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Design and nutritional characterization of vegan verrines: an innovative approach to plant-based snacks

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Abstract. The growing global transition toward plant-based diets calls for developing innovative, nutrient-dense culinary formats that bridge nutritional gaps and satisfy diverse consumer preferences. This study reports the formulation and compositional characterization of two structured, bi-layered vegan verrine prototypes: VT (vegan verrine with turmeric), comprising chickpea, quinoa, red bean, and turmeric; and VM (vegan verrine with *Moringa oleifera*), consisting of red lentil, buckwheat, pea, and *M. oleifera* leaf powder. Comparative compositional analyses revealed that VM offered significantly higher protein and mineral levels, whereas VT exhibited elevated fat and carbohydrate content. Antioxidant evaluations further highlighted VM's enhanced bioactivity, with higher total phenolic content (184.14 µg GAE/g vs. 114.42 µg GAE/g) and free radical scavenging capacity (112.24 µM Trolox/g vs. 106.52 µM Trolox/g). These findings underscore the potential of bioactive-rich components, *M. oleifera* and turmeric, to tailor plant-based formulations to targeted nutritional goals.

Keywords: legumes, pseudo-cereals, essential amino acids, vegan.

Designul și caracterizarea nutrițională a verinelor vegane: o abordare inovatoare a gustărilor pe bază de plante

Rezumat. Schimbarea globală tot mai accentuată către diete bazate pe plante necesită dezvoltarea de formule culinare inovatoare, bogate în nutrienți, care să acopere deficiențele nutriționale și să satisfacă diversele preferințe ale consumatorilor. Acest studiu prezintă formularea și caracterizarea compozițională a două prototipuri de verine vegane structurate, bistratificate: VT (verine vegane cu turmeric), constând din năut, quinoa, fasole roșie și turmeric; și VM (verine vegane cu *Moringa oleifera*), conținând linte roșie, hrișcă, mazăre și pudră de frunze *M. oleifera*. Analizele comparative ale compoziției au arătat că VM a oferit niveluri semnificativ mai ridicate de proteine și minerale, în timp ce VT a prezentat un conținut ridicat de grăsimi și carbohidrați. Evaluările antioxidanților au evidențiat în continuare bioactivitatea îmbunătățită a VM, cu un conținut fenolic total mai mare (184,14 µg GAE/g vs. 114,42 µg GAE/g) și o capacitate de eliminare a radicalilor liberi (112,24 µM Trolox/g vs. 106,52 µM Trolox/g). Aceste descoperiri subliniază potențialul alimentelor bogate în componente bioactive, *M. oleifera* și turmericul, de a adapta formulele pe bază de plante la obiectivele nutriționale vizate.

Cuvinte-cheie: leguminoase, pseudo-cereale, aminoacizi esențiali, vegan.

1. Introduction

Human nutrition depends on a balanced intake of macronutrients and micronutrients to support metabolic functions and physiological health [1, 2]. Proteins, carbohydrates, and lipids are the primary metabolites that serve as energy sources and structural components in the body [3]. Vitamins and minerals act as essential cofactors and regulatory molecules in numerous biochemical pathways, and insufficiency of any nutrient class can impair metabolism and health [3, 4]. For example, pseudocereals (quinoa and amaranth) provide high-quality protein and unsaturated fatty acids, dietary fiber, and a range of vitamins and minerals [5].

In recent years there has been a marked shift toward plant-based diets driven by health, ethical, and environmental concerns [6, 7]. Growing evidence and consumer surveys indicate that plant-derived proteins are increasingly popular, and their demand is rising globally [8, 9]. Transitioning from animal to plant protein was seen as one strategy to meet the protein needs of a growing population and reduce environmental impact [10]. A recent study by da Silva et al. (2022) reported a global trend in adopting plant-forward diets, driven by concerns related to chronic disease prevention, environmental sustainability, and animal welfare. This change was particularly observed in Western countries, where sales of plant-based products (dairy and meat analogs) have seen annual growth rates exceeding 10% [2, 10]. From a nutritional standpoint, plant-based diets were associated with reduced risks of obesity, cardiovascular disease, and type 2 diabetes [11]. However, plant-derived proteins often lack essential amino acids and tend to have lower digestibility than animal proteins [12, 13]. This limitation was acknowledged in multiple studies, particularly in the Food and Agriculture Organization (FAO) report on protein quality assessment [14], which emphasizes the need to evaluate plant protein sources using indicators like the Digestible Indispensable Amino Acid Score [15, 16, 17].

Pseudocereals have been recommended for high-quality protein, unsaturated fats, and micronutrients [18]. These plant foods have promising amino acid profiles and nutrient density, and their consumption has been linked with health benefits (improved lipid profiles and reduced risk of chronic disease) [18, 19]. In particular, pseudocereals are naturally gluten-free and contain substantial amounts of lysine and other essential amino acids, complementing the nutrient profile of cereals [20]. Cereals (wheat, rice, maize) typically have low lysine content, whereas legumes are often deficient in sulfur-containing amino acids (methionine and cysteine) [21]. This limitation is well recognized, and food formulation strategies routinely combine different plant sources to achieve complete protein nutrition [12, 15, 16, 17]. For example, mixing legumes with cereals and pseudocereals improves the overall protein quality by complementing each other's amino acid patterns [22, 23]. Quinoa and amaranth, being high in lysine, can offset the lysine deficiency of cereals, while legumes supply the sulfur amino acids that are low in grains [24]. Through such combinations, high-protein vegan foods can meet human requirements for essential amino acids and offer balanced nutrition [18, 25].

Over the past decade, Europe has experienced a significant transformation in dietary preferences, marked by an accelerated adoption of plant-based food products [26]. Between 2018 and 2022, sales of plant-based meat analogs increased by approximately 49% reflecting a broader societal shift toward sustainable and health-promoting consumption patterns [27]. The dietary transition was underpinned by a confluence of factors, including heightened awareness of the environmental impact of livestock farming (greenhouse gas emissions, land and water use), growing ethical concerns regarding animal welfare, and epidemiological evidence linking plant-based diets to reduced risks of chronic diseases such as cardiovascular disorders, type 2 diabetes, and obesity [27, 28]. The prevalence of flexitarian diets has surged, particularly in countries such as Germany, the Netherlands, and the United Kingdom, where over 40% of consumers report actively reducing meat consumption [29]. The European Farm to Fork Strategy further reinforced this evolution, which aims to promote sustainable food systems through reduced reliance on animal proteins and improved nutritional profiles of food products [30, 31].

In this context, the present study focuses on developing high-protein vegan snacks formulated from legume- and pseudocereal-based ingredients. The study describes

(1) the selection and combination of plant protein sources to enhance nutritional quality,
(2) the compositional analysis of the resulting vegan snacks,
(3) the implications for healthy plant-based diets.

2. Methods

2.1. Materials

The legumes (chickpeas, red lentils, red beans, peas) and pseudocereals (quinoa, buckwheat) were sourced from organic suppliers in Cluj-Napoca, Romania. Turmeric powder (*Curcuma longa*) and *Moringa oleifera* leaf powder were acquired from specialized health stores in Cluj-Napoca, Romania. Methanol (HPLC grade), DPPH (2,2-diphenyl-1-picrylhydrazyl), Folin–Ciocalteu reagent, and sodium carbonate (Na_2CO_3) were procured from Sigma-Aldrich (Steinheim, Germany).

2.2. Evaluation of consumer preferences and market viability assessment

To evaluate consumer preferences and market viability of legume-based and pseudocereal-derived products, a structured online questionnaire distributed *via* Google Forms was designed to quantify preferences, sensory experiences, and health benefit awareness among diverse consumer segments. The questions were classified in three domains: (1) demographic and behavioral variables (age, gender, dietary habits), (2) Likert-scale assessments of sensory attributes (taste, texture, aroma) and ingredient affinity, and (3) validated metrics evaluating nutritional knowledge and perceived health impacts. Ethical adherence included informed consent, anonymized responses, and purposive sampling to ensure representation of health-conscious and conventional dietary cohorts.

2.3. Vegan verrine snacks formulation

For the vegan verrine snacks preparation, the raw materials were selected based on the outcomes of an online questionnaire that quantified consumer preferences, sensory expectations, and health-benefit awareness for legume- and pseudocereal-derived products. Initially, legumes (chickpeas, red lentils, red beans, peas) and pseudocereals (buckwheat, quinoa) were hydrated under conditions optimized for seed-coat permeability. Legumes were soaked in water at 4 °C for 24 h to achieve ≥80 % rehydration, whereas pseudocereals required 2 h of hydration. Thereafter, legumes were boiled at 100 °C for 120 min to ensure cell-wall disruption, while pseudocereals underwent a shorter 20 min boil to promote starch gelatinization without degradation. Each ingredient was converted into a homogeneous paste *via* high-shear mixing (10,000 rpm, 5 min). Two distinct formulations were developed to balance macronutrient profiles and phytochemical content: VT (32 g chickpea, 32 g quinoa, 32 g red bean, 0.1 g salt, 0.5 g turmeric) and VM (32 g red lentil, 32 g buckwheat, 32 g pea, 0.1 g salt, 0.5 g *M. oleifera* powder). Stratification into glass containers followed a layer-by-layer assembly (5 mm per layer), alternating legume and pseudocereal matrices to enhance textural contrast. Each layer was stabilized *via* refrigeration (4 °C, 10 min between layers) to induce hydrocolloid gelation. Final decoration incorporated inactive dry yeast flakes and broccoli microgreens.

2.4. Nutritional composition

The nutritional composition of the verrines was analyzed using standardized methodologies from the American Association of Cereal Chemists (AACC) [32]. Moisture, fat, and ash content were determined through AACC methods 44-15.02, 30-25.01, and 08-01.01, respectively. Protein content was quantified *via* the Kjeldahl method (AACC 46-11.02), applying a conversion factor of 5.7 to calculate protein from nitrogen. Total carbohydrates (%) were derived by subtracting the sum of moisture, ash, protein, and lipid percentages from 100, as outlined in Equation (1) [33]:

$$\text{Total carbohydrate (\%)} = 100 - [\text{moisture (\%)} + \text{ash (\%)} + \text{proteins (\%)} + \text{lipids (\%)}] \quad (1)$$

Caloric content was computed using Atwater's conversion factors (4.0 kcal/g for carbohydrates and protein, 9.0 kcal/g for fat), as shown in Equation (2):

$$\text{Energy value (kcal/100 g)} = (\text{Carbohydrates} \times 4.0) + (\text{Protein} \times 4.0) + (\text{Fat} \times 9.0) \quad (2)$$

2.5. Rheological measurements

For rheological characterization, all samples were analyzed at a controlled temperature of 4 °C using an Anton Paar MCR 72 rheometer (Anton Paar, Graz, Austria). Dynamic oscillatory measurements were conducted using a Peltier-controlled plate–plate system (P-PTD 200/Air), equipped with precise temperature regulation to ensure measurement stability. The measuring geometry consisted of a smooth, parallel plate setup (model PP-50-67300) with a diameter of 50 mm. The oscillatory shear strain was maintained at a constant amplitude of 0.1%, while the angular frequency (ω) was applied over a logarithmic sweep ranging from 0.628 to 628 rad/s to evaluate the frequency-dependent viscoelastic behavior. Upon loading the sample onto the measuring surface, the gap between the plates was carefully adjusted to 1 mm. Any excess sample was removed to ensure uniformity, and the sample was allowed to equilibrate undisturbed for 5 minutes before measurement, to minimize structural disturbances and ensure reproducibility.

2.6. Biological activity

2.6.1. Extraction

The verrines (1 mg/mL) were dissolved in methanol and ultrasonically treated in an ultrasonic bath (Elma Schmidbauer GmbH, Singen, Germany) at 37 kHz for 30 min [34]. The samples were centrifuged at 12298×g for 10 min, and the polyphenols were extracted into the supernatant. The supernatant was then filtered through a 0.45 μm nylon filter, and the extract was further used for the biological activity.

2.6.2. Antioxidant activity

The free radical scavenging capacity (antioxidant activity) of the extracts was analyzed *via* the DPPH (1,1-diphenyl-2-picrylhydrazyl) method, conducted according to a published protocol [35]. Briefly, 35 μL of verrines extract was combined with 250 μL of DPPH solution and incubated for 30 minutes at room temperature in the dark. Absorbance measurements were taken at 515 nm using a BioTek Instruments microplate reader (Winooski, VT, USA). The antioxidant activity was calculated using Equation (3):

$$\text{DPPH scavenging activity (\%)} = \left[\frac{A_b - A_s}{A_b}\right] \times 100 \quad (3)$$

where A_b denotes the absorbance of the blank and A_s corresponds to the absorbance of the sample.

2.6.3. Total Phenolic Content

The total phenolic content of each verrine extract was quantified by a slightly modified Folin–Ciocalteu method and expressed as mg of gallic acid equivalents (GAE)/100 g dry weight (D.W.) [36]. An aliquot of the extract (25 μL) was initially mixed with 1.8 mL of distilled water, followed by adding and homogenizing 120 μL of Folin–Ciocalteu reagent. Five minutes later, 340 μL of 7.5% Na_2CO_3 aqueous solution was added to the mixture. The samples were incubated for 90 minutes at room temperature in the dark, and then their absorbance was read at 750 nm against the blank, using a microplate reader (BioTek Instruments, Winooski, VT, USA).

2.6.4. Statistical analysis

All measurements and analyses were made on three prepared samples, and the results are presented as means ± standard deviations (SD). One-way analysis of variance (ANOVA) and Tukey's comparison test *via* Minitab statistical software (version 16.1.0; LEAD Technologies, Inc., Charlotte, NC, USA) were applied to analyze the differences among samples with significance levels of $p < 0.05$. Statistical significance was assumed at the 95% confidence level for differences in mean values.

3. Results

3.1. Assessment of consumer preferences and market viability

Evaluating consumer preferences and dietary trends is essential for understanding the acceptance and scalability of novel plant-based formats such as verrine snacks. The results of the structured questionnaire (Figure 1) provide key insights into the target demographic and their consumption behaviors, which inform both formulation and market positioning strategies.

Figure 1A illustrates the dietary segmentation of the survey respondents. Most (88%) identified as "usual consumers," indicating no strict adherence to vegan, vegetarian, or raw vegan diets. Only 10% reported following a vegan diet, while raw vegans and vegetarians represented negligible proportions (0% and 2%, respectively). This suggests that although the primary market remains omnivorous, there is an emergent interest in plant-based options among general consumers, highlighting an opportunity for product innovation that appeals to flexitarians and health-conscious individuals.

Figure 1B shows that legumes were more frequently consumed than pseudocereals across all respondent categories. Daily consumption of legumes surpassed that of pseudocereals, suggesting a higher level of habitual integration into diets. Pseudocereals, though gaining traction, were predominantly consumed on a weekly or monthly basis. These data provide strategic cues for ingredient prioritization in formulation and marketing, especially if seeking to position the product as both novel and nutritionally functional.

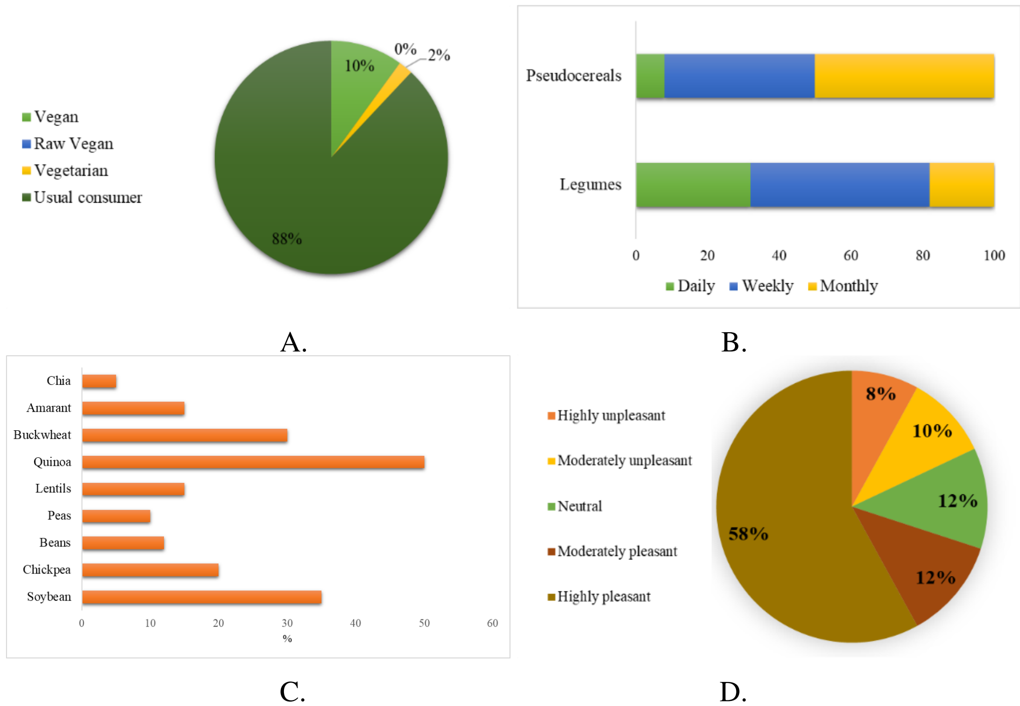

Figure 1. Questionnaire outcomes. A. Demographic segmentation of dietary adherence; B. Frequency distribution of ingredient preference among dietary cohorts; C. Consumption frequency patterns of pseudocereals vs. legumes across dietary regimens; D. Likert-scale visualization of consumer receptivity to plant-based verrine snacks.

Ingredient preference data (Figure 1C) reveal a pronounced inclination toward more familiar legumes and pseudocereals. Quinoa emerged as the most preferred ingredient, followed by soybeans and buckwheat. Conversely, chia and amaranth were the least commonly accepted ingredients, potentially due to limited exposure or perceived complexity in preparation.

Consumer response to the sensory evaluation of vegan verrines, measured *via* a Likert scale (Figure 1D), indicates a generally favorable perception. A cumulative 70% of respondents rated the appetizers as either “highly pleasant” (58%) or “moderately pleasant” (12%), while only 18% expressed unfavorable reactions. The 12% neutral responses suggest potential for improvement in palatability or presentation to further convert hesitant consumers. Importantly, the high acceptability rate among a majority omnivorous population reinforces the product’s market viability outside strictly vegan niches. The existence of 12% neutral responses indicates a disconnect that could be addressed through improvements in the flavor profile or presentation of the snacks, ultimately aiming to convert hesitant customers into enthusiastic consumers. Moreover, the broad acceptability of these snacks across an omnivorous population underscores their market viability.

These findings support the viability of vegan verrine snacks as a promising entry into the mainstream market. Although opportunities exist to enhance familiarity with select novel ingredients and improve sensory appeal, the overwhelmingly positive reception, particularly among non-vegan consumers, suggests strong potential for cross-segment adoption. Strategic targeting of flexitarian and health-aware demographics may further accelerate acceptance and demand.

The study received questionnaire responses from 50 participants (Table 1). The participants were predominantly female (74%), with 26% male participants. The age distribution showed that most participants (80%) were between 18 and 35 years old, suggesting a heightened interest in innovative food products within this demographic group.

3.2. Nutritional composition

The nutritional composition (Table 2) of the two vegan verrine formulations, VT (with turmeric) and VM (with *M. oleifera*), revealed statistically significant differences ($p < 0.05$) across all analyzed parameters, reflecting the nutritional impact of their distinct plant-based components.

The moisture content was significantly higher in VM (74.76%) compared to VT (72.57%). This difference may be attributed to the water-binding capacity of *M. oleifera* leaves, which are known for their high fiber content and hydrophilic nature. A higher moisture level in VM may enhance the product’s sensory profile by contributing to a softer, creamier texture, but it could also affect microbial stability and shelf life.

Regarding protein content, VM stood out with a markedly higher value of 27.38% compared to 19.18% in VT. In contrast, VT had a significantly higher fat content (10.58%) than VM (8.46%). This difference could be due to fat-based ingredients that carry turmeric, often necessary to enhance curcumin bioavailability. While fat contributes to

Table 1. Demographic variables of the participants.

Demographic variable	**Characteristics**	**n**
Gender	Male	13
	Female	37
Age group	18-35	40
	36-55	2
	56-65	5
	66 or older	2
Education	Less than High School	3
	Technical School	10
	Graduate	22
	College Graduate	6
	Graduate degree or higher	9
Regional location	Rural	21
	Urban	29

Table 2. Nutritional composition of the vegan verrine snacks.

Verrines Samples	**Nutritional parameters**					
	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Total carbohydrate (%)	Energy value (kcal/100 g)
VT	$72.57^{B} \pm 0.16$	$19.18^{B} \pm 0.10$	$10.58^{A} \pm 0.13$	$0.75^{B} \pm 0.13$	$89.59^{A} \pm 0.11$	$119.28^{A} \pm 0.01$
VM	$74.76^{A} \pm 0.12$	$27.38^{A} \pm 0.20$	$8.46^{B} \pm 0.15$	$1.40^{A} \pm 0.10$	$69.74^{B} \pm 0.10$	$105.59^{B} \pm 0.05$

All data are presented as mean ± SD of three independent determinations. Means followed by different letters in the same column differ significantly ($p < 0.05$). VT – verrine with turmeric; VM – verrine with *M. oleifera*.

the palatability and mouthfeel of the product, a lower fat content in VM may be preferable for calorie-conscious consumers and those following low-fat diets.

The ash content reflects the high micronutrient density of *M. oleifera*, known for its rich supply of essential minerals like calcium, potassium, and iron. This property supports VM's potential role as a functional food that prevents mineral deficiencies. Interestingly, VT demonstrated a significantly higher carbohydrate content (89.59%) than VM (69.74%).

Furthermore, regarding energy value, VT had the highest caloric content, followed by VM. The elevated energy value of VT is primarily driven by its higher fat and carbohydrate content, whereas VM offers more protein and minerals per calorie. Thus, VT may be more suitable for those needing increased energy intake, while VM provides greater nutrient density in a lower-calorie format.

3.3. Rheological measurements

The rheological behavior of each layer of the verrine formulations was assessed under oscillatory shear conditions to evaluate their viscoelastic properties (Figure 2). For both formulations, the storage modulus (G') exceeded the loss modulus (G'') across the entire frequency range (0.628–628 rad/s), indicating predominantly elastic (solid-like) behavior and suggesting the presence of a stable three-dimensional network within the matrix [37].

In the VT formulation, which contained chickpea + turmeric, red bean, and quinoa layers, G' values ranged from 95,000 Pa to over 165,000 Pa and increased with frequency. This demonstrates enhanced structural reinforcement under higher oscillatory stress. Notably, quinoa significantly contributed to stiffness, exhibiting the highest individual G' values of approximately 180,000 Pa, while the chickpea–turmeric layers showed a more cohesive viscoelastic structure than red bean. G'' values followed a similar frequency trend but remained lower than G', confirming a strong gel-like consistency.

In the VM formulation, which included red lentil, buckwheat, and pea + *M. oleifera* layers, the G' and G'' values were consistently higher than those of VT, particularly at mid-to-high frequencies. The G' of the *Moringa*-enriched pea paste exceeded 190,000 Pa at higher frequencies, indicating that the functional ingredients enhanced structural integrity. Red lentil also contributed high G' values (ranging from 170,000 to 200,000 Pa), reflecting its known ability to structure starch–protein matrices [38].

3.4. Biological activity

The results from the DPPH assay indicate that both formulations, VT and VM, exhibit significant free radical scavenging activity, with VM showing slightly superior activity compared to VT (Table 3). This suggests that *M. oleifera*, a plant known for its high polyphenolic content, might contribute to the higher antioxidant activity observed in VM.

The TPC results demonstrate that *M. oleifera* has a significantly higher phenolic content compared to turmeric. The results are consistent with the well-documented high phenolic content of *M. oleifera*, which is rich in flavonoids, phenolic acids, and other polyphenolic compounds that contribute to its overall antioxidant capacity.

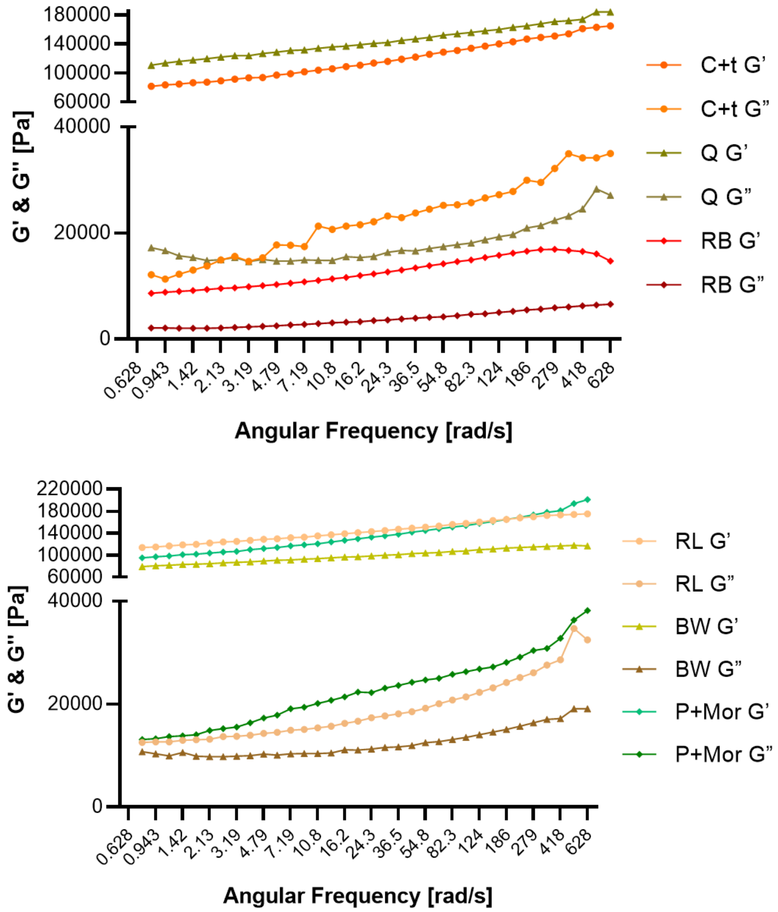

Figure 2. The storage (G') and loss (G") shear moduli of VT (C+t – chickpea and turmeric, Q – quinoa, RB – red bean) and VM (RL – red lentil, BW – buckwheat, P+Mor – Pea + *M. oleifera* powder) samples.

Table 3. Antioxidant activity (DPPH) and total phenolic content (TPC) of the vegan verrine snacks.

Verrines Samples	DPPH (µM Trolox/g D.W.)	TPC (µg GAE/g D.W.)
VT	$106.52^{B} \pm 0.06$	$114.42^{B} \pm 0.08$
VM	$112.24^{A} \pm 0.12$	$184.14^{A} \pm 0.06$

Values are expressed as mean ± standard deviation. For each characteristic, identically superscript capital letters in the same row indicate no significant differences ($p > 0.05$) between samples. D.W.- dry weight.

4. Discussions

4.1. Consumer preferences and market viability

Evaluating consumer preferences and dietary trends is essential for understanding the acceptance and scalability of novel plant-based formats such as verrine snacks. Recent studies indicate a significant shift towards plant-based diets due to increasing health consciousness, ethical considerations regarding animal welfare, and environmental sustainability [39, 40]. Consumers are willing to pay a premium for plant-based meat substitutes, yet they often express lower acceptance due to sensory attributes such as taste and texture [39]. Additionally, motivations to adopt plant-based foods are influenced by personal beliefs and societal endorsements; the Theory of Planned Behavior highlights these drivers as crucial for fostering consumer intention towards plant-based eating [40]. Consumer acceptance tests reveal that the sensory properties of food, such as appearance, aroma, and overall taste, are decisive in the acceptance of vegetarian diets and innovative culinary formats [41]. A recent study emphasizes the need for the food industry to develop products that fulfill nutritional requirements and appeal to taste preferences and aesthetic presentation [40, 41]. Successful culinary innovations, like the verrine format, could leverage these factors, aligning with emerging dietary trends and enhancing the visibility of plant-based offerings to consumers [41].

The increasing interest in plant-based dietary options among traditionally omnivorous consumers underscores a significant market opportunity for innovation tailored to flexitarians and health-conscious individuals [39, 40, 41]. Over the past five years, research indicates a notable rise in the adoption of flexitarian diets, characterized by reduced meat consumption and an increased focus on plant-based foods [41]. A 2022 survey revealed that over 50% of American consumers identified as flexitarians or expressed interest in incorporating more vegetarian meals into their diets, reflecting a growing acceptance of plant-based alternatives [42]. This shift is driven mainly by health concerns, with many consumers recognizing the nutritional benefits associated with increased consumption of fruits, vegetables, and legumes [43].

Furthermore, the COVID-19 pandemic has amplified this trend; consumers are more health-conscious and regard plant-based eating as a proactive approach to improve immunity and overall well-being [44]. Companies have responded accordingly, introducing innovative products that cater to these preferences while emphasizing taste, convenience, and nutritional value [45]. Appealing to flexitarians' sensory attributes and dietary preferences can enhance product acceptance and market penetration. As a result, product developers and marketers are strategically positioned to capitalize on this emerging interest by innovating offerings that align with the evolving dietary patterns of today's consumers [46].

The current consumer landscape regarding plant-based culinary ingredients reveals noteworthy preferences, with quinoa emerging as a leading choice, followed by soybeans and buckwheat [47, 48]. In contrast, ingredients such as chia and amaranth experience lower acceptance, likely due to their perceived complexity in preparation or limited familiarity among consumers [49]. This trend reflects a broader need within the food industry to balance innovative offerings with the familiar, as consumers often gravitate towards ingredients they recognize and feel comfortable using in their cooking [47, 49].

Incorporating familiar ingredients like quinoa and soy into product innovations can help mitigate food neophobia, a significant barrier to accepting new and unfamiliar foods [50]. Research indicates that enhancing consumer education around the preparation and culinary potential of less familiar ingredients, such as chia and amaranth, may increase their acceptability [51]. Additionally, integrating evidence-based practices, such as culinary medicine curricula, can empower consumers with the skills to prepare nutritious meals using these ingredients, thereby potentially increasing their consumption [50]. The findings underscore the importance of understanding consumer preferences while promoting healthful innovations that encourage the inclusion of a broader array of plant-based ingredients [39, 40, 41, 42, 43, 47, 49].

The consumption patterns of legumes and pseudocereals reveal critical insights into consumer preferences and dietary trends that can significantly impact product formulation and marketing strategies. Recent research has indicated that legumes, with their established role in various traditional cuisines and health-promoting properties, are integrated into daily diets more frequently than pseudocereals, which are often consumed weekly or monthly [52]. These findings suggest a higher level of habitual acceptance and familiarity with legumes, likely due to their longstanding presence in dietary practices and their versatile culinary applications [53]. While pseudocereals, such as quinoa and amaranth, are gaining popularity, they remain less frequently consumed, which may limit their market penetration [54]. The rise in interest in these ingredients can be attributed to their nutritional benefits, high protein content, and essential amino acids. However, the less frequent integration into daily meals indicates a need for strategies that enhance their familiarity and appeal to consumers [54, 55].

Companies seeking to innovate can leverage these consumption patterns by prioritizing legumes in product formulations, potentially positioning their new offerings as familiar and nutritionally beneficial [56]. Simultaneously, efforts should be made to educate consumers about the advantages and culinary versatility of pseudocereals, helping to increase their acceptance and use within the diet [57]. Ultimately, aligning product development with consumer habits will be crucial for elevating the profile of both legumes and pseudocereals in the marketplace [56, 57].

4.2. Nutritional composition

The distinct compositional profiles of VT and VM reflect ingredient-driven trade-offs between energy density and nutrient functionality. VM's elevated moisture correlates with *M. oleifera*'s high soluble fiber content (10–15%), which binds water by capillary action and hydrogen bonding, as demonstrated in hydrocolloid-rich systems [58]. Also, VM's superior protein content reflects findings on Moringa-fortified foods, where leaf proteins (18S globulins) complement plant matrices by electrostatic interactions, enhancing retention [59]. The energy disparity (VT > VM) highlights VT's caloric reliance on fats and carbohydrates, akin to energy-dense therapeutic foods, while VM's nutrient-mineral synergy aligns with "clean label" trends emphasizing protein and micronutrient density [60, 61]. However, VM's mineral richness may introduce sensory trade-offs, such as metallic notes from iron, a hurdle reported in mineral-fortified foods [61].

4.3. Rheological measurements

Measurements of the storage modulus (G') and loss modulus (G'') as functions of angular frequency (ω) revealed a frequency-dependent response typical of structured, gel-like systems [62]. The quinoa layer's exceptional stiffness was consistent with studies highlighting quinoa's superior gelling capacity compared to common legumes. Quinoa's high protein content (14–18%) and balanced amino acid profile promote extensive cross-linking *via* disulfide bonds and hydrophobic domains, while its starch granules (2–3 μm diameter) act as inert fillers that restrict polymer mobility, amplifying rigidity [63]. In contrast, the cohesive chickpea-turmeric layer's viscoelasticity may reflect interactions between chickpea vicilin-legumin proteins and curcumin, a hydrophobic polyphenol in turmeric [64, 65]. Curcumin is known to bind proteins via hydrophobic and π-π interactions, forming soluble complexes that stabilize networks—a phenomenon documented in soy protein-curcumin gels [66].

The VM formulation's elevated moduli compared to VT may be linked to Moringa's phytochemicals, such as chlorogenic acid and glucosinolates, which can modify protein conformation [67]. For example, phenolic acids in Moringa can undergo Maillard-like reactions with pea proteins during processing, introducing covalent cross-links that stiffen the network—a mechanism reported in lentil protein–phenolic gels [68]. Similarly, red lentil's high G' correlates with its starch–protein matrix behavior: during heating, lentil starch gelatinizes to form a continuous phase reinforced by denatured proteins, as described previously [69, 70]. The frequency-dependent G' increase in VM contrasts with some legume gels, where G' plateaus or declines at high frequencies due to network breakdown. This divergence suggests that VM's matrix possesses a higher density of junction zones, likely due to Moringa's cross-linking activity and lentil's amylose–protein interactions, which resist deformation under rapid shear [67, 69, 70].

Interestingly, the VT formulation's shear-thickening behavior diverges from conventional polymer gels, which often exhibit shear-thinning. This anomaly could reflect strain-induced crystallization or alignment of quinoa starch helices and chickpea protein fibrils—a phenomenon observed in xanthan–chitosan complexes under oscillatory shear [71]. Such behavior implies that VT's network reorganizes dynamically under stress, a property advantageous for layered foods requiring structural resilience during handling [71, 72].

4.4. Biological activity

Curcuma longa and *M. oleifera* are celebrated for their high levels of bioactive compounds, which provide essential health advantages thanks to their antioxidant, anti-inflammatory, and immunomodulatory effects [73]. Turmeric is well-known for its key ingredient, curcumin, a phenolic compound recognized for its potent antioxidant properties [73, 74]. Curcumin serves as an effective free radical scavenger, capable of decreasing oxidative stress and influencing immune responses [74]. However, its limited bioavailability requires the incorporation of lipid-based carriers to improve absorption [73, 74].

M. oleifera, commonly known as a "superfood," is prized for its rich content of flavonoids, phenolic acids (quercetin and chlorogenic acid), carotenoids, and essential vitamins (A, C, E), as well as minerals (calcium, iron) [75, 76]. These phytochemicals are responsible for the plant's remarkable antioxidant and immunomodulatory effects [76, 77]. *M. oleifera* showcases its impressive antioxidant properties through compounds like quercetin, kaempferol, and chlorogenic acid, which are linked to anti-inflammatory, anticancer, and heart-protective benefits [77]. On the other hand, turmeric's antioxidant effects predominantly come from curcumin. Although curcumin is effective, it is usually found in lower concentrations in plant-based forms and needs particular delivery methods to ensure it is bioavailable [76, 77].

The antioxidant properties of VT and VM indicated significant free radical scavenging activity for both formulations. Remarkably, VM exhibited higher antioxidant efficacy than

VT, likely attributed to the greater variety of polyphenols in *M. oleifera* [77]. The TPC (total phenolic content) results further validate these findings, showing a notably greater phenolic concentration in VM (184.14 μg GAE/g D.W.) compared to VT (114.42 μg GAE/g D.W.). These results are consistent with the extensively documented phytochemical profile of *M. oleifera*, which is abundant in flavonoids and phenolic acids [77]. The combination of turmeric and *M. oleifera* with pseudocereals (quinoa, amaranth, and buckwheat) and legumes (chickpeas and lentils) produces a nutritionally comprehensive profile that is abundant in proteins, fibers, and bioactive compounds [78]. Additionally, the dietary fibers and polyphenols present in these formulations support gut health by fostering a balanced microbiota, highlighting the significance of turmeric- and *M. oleifera*-enriched vegan verrines as valuable functional food products [79, 80].

5. Conclusions

This study developed and characterized two innovative vegan verrine formulations using legumes, pseudocereals, turmeric, and *M. oleifera*. The VM formulation showed superior nutritional value, particularly in protein, minerals, and antioxidant capacity, compared to VT. Consumer evaluation demonstrated high acceptability, particularly among flexitarian individuals. Rheological and bioactivity analyses revealed that both formulations possess desirable textural and functional properties, with potential for use as convenient, nutrient-rich, plant-based appetizers. Future perspectives should explore the integration of fermentation technologies and encapsulation systems further to enhance the bioavailability and stability of sensitive bioactives. Additionally, expanding the sensory and shelf-life assessment under real-market conditions would provide valuable insights into product scalability and commercialization potential.

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