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Quality of commercial vegan protein powders and reconstituted beverages: sensory, sorption and physicochemical assessment

Millena Ruszkowska[1]
Magdalena Polechońska[2]

[1] Department of Quality Management, Gdynia Maritime University, Gdynia, Poland
[2] Independent researcher

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Corresponding author
Millena Ruszkowska
m.ruszkowska@wznj.umg.edu.pl

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Abstract

The growing adoption of plant-based diets and the widespread use of protein supplements have increased the need for a comprehensive evaluation of commercial vegan protein powders and beverages prepared from them. In addition to nutritional composition, product quality depends on sensory performance, storage stability, moisture sorption behaviour and flow properties. This study aimed to compare three commercially available vegan protein powders and their reconstituted beverages with similar declared flavour profiles but different plant-protein compositions.

The study included a pea-rice-almond-hemp protein complex, a multicomponent plant-protein blend and a soy protein isolate. Beverages were prepared according to the manufacturers' instructions and evaluated by 12 assessors trained in sensory analysis. Colour, odour, consistency, and taste were rated on a five-point scale and combined using predefined weighting coefficients. Moisture content and water activity of the powders were determined, and water-vapour sorption isotherms were obtained using the static desiccator method at 25°C over

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a water-activity range of 0.07–0.92. The Brunauer-Emmett-Teller (BET) model was used to estimate monolayer capacity and specific sorption surface area. Loose and tapped bulk density, Hausner ratio, Carr index, angle of repose and angle of slide were measured in powder samples, whereas CIE L*a*b* colour parameters were measured for powders and reconstituted beverages.

The soy protein isolate achieved the highest overall sensory score (4.58), whereas the most expensive multi-component blend received the lowest score (2.77), mainly because of lower odour and taste ratings. All powders had low initial water activity (0.3142–0.3602), but their sigmoidal sorption isotherms indicated marked susceptibility to moisture uptake at higher water activity. BET monolayer capacity ranged from 4.58 to 4.65 g H_2O/100 g dry matter. Hausner ratios of 1.36–1.48 and Carr indices of 26.40–32.33% indicated moderate-to-high cohesiveness and poor flowability. Instrumental colour analysis revealed clearly perceptible differences among the products both before and after reconstitution.

Product price was not a reliable indicator of sensory quality. A multidimensional assessment is required because plant-protein composition simultaneously affects sensory acceptance of beverages, moisture-related storage stability and powder handling performance.

Introduction

Protein powders serve both as convenient dietary protein sources, particularly for physically active individuals, and as technologically formulated foods whose stability, flowability and ease of preparation determine their practical value (Jäger et al. 2017; Gorissen et al. 2018; Loveday 2020). Quality assessment is especially complex for vegan products because plant-derived raw materials differ in amino acid composition, fibre content, lipid fraction, antinutritional compounds and characteristic flavour notes. Recent studies also show that the functional performance of commercial plant-protein ingredients depends on botanical source, protein purity, processing history and batch-to-batch variability (Jakobson et al. 2023; Ma et al. 2022). Consequently, the choice of protein source and functional ingredients affects not only nutritional value but also sensory acceptance and powder behaviour during storage and reconstitution.

The current growth of the plant-based protein powder segment reflects a broader transformation of the food market, including increasing interest in plant-based diets, reduced consumption of animal-derived products and the search for alternative protein sources (Cader, Lesiów 2021). Reviews indicate that plant proteins can be obtained from a wide range of botanical sources, including legumes, cereals, pseudocereals, seeds, and nuts, and that their market potential depends on the combined nutritional, functional and sensory value they provide (Sharma et al. 2025). Replacing animal proteins with plant-derived alternatives is also consistent with strategies intended to reduce the environmental impact of food systems (Poore, Nemecek 2018).

From the consumer perspective, the taste, odour, colour and texture of the product after preparation are of primary importance (Bączkowicz et al. 2007). Review evidence shows that plant-based products frequently encounter sensory barriers, particularly those associated with raw-material-derived odour and taste and with texture after reconstitution (Appiani et al. 2023). A recent characterization of 24 commercial plant protein powders confirmed large differences in techno-functional and sensory properties, including raw-material flavour, bitterness, astringency, colour tone, and mouthfeel (Jakobson et al. 2023). For powdered protein products, the physical properties of the dry material are equally important, including caking tendency, cohesiveness, flowability, bulk density, angle of repose, and angle of slide. These parameters affect dosing, transport, storage, packaging performance and ease of use (Domian 2005; Janiszewska et al. 2008; Jedlińska et al. 2013; Kowalska, Lenart 2003; Kowalska et al. 2015; Ma et al. 2022).

The storage quality of powdered foods is strongly associated with the state of water in the product. Moisture content alone is insufficient to predict stability; therefore, water activity measurements and sorption-isotherm analysis are commonly used (Kowalska et al. 2011; Ocieczek et al. 2017; Ruszkowska, Wiśniewska 2017; Samborska et al. 2011). Sorption models, including the Brunauer-Emmett-Teller (BET) equation, enable estimation of monolayer capacity and specific sorption surface area, thereby providing information on susceptibility to moisture uptake and the potential deterioration of quality during storage (Brunauer et al. 1938; Ocieczek, Ruszkowska 2018).

The aim of this study was to compare the quality of selected commercial vegan protein powders and the beverages prepared from them in terms of sensory, sorption and physicochemical properties. Sensory quality was assessed after reconstitution, whereas sorption behaviour, water status, density, flowability and powder colour were assessed for the dry powders. Three research questions were addressed: (1) do the products undergoing analysis exhibit favourable flowability and low cohesiveness; (2) do products with similar declared chocolate or chocolate-nut flavour profiles differ in terms of their instrumentally measured colour in powder form and/or after reconstitution, indicating visual non-equivalence despite comparable flavour declarations; and (3) is a higher unit price associated with superior sensory quality of the beverages after preparation?

Materials and Methods

Study Materials

The study material comprised three commercial vegan protein powders purchased from online retailers. The samples were coded as Products I–III. According to the manufacturers, all products had similar flavour profiles, described as chocolate or chocolate-nut. The beverages were prepared with water using the powder-to-water ratios specified by the respective manufacturers. The products are characterised in tables 1 and 2.

Table 1. Characteristics of the Protein Powders

Product	Ingredient composition declared by the manufacturer	Serving and preparation	Price [PLN/100 g; PLN/serving]
I	Protein complex comprising pea, rice, almond, and hemp protein concentrates; technological and flavouring ingredients, including cocoa, thickeners, sweeteners, and anti-caking agents.	30 g in 300–350 mL water	8.99; 2.69
II	Plant-protein blend comprising pea protein isolate, brown rice protein, pumpkin seed protein, flaxseed, and quinoa flour; cocoa, sunflower lecithin, stevia, xanthan gum, and an enzyme complex.	35 g in 250 mL water	15.90; 5.56
III	Soy protein isolate (94.8%) with cocoa, flavourings, fructose, and sweeteners.	30 g in 200 mL water or milk	8.00; 2.39

Source: Authors' own compilation based on manufacturers' declarations and purchase prices.

Table 2. Declared Nutritional Value of the Products

Component	I: per 100 g	I: 30 g serving	II: per 100 g	II: 35 g serving	III: per 100 g	III: 30 g serving
Energy value [kcal]	395.00	118.50	375.00	131.25	368.00	110.40
Protein [g]	72.00	21.60	72.00	25.20	85.33	25.60
Carbohydrate [g]	21.00	6.30	5.50	1.93	4.07	1.22
of which sugars [g]	8.00	2.40	0.60	0.21	1.52	0.46
Fat [g]	2.50	0.75	6.00	2.10	1.13	0.34
of which saturates [g]	0.20	0.06	1.50	0.53	0.10	0.03
Salt [g]	0.50	0.15	1.68	0.59	0.07	0.02

Source: Authors' own compilation based on manufacturers' declarations; serving values were recalculated from per-100-g declarations and recommended serving masses, and all values were presented with consistent decimal precision.

Sensory Evaluation

Sensory evaluation was conducted in a sensory laboratory using a five-point scoring method. The panel comprised 12 assessors trained in sensory analysis. Four quality attributes were evaluated: colour, odour, consistency and taste. The following weighting coefficients were applied: colour, 0.2; odour, 0.3; consistency, 0.1; and taste, 0.4. The scale ranged from 1 to 5, where 1 indicated a highly unacceptable attribute and 5 indicated a highly acceptable attribute. The beverages were prepared immediately before evaluation. The test was designed as an analytical sensory assessment by a trained panel and therefore should not be interpreted as a consumer hedonic preference test.

Sorption Properties

Sorption properties were determined using the static desiccator method. Approximately 3 g of each powder was placed in atmospheres of controlled relative humidity generated by saturated salt solutions, covering a water-activity range of a_v = 0.07–0.92 at 25°C. The samples were allowed to reach sorption equilibrium for 79 days. Crystalline thymol was placed in the higher-water-activity desiccators to inhibit microbial growth. After equilibration, the samples were visually inspected; no visible mould growth or atypical changes in appearance were observed. However, microbiological analyses were not performed, so the sorption results were interpreted as physical-stability indicators rather than direct microbiological shelf-life data. All determinations were performed in triplicate. Equilibrium moisture content was calculated from changes in sample mass, and the experimental data were fitted to the BET equation. Monolayer capacity, the energy constant, the coefficient of determination and the specific sorption surface area were calculated.

Physicochemical Properties and Statistical Analysis

Moisture content was determined by oven drying at 104°C and expressed as g/100 g dry matter. Water activity was measured at 20°C using an AquaLab 4TE instrument. Loose bulk density was determined after freely pouring 100 g of powder into a graduated cylinder, whereas tapped bulk density was measured after 100 taps of the cylinder. The Hausner ratio and Carr index were then calculated. The angle of repose was determined using the funnel method. The angle of slide was measured on smooth and rough surfaces as the inclination angle at which the formed powder layer began to move.

The colour of the powders and reconstituted beverages was measured using a Konica Minolta CR-400 colorimeter in the CIE L*a*b* system, with a 2° standard observer and D65 illuminant. Six replicate measurements were obtained for each sample. The total colour difference, ΔE*, was also calculated between products; values above 5 were interpreted as clearly perceptible colour differences. Statistical analysis was performed using one-way analysis of variance followed by the least significant difference (LSD) test at a significance level of $\alpha = 0.05$.

Results

Product Characteristics

The products differed in composition and declared nutritional value. Product I was based on a plant-protein complex dominated by pea, rice, almond and hemp proteins. Product II was a multicomponent blend containing pea, brown rice, pumpkin seed, flaxseed and quinoa proteins or ingredients, together with an enzyme complex. Product III had the simplest formulation and was based primarily on soy protein isolate. Product III had the highest declared protein content (85.33 g/100 g), whereas Products I and II each contained 72 g/100 g. Product II had the highest price per 100 g and per serving.

Sensory Evaluation

The sensory results are presented in table 3. The colour and consistency of all beverages received high scores and did not differ significantly among products. Differences in overall sensory quality were primarily attributable to odour and taste. Product III received the highest ratings, with scores of 4.75 for odour, 4.25 for taste, and 4.58 overall. Product II received the lowest ratings, with an overall score of 2.77. Thus, the highest-priced product did not achieve the highest sensory quality.

Table 3. Five-Point Sensory Evaluation of the Protein Beverages

Quality attribute	Weighting coefficient	Product I	Product II	Product III
Colour	0.2	4.83	4.83	4.92
Odour	0.3	2.67^{b}	1.83^{a}	4.75^{c}
Consistency	0.1	4.58	4.50	4.67
Taste	0.4	3.25^{b}	2.00^{a}	4.25^{c}
Overall score	-	3.53^{b}	2.77^{a}	4.58^{c}

Values are means; different superscript letters within a row indicate significant differences at $p \leq 0.05$, unless otherwise stated.

Source: Authors' own study.

Water Status and Sorption Properties

The initial water activity of all samples was low, ranging from 0.3142 to 0.3602. These values are consistent with limited potential for microbial growth under appropriate storage conditions, although they do not eliminate the susceptibility to moisture uptake that is typical of powdered foods. During the 79-day equilibration period, no visible microbial growth was observed; nevertheless, the absence of microbiological testing means that these results should not be treated as shelf-life validation. Product I had a significantly higher moisture content than Products II and III. The sorption isotherms were sigmoidal, as is typical of products rich in macromolecular constituents. At high water activity, particularly above $a_v \approx 0.69$, adsorption increased markedly; this region should therefore be regarded as critical with respect to loss of storage stability.

The BET parameters indicated similar monolayer capacities for the three powders. The highest v_m value was obtained for Product II (4.65 g H_2O/100 g dry matter), and the lowest for Product III (4.58 g H_2O/100 g dry matter) (table 4).

The high coefficients of determination (0.9971–0.9997) confirmed a good fit of the BET model within the range that was analyzed. Nevertheless, interpretation of the model should be restricted to the water-activity range over which the experimental and theoretical courses remain consistent.

Table 4. Initial moisture content, water activity, and BET model parameters

Product	Moisture content [g/100 g dry matter]	a_v[-]	V_m [g H_2O/100 g dry matter]	C_e	R^2	SSE	RMS	Specific sorption surface area [m²/g]
I	$6.5772^{b} \pm 0.009$	$0.3602^{b} \pm 0.0097$	4.63	110.86	0.9971	0.42	0.49	162.69
II	$6.1127^{a} \pm 0.201$	$0.3142^{a} \pm 0.0083$	4.65	123.40	0.9982	0.46	0.53	163.50
III	$6.1484^{a} \pm 0.102$	$0.3183^{a} \pm 0.0168$	4.58	140.17	0.9997	0.33	0.36	160.75

Values are means; different superscript letters within a column indicate significant differences at $p \leq 0.05$, unless otherwise stated.

Source: Authors' own study.

Bulk Density, Cohesiveness and Flowability

Bulk-density and flowability results are presented in table 5. Loose bulk density ranged from 0.41 to 0.44 g/cm³, whereas tapped bulk density ranged from 0.59 to 0.64 g/cm³. The Hausner ratio was 1.36 for Product I and 1.47–1.48 for Products II and III, indicating moderate cohesiveness for Product I and high cohesiveness for the other two products. Carr index values ranged from 26.40% to 32.33%, classifying all samples as poorly flowing powders. The very high angles of repose, close to 89°, further confirmed the unfavourable flow properties of the materials (table 6). The angle of slide was strongly affected by surface type, ranging from 66° to 80° on the rough surface and from 48° to 57° on the smooth surface.

Table 5. Bulk density and indices of cohesiveness and flowability

Product	ρ_l [g/cm³]	ρ_t [g/cm³]	Hausner ratio	Carr index [%]
I	$0.43^{b} \pm 0.01$	$0.59^{a} \pm 0.01$	$1.36^{a} \pm 0.02$	$26.40^{a} \pm 1.18$
II	$0.44^{b} \pm 0.01$	$0.64^{b} \pm 0.02$	$1.47^{b} \pm 0.03$	$31.75^{b} \pm 1.38$
III	$0.41^{a} \pm 0.01$	$0.60^{a} \pm 0.01$	$1.48^{b} \pm 0.02$	$32.33^{b} \pm 0.90$

Values are means; different superscript letters within a column indicate significant differences at $p \leq 0.05$, unless otherwise stated.

Source: Authors' own study.

Table 6. Angle of repose and angle of slide of the powders analyzed

Product	Angle of repose [°]	Angle of slide – rough surface [°]	Angle of slide – smooth surface [°]
I	$89.33^{c} \pm 0.03$	$66^{a} \pm 2$	$48^{a} \pm 4$
II	$89.11^{a} \pm 0.04$	$80^{b} \pm 4$	$57^{b} \pm 4$
III	$89.22^{b} \pm 0.05$	$77^{b} \pm 3$	$51^{a} \pm 2$

Values are means; different superscript letters within a column indicate significant differences at $p \leq 0.05$, unless otherwise stated.

Source: Authors' own study.

Colour of Powders and Reconstituted Beverages

Instrumental colour analysis revealed distinct differences among the products. In powder form, Product I was the darkest (L* = 59.09), whereas Product III was the lightest (L* = 71.03) (table 7). All powders had positive a* and b* values, confirming the presence of red and yellow tones characteristic of cocoa-containing products. After reconstitution, the beverages were considerably darker than the corresponding powders, reflecting differences in light scattering and the effect of the aqueous phase on colour perception. Based on the mean L*a*b* values, ΔE* differences between the powders were 6.84 for I–II, 12.38 for I–III, and 6.27 for II–III. For the beverages, the corresponding values were 8.79, 7.12, and 4.50. Thus, colour differences were clearly perceptible to the observer, particularly between the powdered products.

Table 7. CIE L*a*b* colour parameters of the powders and reconstituted beverages

Form	Product	L*	a*	b*
Powder	I	$59.09^{a} \pm 0.12$	$6.97^{b} \pm 0.06$	$13.93^{b} \pm 0.04$
Powder	II	$64.85^{b} \pm 0.74$	$3.30^{a} \pm 0.05$	$13.55^{ab} \pm 0.08$
Powder	III	$71.03^{c} \pm 0.20$	$3.95^{a} \pm 0.05$	$12.71^{a} \pm 0.09$
Beverage	I	$36.98^{a} \pm 0.41$	$6.37^{c} \pm 0.17$	$8.12^{a} \pm 0.37$
Beverage	II	$44.57^{b} \pm 1.30$	$5.08^{b} \pm 0.19$	$12.36^{b} \pm 0.25$
Beverage	III	$43.90^{b} \pm 0.16$	$4.69^{a} \pm 0.04$	$7.93^{a} \pm 0.06$

Values are means; different superscript letters within a column indicate significant differences at $p \leq 0.05$, unless otherwise stated.

Source: Authors' own study.

Discussion

The findings demonstrate that the quality of commercial vegan protein powders cannot be evaluated solely on the basis of protein content or price. Product III, based on soy protein isolate, had both the highest declared protein content and the highest sensory score. By contrast, Product II received the lowest odour and taste ratings despite being the most expensive and having the most complex formulation. This result is consistent with observations for plant-based foods, in which consumer acceptance is often limited by undesirable raw-material-derived flavour notes and sensations described as powdery, bitter, earthy, or cereal-like (Appiani et al. 2023; Jakobson et al. 2023; Sharma et al. 2025).

Differences in product composition may have affected both sensory performance and physical properties. Product II contained multiple plant components, including pea protein, brown rice protein, pumpkin seed protein, flaxseed and quinoa flour. Such a formulation may improve amino acid complementarity, but it may also produce a complex sensory profile that is more difficult to mask with a chocolate-nut flavour. Product III, which was based on soy protein isolate and had a simpler formulation, may have exhibited more predictable functional and sensory behaviour after reconstitution. This interpretation is supported by recent studies indicating that plant-protein functionality and sensory perception are strongly influenced by protein source, purity, processing conditions and the presence of non-protein components (Gorissen et al. 2018; Loveday 2020; Ma et al. 2022).

The low water activity of the powders is favourable from a microbiological perspective, but it does not eliminate the risk of quality deterioration during storage. Protein powders may adsorb moisture intensively from the environment, leading to poorer flowability, caking, changes in the consistency of the reconstituted beverage, and accelerated physical and chemical changes. The marked increase in sorption at higher water activity highlights the importance of airtight packaging and limited exposure to humid air. In practical terms, packaging materials with an effective water-vapour barrier and clear storage instructions for the period after opening are required. Because microbiological analyses were not included, future storage trials should combine water-activity and moisture monitoring with microbiological verification.

The Hausner ratio and Carr index values indicate unfavourable flow behaviour for all three products. This finding is relevant to both consumers and manufacturers. Under household conditions, poor flowability complicates dosing and may increase variation in serving mass. In industrial operations, it may cause difficulties during feeding, hopper discharge, unloading, packaging and maintenance of mixture uniformity. Similar practical implications have been reported for commercial protein powders, for which physical properties were linked to suitability for handling and transfer operations (Świtalski et al. 2021; Jakobson et al. 2023; Ma et al. 2022).

Colour received high sensory scores, although instrumental measurement revealed significant and perceptible differences among the products. This apparent discrepancy may be explained by the fact that sensory evaluation assessed colour acceptability in the context of a chocolate-flavoured beverage, whereas

CIE L*a*b* measurement objectively captured differences associated with cocoa content, the intensity of flavouring ingredients, protein source, particle size, and the amount of water used for reconstitution. In practice, such differences may shape consumer expectations and perceived consistency with the declared flavour.

The principal limitation of this study is the small number of products analyzed. The study also did not assess amino acid profiles, protein digestibility, contaminants, or stability under real-time storage conditions. In addition, microbiological changes after the sorption equilibration period were not verified analytically. Because sensory evaluation was conducted by a trained panel rather than a representative consumer sample, the results should not be directly interpreted as preferences of the wider consumer population. Despite these limitations, the study demonstrates that routine quality assessment of vegan protein powders should simultaneously consider sensory properties of reconstituted beverages, water status, colour and powder flow behaviour.

Conclusions

1. The commercial vegan protein powders and the beverages prepared from them analyzed in this paper differed in sensory quality, sorption properties, flowability and colour despite having similar flavour profiles declared by the manufacturers. Sensory conclusions refer to reconstituted beverages, whereas sorption and flowability conclusions refer to the dry powders.
2. The soy-protein-isolate product received the highest sensory rating for the beverage after preparation, whereas the most expensive multicomponent product received the lowest overall score. Unit price was therefore not a reliable indicator of sensory quality.
3. All powders had low water activity; however, the course of the sorption isotherms indicated susceptibility to intensive moisture uptake at higher water activity. Limiting exposure to humid air is therefore essential for maintaining product stability.
4. The Hausner ratio, Carr index and very high angles of repose indicated poor flowability and moderate-to-high cohesiveness, which may impede dosing, transport and packaging operations.
5. Instrumental colour analysis confirmed clearly perceptible differences among the products both in powder form and after reconstitution. A declared chocolate flavour did not ensure uniform colour characteristics.
6. Further research should include a larger number of products, amino acid profiling, in vitro digestibility assessment, analysis of potential contaminants, microbiological verification during storage, and storage trials under controlled humidity and temperature conditions.

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Author Contributions

Author Contributions
Conceptualization: M.R.
Methodology: M.R.
Formal analysis: M.R.
Investigation: M.R., M.P.
Data curation: M.R., M.P.
Writing – original draft preparation: M.R.
Writing – review and editing: M.R., M.P.
Visualization: M.R., M.P.
Supervision: M.R.
Project administration: M.R.

Supplementary Materials

Not applicable.

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Ethics Approval Statement

Formal ethical approval was not sought because the study involved a non-invasive sensory evaluation of commercially available food products conducted with adult panellists. The study did not involve any medical intervention, collection of biological samples, deception or processing of sensitive personal data. The procedures posed no more than minimal risk to the participants, and participation was entirely voluntary.

Informed Consent Statement

Before participating in the study, all panellists were informed about the purpose and procedures of the sensory evaluation, the voluntary nature of their participation and their right to withdraw at any time. Completion and submission of the sensory evaluation form were regarded as confirmation of the participants' consent to take part in the study.

Data Availability Statement

The data presented in this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI Use

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for English-language editing and technical formatting. The authors reviewed and approved all revisions and take full responsibility for the final content.

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Not applicable.

Conflict of Interest

Millena Ruszkowska (M.R.) is a member of the Editorial Board of "Państwo i Społeczeństwo / State and Society". To manage this potential conflict of interest, she had no involvement in the selection of reviewers, the evaluation of the manuscript, or the editorial decision regarding this submission. The peer-review process and editorial decision were handled independently by another editor with no conflict of interest. Magdalena Polechońska (M.P.) declares that she has no competing interests.