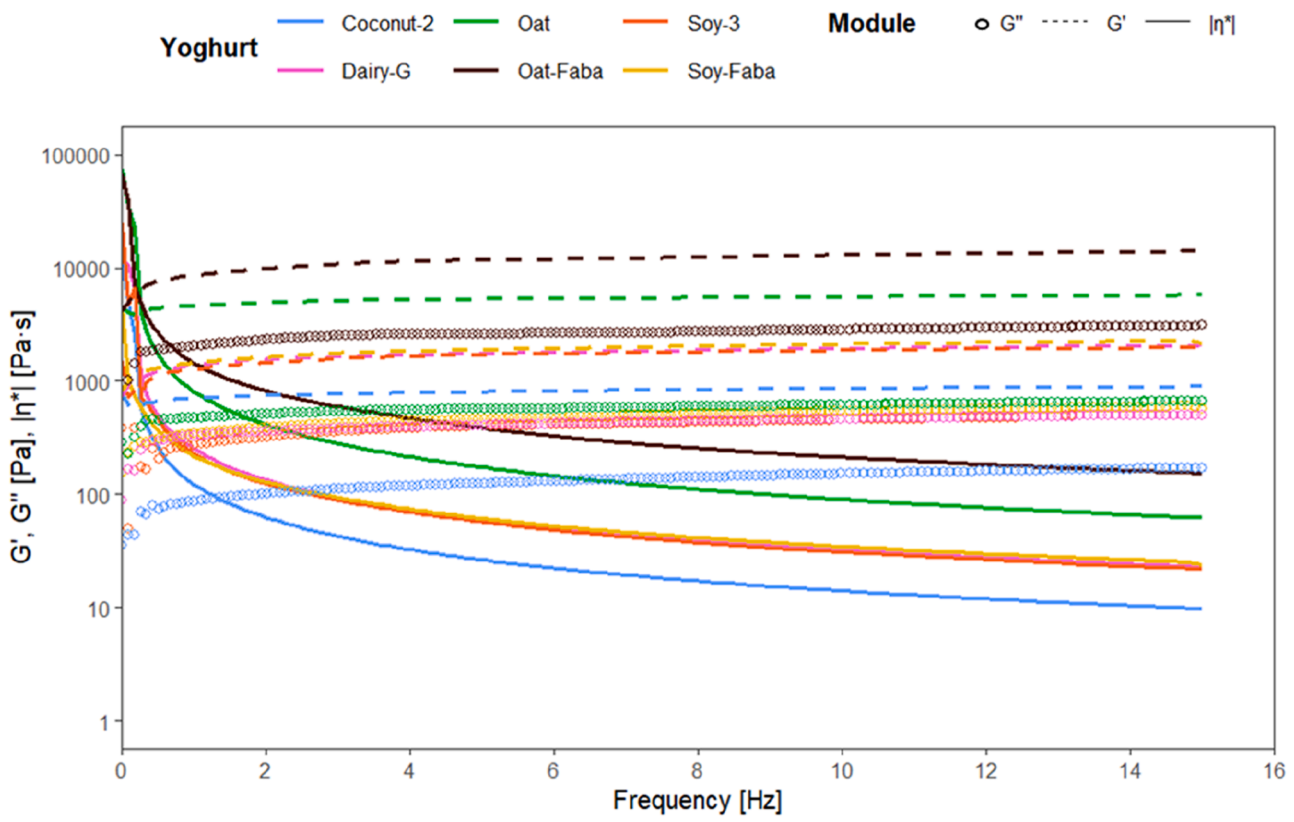



**Figure 4.** Results of frequency sweep test: dependence of storage modulus G′, loss modulus G″ and complex viscosity |η* | on frequency of high viscosity yoghurts.

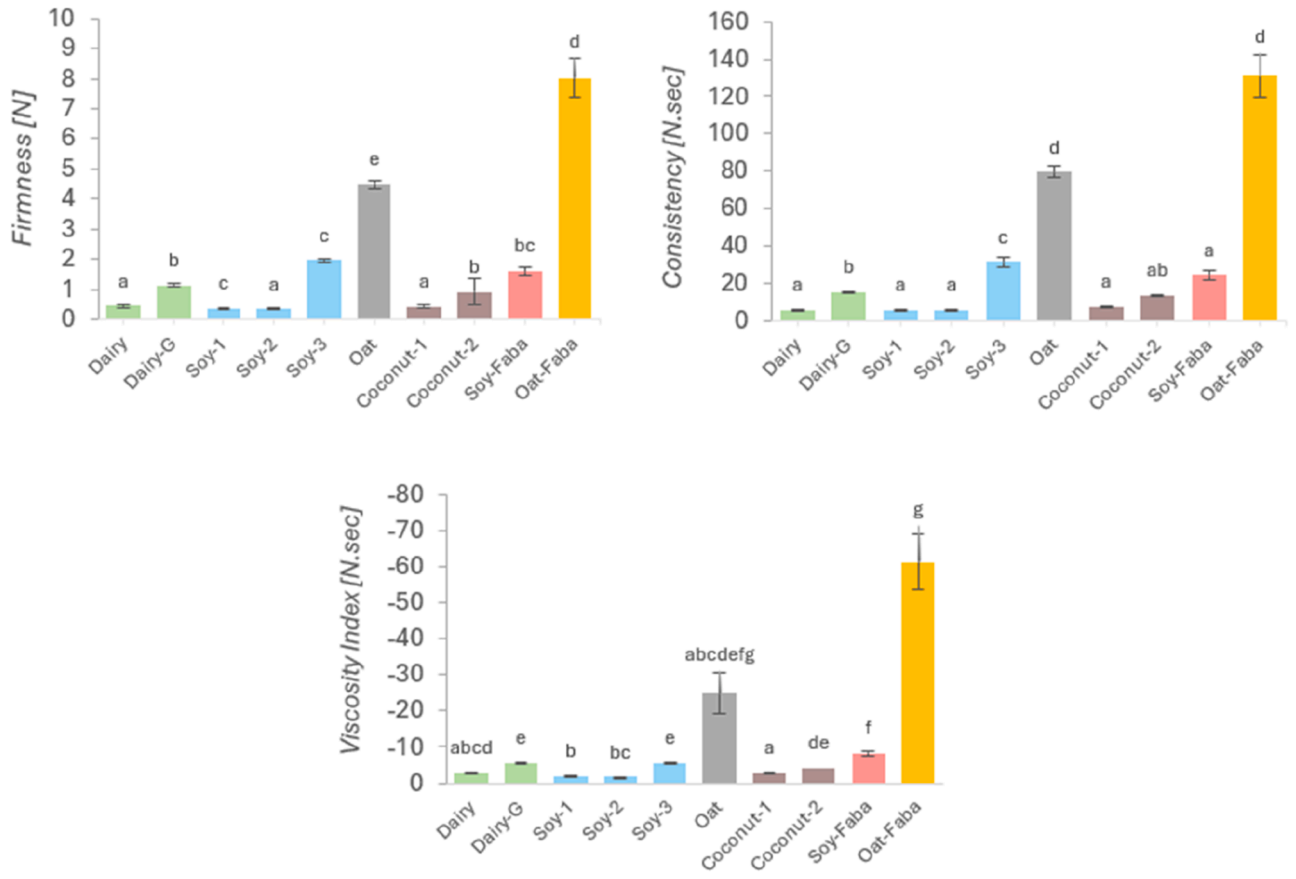



**Figure 5.** Textural properties of commercial yoghurts: Mean of Firmness, Consistency and Viscosity index. Significant differences ($p \leq 0.05$) are indicated with different letters.

and enhance the overall texture (Omelchenko et al., 2014). No significant differences were found in viscosity between dairy Greek-style yoghurt and coconut Greek-style yoghurt, nor between dairy Greek yoghurt and soy Greek yoghurt. Similar textural properties for Greek-style yoghurt were also found in the study of Le Ba et. al. (Le Ba et al., 2025).

These textural behaviours were consistent with the viscoelastic results: in all samples, G′ exceeded G″ and tan δ remained below 0.3, confirming their solid-like gel nature. Oat, Oat-Faba and Coconut-3 exhibited highly elastic networks at low deformation but underwent marked thixotropic breakdown under shear, explaining their very high firmness and consistency. In contrast, soy formulations showed smaller decreases in G′ and G″ during the thixotropy test, suggesting more shear-resistant structures that produced texture profiles similar to dairy in terms of firmness, consistency and viscosity.

## 4. Conclusion

A market analysis was conducted to gain a deeper understanding of current trends in the plant-based yoghurt sector. Subsequently, the physicochemical and rheological properties of eight commercial plant-based yoghurts and two dairy yoghurts available on the Irish market were evaluated. The plant-based yoghurt market features a variety of formulations, with blended products gaining popularity for improving texture, nutrition, and sensory appeal. Flavouring strategies, especially the use of fruity aromas, help improve consumer acceptance by masking undesirable tastes. Market trends also show a strong focus on dietary benefits, allergen-free claims, and an increasing emphasis on protein content as a key nutritional attribute. In this study, the analysis of commercial yoghurts showed that soy and coconut-based products can closely resemble dairy yoghurts in terms of colour, texture, and rheological behaviour, a similarity often achieved through the use of hydrocolloids and other formulation strategies. These findings highlight the considerable potential of plant-based yoghurts as viable alternatives to traditional dairy products. At the same time, it is important to recognise that differences in ingredient composition, stabiliser systems, and fermentation conditions can influence their properties, and thus direct technical comparisons with dairy yoghurts should be interpreted with caution. Looking ahead, several areas of innovation could further enhance the quality and acceptance of plant-based yoghurts. The exploration of fermentation dynamics using non-dairy starter cultures may offer significant benefits, such as improved flavour profiles, greater probiotic potential, and the reduction of antinutritional compounds like phytic acid and tannins. From a technological perspective, advances in clean-label formulation, precision fermentation, and ingredient micro structuring present new opportunities to more closely replicate the mouthfeel, creaminess, and protein quality of dairy counterparts. In addition, incorporating life cycle assessments (LCA) and broader sustainability metrics into product development will be crucial to ensure that future plant-based yoghurts not only achieve sensory and nutritional benchmarks but also align with environmental goals set by the EU Green Deal and global sustainability frameworks. Overall, these findings highlight the availability of plant-based yoghurts in the current market, particularly in the Irish market, allowing the identification of key attributes and emphasising the importance of formulation to achieve greater resemblance to dairy products in the future.

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## Ethical Statement – Studies in Humans and Animals

This study doesn't involve any studies in humans and animals.

## CRediT authorship contribution statement

**Sofia Oldano:** Writing – original draft, Methodology, Formal analysis, Data curation. **Arianna Ressa:** Writing – review & editing. **Laura Nyhan:** Writing – review & editing. **Emanuele Zannini:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Elke Arendt:** Writing – review & editing, Supervision, Resources, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2026.101058.

## Data availability

Data will be made available on request.

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## Further reading

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