

NUTRITIONAL AND SENSORY POTENTIAL OF INNOVATIVE VEGETABLE SAUCES IN THE CONTEXT OF PROCESSING CHANGES AND TECHNOLOGICAL MODIFICATIONS

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<https://doi.org/10.55251/jmbfs.13822>

ARTICLE INFO

Received 14. 1. 2026
Revised 17. 3. 2026
Accepted 24. 3. 2026
Published 1. 4. 2026

Regular article



ABSTRACT

The aim of this study was to develop and evaluate innovative vegetable-based sauces as functional alternatives to commercial tomato ketchup, focusing on formulation strategy, technological processing, and bioactive enrichment. Five formulations (S1–S5) were developed using a standardized base of beetroot purée (40%) and apple purée (40%), supplemented with specific vegetable matrices (tomato, carrot, pumpkin, sweet potato, eggplant, and bell pepper). The sauces were processed using controlled thermal treatment (88°C, 3 min), facilitated by a naturally acidic pH (< 4.6). Physicochemical analysis, bioactive compound profiling (total polyphenols, betacyanins, carotenoids), and weighted sensory evaluation were conducted. Statistically significant differences ($p < 0.05$) were observed among formulations. The sauce incorporating eggplant and pepper (S5) exhibited the highest total polyphenol content (2026.9 mg GAE.kg⁻¹ DM), while the tomato-based variant (S1) achieved the highest sensory score (85.5 points), surpassing the commercial control in flavor harmony and aroma. Consistency, measured by Bostwick flow, was significantly more stable in the innovative sauces than in commercial ketchup, driven by the natural polysaccharide matrix of the root and tuber components. The results demonstrate that multi-component vegetable sauces can achieve superior nutritional profiles and high consumer acceptance, providing a viable strategy for developing clean-label condiments with reduced sodium and enhanced antioxidant potential.

Keywords: vegetable sauce, beetroot, apple purée, polyphenols, sensory quality, technological stability

INTRODUCTION

Ketchup is a popular tomato-based sauce valued for its flavor, aroma, and consistency (Sikora *et al.*, 2008; Hagggar *et al.*, 2023). However, traditional ketchup often offers limited nutritional benefits, primarily determined by the stability of tomato-derived bioactive compounds. Driven by increasing consumer demand for functional foods with high antioxidant and fiber content, there is significant potential for innovation in vegetable-based sauces (Melgar *et al.*, 2017). Combining diverse vegetables can enhance nutritional profiles while introducing novel sensory characteristics (Nawirska-Olszańska *et al.*, 2011).

In this study, various vegetables were selected to provide a synergistic blend of bioactive compounds and functional properties. Tomatoes serve as the primary source of lycopene and phenolic acids, which are crucial for antioxidant activity (Guemouni *et al.*, 2023). Beetroot contributes betalains and saponins (Stoica *et al.*, 2024), while pumpkins and carrots enhance the formulation with β -carotene and dietary fiber, the latter being essential for both prebiotic effects and the final texture (Jacobo-Velazquez, 2023; Rahman *et al.*, 2024). Furthermore, the addition of eggplant, peppers, and sweet potatoes introduces a complex matrix of anthocyanins, capsaicinoids, and complex carbohydrates, which support the overall antioxidant potential and stability of the product (Wang *et al.*, 2018; Marin *et al.*, 2004).

Despite the growing market for vegetable spreads, research focusing on the systematic replacement of tomato solids with diverse vegetable matrices to create ketchup-like alternatives remains limited. The novelty of this study lies in the formulation strategy and comprehensive technological evaluation of these vegetable-based alternatives. We specifically examine how different vegetable combinations influence the physicochemical parameters, bioactive stability, and sensory profiles compared to conventional tomato ketchup, providing a framework for developing healthier, functional condiments.

MATERIAL AND METHODS

The innovative vegetable sauces were developed based on an original formulation, utilizing beetroot and apple purées as the primary base. Apple purée was incorporated to naturally reduce the necessity for added sucrose and texture-modifying agents. The following cultivars were used: apples (cv. Gala), tomatoes

(cv. Uno Rosso), beetroot (cv. Betina), carrots (cv. Nantes 3), peppers (cv. Slovakia), butternut squash (cv. Liscia), eggplant (cv. Klasik), and sweet potatoes (cv. Beauregard). All raw materials were sourced from the Nové Zámky region (Slovakia), characterized by fertile chernozem soils and a warm climatic zone suitable for thermophilic crops.

The production of the innovative vegetable sauces followed a standardized technological procedure. Fresh raw materials were sorted, washed, and prepared (peeling for beetroot, carrot, sweet potato, and butternut squash; cutting for pepper, eggplant, and apples). The ingredients were then softened using a combi-steamer (Electrolux Professional, Sweden) at 120°C for 20 minutes (60 minutes for beetroot).

Table 1 Formulations of innovative vegetable sauces

Ingredient (g.kg ⁻¹)	S1	S2	S3
Beetroot purée	400	400	400
Apple purée	400	400	400
Tomato purée	200	-	-
Carrot purée	-	200	-
Pumpkin purée	-	-	200
Sweet potato purée	-	-	-
Eggplant purée	-	-	-
Pepper purée	-	-	-
Spirit vinegar (8%) (ml)	20	20	20
Sucrose	20	20	20
Salt (NaCl)	6	6	6
Dried onion	0.2	0.2	0.2
Dried garlic	0.2	0.2	0.2
Spice blend: cinnamon, cloves, star anise, nutmeg, coriander	0.4	0.4	0.4

After cooling, the materials were processed into purées using a food mill (Robot Coupe C80, France) with a 0.5 mm mesh sieve.

The individual purées were blended according to the formulations (Table 1), followed by pH adjustment to ensure optimal thermal stabilization. The mixtures were homogenized using a high-shear homogenizer (Heidolph SilentCrusher M, Germany) at 10 000 rpm for 3 minutes. Finally, the sauces were filled into sterile glass containers and pasteurized at 88°C for 3 minutes (ensuring pH < 4.6 for microbiological stability).

Analytical methods and procedures

Determination of Refractometric Dry Matter

Refractometric dry matter was measured using a digital Rudolph J47WR refractometer (0–100 °Brix). The instrument was calibrated with distilled water (0 °Brix), and a small amount of sample was applied to the measurement surface. Dry matter content was displayed directly in °Brix.

Determination of pH Value

pH was measured using an ExStik Waterproof digital pH meter (range 0–14, -5 to +50 °C). The device was calibrated with pH 4 and pH 7 buffers, and samples were placed in 25 mL beakers for electrode immersion. The pH value was read directly from the screen.

Determination of Salt Content

Salt content was determined by titration using an automatic TitroLine 5000 titrator. A 2 g sample was mixed with 80 mL distilled water and 0.5 mL nitric acid (4 mol.L⁻¹) in a 150 mL beaker, stirred magnetically, and titrated with 0.1 mol.L⁻¹ AgNO₃. The NaCl content was read directly from the titrator display.

Determination of Total Polyphenol Content

The total polyphenol content was determined using a spectrophotometric method according to **Lachman et al. (2003)**, employing the Folin–Ciocalteu reagent. Extraction was performed in 80% ethanol using a Heidolph GSL 3006 shaker at 150 rpm for 24 h. For analysis, 50 µl of the extract was pipetted into a 50 mL volumetric flask, followed by 2.5 mL of Folin–Ciocalteu reagent (diluted 1:2, v/v), 5 mL of Na₂CO₃ solution (20%), and distilled water up to 50 mL. After 2 hours of reaction, absorbance was measured at 765 nm. The polyphenol content was calculated from a gallic acid calibration curve prepared in the range of 5–200 mg.L⁻¹.

Determination of Total Betacyanin Content

The total betacyanin content was determined using the spectrophotometric method described by **Bucur et al. (2016)**. A 5 g portion of each sample was weighed and extracted with 15 mL of distilled water for 10 minutes under stirring. The mixture was filtered into a 50 mL volumetric flask. This extraction was repeated three times, and the final volume of the stock solution was adjusted to 50 mL. The extract was diluted in a 1:2 ratio and mixed for 5 minutes, followed by centrifugation at 4000 rpm for 10 minutes. The supernatant was collected, and the procedure was repeated to ensure maximum extraction of betacyanins.

One milliliter of the diluted extract was pipetted into two test tubes. To each tube, 1 mL of 0.01% HCl in ethanol was added. Then, 10 mL of 2% aqueous HCl solution was added to the first tube, and 10 mL of a pH 3.5 buffer solution (a mixture of 0.2 mol.L⁻¹ Na₂HPO₄ and 0.1 mol.L⁻¹ citric acid) was added to the second. Absorbance was measured at 520 nm against a blank sample using the same PV4 spectrophotometer (VWR, Radnor, USA). The total betacyanin content was calculated using the following formula:

$$BT = (A_1 - A_2) \times Df \times MW \times 1000 / (\epsilon \times l) \text{ (mg.kg}^{-1}\text{)}$$

where:

- A₁, A₂ – absorbance of the sample,
- Df – dilution factor,
- MW – molecular weight of betanin (550 g.mol⁻¹),
- ε – molar extinction coefficient (60 000 L.mol⁻¹.cm⁻¹),
- l – path length of the cuvette (1 cm).

Determination of Total Carotenoid Content

The total carotenoid content was determined according to the method of **Hegedúsová et al. (2016)**. Carotenoids were extracted from the homogenized sample using acetone. The resulting acetone extract was repeatedly mixed with petroleum ether, and the phases were separated using distilled water. The petroleum ether phase, containing carotenoids, was dried with anhydrous sodium sulfate, quantitatively transferred into a volumetric flask, and adjusted to a final volume of 25 mL with petroleum ether.

Absorbance of the samples was measured spectrophotometrically using a PV4 spectrophotometer (VWR, Radnor, USA) at a wavelength of 450 nm. The carotenoid content was calculated using the following formula:

$$\text{Carotenoids} = (A \times V \times 100) / (m \times E) \text{ (mg.kg}^{-1}\text{)}$$

where:

- A – absorbance at 450 nm,
- V – volume of extract (mL),
- E – extinction coefficient (2592 for β-carotene),
- m – sample weight (g).

Determination of Consistency (Bostwick Consistency)

Sauce consistency was measured at 20 °C using a Bostwick consistometer (**Barringer et al., 1998**). The sample was poured to the rim, leveled, and the flow distance after 30 s was recorded in cm.30⁻¹.

Sensory Analysis

Sensory evaluation was conducted by a semi-trained panel of 20 members (aged 20–45) using a weighted 5-point hedonic scale. The assessed attributes included appearance (color), aroma, consistency, and taste (intensity and harmony), along with an overall impression. To ensure objectivity, each attribute was assigned a specific importance coefficient (Table 2), resulting in a maximum total score of 100 points.

Samples were served at room temperature in transparent containers coded with three-digit random numbers. Panelists used drinking water as a neutralizer between samples. The qualitative quality of the sauces was categorized based on the final score: Excellent (100–80), Very Good (79–60), Standard (59–40), and Substandard/Poor (<40).

Table 2 Evaluation table for vegetable sauces

Sensory attribute	point rating	importance coefficient	max. weighted score
Appearance (color)	1 – 5	3	15
Aroma	1 – 5	4	20
Consistency	1 – 5	4	20
Taste (intensity)	1 – 5	4	20
Taste (harmony)	1 – 5	4	20
Overall impression	1 – 5	1	5
Total			100

Statistical Evaluation

To evaluate statistically significant differences between the samples, one-way analysis of variance (ANOVA) was performed. For subsequent post-hoc comparison of means between the commercial control and the innovative vegetable sauces, the Tukey HSD (Honestly Significant Difference) test was employed. All statistical tests were conducted using Statistica 12 software (**StatSoft, USA**), with the threshold for statistical significance set at p<0.05. Results are presented as mean values ± standard deviation (n=3).

RESULTS AND DISCUSSION

Consumers increasingly value foods rich in functional components such as antioxidants, fiber, and other bioactive compounds, reflecting a trend toward innovative vegetable sauces that combine nutritional value with appealing taste (**Giménez et al., 2022**).

The results for basic qualitative indicators and bioactive compounds are summarized in Table 3.

Table 3 Physicochemical properties and bioactive compounds of innovative vegetable sauces

	refractometric solids (°Brix)	pH	salt content (%)	consistency (cm.30 s ⁻¹)	total polyphenol (mg GAE.kg ⁻¹ DM)	betacyanin (mg.kg ⁻¹ DM)	total carotenoids (mg.kg ⁻¹ DM)
C	22.6 ± 0.2 ^c	4.20 ± 0.02 ^c	2.33 ± 0.09 ^c	7.83 ± 0.06 ^c	507.6 ± 21.9 ^a	8.8 ± 1.3 ^a	874.4 ± 39.3 ^c
S1	18.6 ± 0.13	4.03 ± 0.03 ^a	1.91 ± 0.02 ^b	7.20 ± 0.10 ^c	1548.8 ± 50.0 ^d	239.0 ± 3.9 ^c	336.9 ± 22.5 ^b
S2	16.9 ± 0.0 ^b	4.16 ± 0.01 ^{bc}	1.81 ± 0.02 ^{ab}	7.00 ± 0.10 ^{ab}	1330.9 ± 57.4 ^c	231.7 ± 4.8 ^{bc}	289.9 ± 11.9 ^b
S3	17.2 ± 0.1 ^c	4.12 ± 0.03 ^b	1.77 ± 0.02 ^a	7.10 ± 0.10 ^{ab}	1033.2 ± 39.8 ^b	226.5 ± 1.8 ^b	212.3 ± 10.7 ^a
S4	18.4 ± 0.1 ^d	4.17 ± 0.02 ^{bc}	1.84 ± 0.02 ^{ab}	6.97 ± 0.06 ^a	1255.9 ± 15.7 ^c	229.6 ± 4.8 ^{bc}	282.9 ± 4.7 ^b
S5	14.7 ± 0.2 ^a	4.06 ± 0.02 ^a	1.90 ± 0.02 ^b	7.57 ± 0.06 ^d	2026.9 ± 63.6 ^c	229.7 ± 7.4 ^{bc}	185.9 ± 9.8 ^a

C - control; S1–S5 - innovative vegetable sauces with varying vegetable purée compositions; ± standard deviation, ^{a-c} homogeneous group, different letters at mean represent statistically significant differences among treatments (p < 0.05)

The soluble solids content of the innovative sauces (14.7 – 18.6 °Brix) remained lower than commercial ketchup but consistently above the legislative minimum for vegetable purées (**Decree No. 132/2014 Coll.**). Our findings are lower compared to **Rahman et al. (2024)**, who reported 24.0–30.8 °Brix in tomato-pumpkin formulations. These results underline the strong influence of raw material selection on soluble solids, which affects perceived sweetness, viscosity, and shelf-life stability.

A critical factor for technological safety is the pH value. All tested sauces maintained a pH below 4.6 (4.03 – 4.17), which is the recognized limit for inhibiting spore-forming pathogens, particularly *Clostridium botulinum* (**Singh et al., 2018**). While **Rahman et al. (2024)** observed pH values up to 5.23 in pumpkin-rich sauces necessitating sterilization above 100 °C – our formulations allow for mild pasteurization. The thermal treatment of acidic products requires temperatures up to 100 °C (**Boix et al., 2022**), which is suitable for naturally acidic products. Controlled thermal processing not only inhibits microbial growth but also neutralizes toxins, enzymes, and other metabolites (**Mansour et al., 2023**). Optimization of thermal processes is critical when developing canned vegetable products, balancing the preservation of key qualitative and bioactive properties with microbial safety (**Chiozzi et al., 2022**).

Consistency measurements (Bostwick flow) showed that innovative sauces were significantly more stable than the commercial ketchup, which exhibited the fastest flow (p<0.05). Mechanistically, this is driven by the inherent polysaccharide composition of the raw materials. Unlike commercial ketchup, which relies on added thickeners, our sauces utilize the high water-binding capacity of natural fibers and starch. These observations confirm that purée type strongly affects consistency through differences in water-binding capacity, fiber content, and polysaccharide composition. This aligns with **Hagggar et al. (2023)**, who investigated sauces based on carrot, red pepper, and pomegranate, highlighting the influence of raw material on total carbohydrates, sugars, and fiber. Similarly, **Ahouagi et al. (2021)** demonstrated that incorporating fruit purée into tomato sauce affected dry matter and pH, while Bostwick consistency remained comparable to the control, showing that modifications in ingredient composition influence textural characteristics without compromising processability.

The total polyphenol content (TPC) was significantly higher in all innovative sauces compared to commercial ketchup (p<0.05). The peak values observed in S5

(eggplant/pepper combination) suggest a strong synergistic contribution of different phenolic classes. Analytically, this enrichment is driven by the diverse phenolic profile of eggplant, which is rich in chlorogenic acid and anthocyanins (nasunin), combined with the flavonoids (quercetin, luteolin) and phenolic acids (caffeic, ferulic) typical of peppers (**Sun et al., 2007; Silva et al., 2021**). The intermediate levels in S1–S4 indicate that while beetroot and apple provide a solid phenolic base, the specific addition of eggplant and pepper creates a more dense antioxidant matrix.

Betacyanins, the dominant pigments in red beetroot, are responsible for the characteristic red-violet hue. Betanin comprises the majority of this pigment group (**Clifford et al., 2015; Pauliuc et al., 2015; Chhikara et al., 2019**). While levels were relatively uniform due to the fixed beetroot proportion, the slight variations observed (p<0.05) between S3 and S1 may be linked to the pigment-matrix interactions. Betacyanin stability is highly pH-dependent; the lower pH environment in S1 (4.03) and S5 (4.06) likely enhanced the stability of the betalain chromophore, as these pigments exhibit maximum stability between pH 4.0 and 5.0. Furthermore, natural polyphenols present in the added vegetables may act as co-pigments, further stabilizing the color through intermolecular associations. Carotenoid content was highest in the commercial control, reflecting the concentration of lycopene in industrial tomato paste (p<0.05). Among the innovative sauces, S1 and S4 (sweet potato) showed the best carotenoid retention. The analytical depth here lies in the protective role of the matrix; the high dietary fiber and complex carbohydrate content in sweet potatoes may provide a protective structural framework that limits the oxidative degradation of β-carotene during thermal processing (**Wang et al., 2018**). Conversely, lower levels in S5 suggest that despite the presence of pigments in peppers, their extractability or stability might have been compromised by the complex eggplant matrix during the homogenization and pasteurization stages.

Sensory analysis provides essential feedback for product development, complementing technological and microbiological assessments to ensure market acceptance (**Hedi et al., 2024**). The results of the weighted sensory evaluation are summarized in Table 4.

Table 4 Sensory assessment of innovative sauces

Criterion	appearance (max 15 pts)	aroma (max 20 pts)	consistency (max 20 pts)	taste – intensity (max 20 pts)	taste – harmony (max 20 pts)	overall impression (max 5 pts)	total score
C	12.8	15.1	15.3	15.8	14.6	4.4	78.0
S1	13.2	16.8	16.4	17.5	17.2	4.4	85.5
S2	11.8	15.4	16.0	15.6	14.7	4.0	77.5
S3	12.6	14.4	15.6	14.2	14.4	3.8	75.0
S4	12.0	14.8	16.2	15.8	14.6	4.0	77.4
S5	12.4	15.2	16.0	15.8	14.65	4.0	78.1

C - control; S1–S5 - innovative vegetable sauces with varying vegetable purée compositions

From the sensory perspective, sauce S1 achieved the highest overall rating (85.5 points) and was classified as an "excellent" innovative sauce. It outperformed the commercial control (C, 78.0 points) across all evaluated attributes, particularly in taste intensity, harmony, and aroma. Analytically, this superiority is likely linked to the synergistic interaction between the tomato purée's glutamates (umami) and the high sugar-to-acid ratio provided by the beetroot and apple base. Evaluators noted a more complex and appealing flavor profile compared to the standard reference. This aligns with **Ahouagi et al. (2021)**, who found that incorporating fruit purées (up to 50%) into tomato-based systems did not adversely affect taste or overall acceptability, but rather enhanced the sensory complexity. Conversely, S3 (pumpkin-based) received the lowest rating (75.0 points) among innovative samples. As demonstrated by **Rahman et al. (2024)**, while pumpkin increases dry matter, higher proportions can reduce sensory attractiveness due to a sweeter, less intense "ketchup-like" flavor profile, which explains the lower scores for taste harmony and aroma in our S3 formulation.

The consistency scores in the sensory evaluation (15.6–16.4 points) strongly correlate with the physical measurements obtained via the Bostwick consistometer. Samples S1, S2, and S4 showed improved consistency perception compared to the commercial control. This sensory "richness" and smoothness can be attributed to the high water-holding capacity of the insoluble fiber fractions and natural starches in the carrot and sweet potato matrices. Our results are supported by **Alqathani (2020)**, who reported that the addition of vegetable-based powders/purées can improve texture without compromising color or leading to syneresis (water separation). The improved consistency of S5 (eggplant/pepper) compared to the control further suggests that even non-starchy vegetables, when correctly homogenized, contribute

CONCLUSION

The results of this study demonstrate that the innovative vegetable sauces (S1–S5), developed as alternatives to commercial tomato ketchup, exhibit favorable

physicochemical and sensory properties. All samples met legislative requirements, with pH values below 4.6 ensuring microbial stability and enabling milder pasteurization (88°C), which is crucial for preserving heat-sensitive bioactive components. The novelty of this work lies in the formulation strategy that utilizes diverse vegetable matrices to naturally stabilize texture and enhance nutritional density without the need for synthetic additives. From a chemical perspective, the innovative sauces contained significantly lower salt levels compared to commercial ketchup, while providing substantially higher concentrations of total polyphenols and betacyanins. Sauce S5 achieved the highest polyphenol content (2026.9 mg GAE.kg⁻¹ DM), highlighting the antioxidant potential of eggplant-pepper combinations. Although carotenoid levels were lower than in the tomato-based control, the innovative sauces showed superior consistency stability (Bostwick flow), driven by the natural fiber and starch content of the vegetables. Sensory evaluation identified sauce S1 as the most suitable substitute for traditional ketchup, achieving the highest score (85.5 points) and an "excellent" classification due to its superior flavor harmony and aroma. While sauce S3 showed lower sensory appeal due to its milder profile, all formulations were classified as "very good" or better. Overall, these findings demonstrate that multi-component vegetable sauces offer a viable technological and sensory alternative to traditional condiments, meeting the consumer demand for products with reduced sodium and naturally enriched bioactive profiles.

Acknowledgments: This work was supported by the Research and Development Agency under contract No. APVV-22-0402.

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