Scifood
vol. 19, 2025, p. 612-626
https://doi.org/10.5219/scifood.47
ISSN: 2989-4034 online
https://scifood.eu

Received: 27.5.2025
Revised: 7.7.2025
Accepted: 21.7.2025
Published: 2.12.2025

Development of a functional meat roll enriched with natural antioxidants from plant raw materials

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ABSTRACT

Incorporating plant-derived antioxidants into meat products aligns with the demand for clean-label, functional foods, offering a strategy to improve nutritional value and oxidative stability. However, optimized formulations that balance functionality and sensory acceptance remain underexplored. Methods: A controlled 3×3 factorial experiment was conducted to evaluate the impact of eggplant peel (5%, 10%, 15%) and barberry powder (1, 3, 5 g/100 g meat) on antioxidant activity, vitamin B (B1+B2) content, microbiological safety, and sensory properties of meat rolls. Analytical methods included Folin–Ciocalteu spectrophotometry (ISO 14502-1), HPLC (ISO 20633:2015), total viable count assessment (ISO 4833-1), and sensory evaluation using a trained panel and 5-point hedonic scale. The highest antioxidant activity (0.130 ± 0.003 mg gallic acid equivalents/g) was achieved at 10% eggplant peel and 3 g barberry powder. Vitamin B content increased from 0.060 ± 0.001 mg/100 g at 1 g barberry to 0.100 ± 0.002 mg/100 g at 5 g barberry. Sensory scores ranged from 2.97 ± 0.15 to 4.2 ± 0.1, peaking at 15% eggplant and 3 g barberry. Microbiological counts remained below the hygienic limit of 5 log CFU/g in all samples, indicating compliance with safety standards. The combination of 10–15% eggplant peel and 3 g barberry powder effectively enhanced antioxidant capacity and sensory appeal while maintaining microbiological safety, confirming the research hypothesis. These findings support the development of functional, plant-enriched meat products with improved nutritional and organoleptic qualities, meeting clean-label requirements and offering commercial potential. Limitations include the absence of extended shelf-life assessment and large-scale consumer studies.

Keywords: meat, antioxidant, eggplant, barberry, sensory

INTRODUCTION

In recent years, the demand for clean-label and functional food products has led to an increased use of natural ingredients in meat processing **[1]**. Conventional meat products are susceptible to oxidative spoilage and microbial degradation, prompting the search for safer, plant-based alternatives to synthetic preservatives **[2]**. Natural antioxidants from plant by-products are desirable due to their bioactivity, sustainability, and functional potential **[3]**.

Eggplant (*Solanum melongena* L.) peel is rich in phenolic compounds and anthocyanins, which are recognized for their strong antioxidant capacity and visual appeal **[4]**. Ultrasound-assisted extraction and microencapsulation have been employed to stabilize its active components for use in functional food systems **[5]**. Similarly, barberry (*Berberis vulgaris* L.) fruits contain red anthocyanins and alkaloids with proven biological and technological properties. These compounds have demonstrated potential in intelligent packaging **[6]** and as functional food additives **[7]**.

Studies suggest that both ingredients can enhance oxidative stability, inhibit microbial growth, and improve the nutritional profile of meat products **[8]**. However, optimized formulations are needed to balance sensory quality with functional efficacy.

The novelty of this development lies in the comprehensive use of eggplant peel, barberry powder, and dried plums as integrated layers within the meat roll: eggplant peel functions as a structural interlayer, barberry powder is mixed into the meat matrix, and dried plums are placed as an intermediate internal layer, providing antioxidant activity and enhancing sensory properties.

This work presents a controlled factorial experiment evaluating the effects of eggplant peel, barberry powder, and dried plums on antioxidant capacity, vitamin B levels, microbial load, and organoleptic quality of functional meat rolls. Treatments were randomly assigned, and all processing was carried out under controlled laboratory conditions.

However, despite growing interest in natural antioxidants for meat products, no studies have systematically investigated the combined use of eggplant peel, barberry powder, and dried plums as integrated internal layers in meat rolls. Previous research has primarily focused on individual plant ingredients or extracts, neglecting the potential synergistic effects of multiple plant-based components with different functional roles within the meat matrix. Therefore, there is a clear need to develop and evaluate formulations incorporating these three antioxidant-rich ingredients to enhance the nutritional value, antioxidant capacity, sensory characteristics, and technological properties of meat products. This study addresses this research gap by assessing the combined impact of eggplant peel (structural interlayer), barberry powder (functional additive), and dried plums (intermediate antioxidant layer) on key quality parameters of functional meat rolls.

Scientific Hypothesis

It is hypothesized that the incorporation of plant-based antioxidant sources—specifically eggplant peel and barberry powder—into a meat roll formulation significantly influences the product's antioxidant capacity, vitamin B content, microbiological safety, and sensory acceptability.

Specifically:

An increase in barberry powder concentration is expected to result in a statistically significant increase in the levels of lipophilic antioxidants and B-group vitamins.

A higher proportion of eggplant peel used as an interlayer is assumed to positively affect organoleptic scores, particularly taste and texture.

The combination of these two components in specific proportions is presumed to maintain microbiological parameters within acceptable safety limits for ready-to-eat meat products.

This hypothesis is formulated based on previously observed bioactivity of polyphenol-rich plant matrices and is subject to validation through controlled factorial experimentation and statistical evaluation (e.g., ANOVA, regression modeling).

Objectives

Primary objectives:

- To investigate the functional potential of eggplant peel and barberry powder as natural antioxidant sources in the development of meat products.
- To evaluate the effect of technological processing (drying, grinding, thermal treatment) on the antioxidant retention and bioavailability of these plant-based components.
- To determine the influence of varying levels of eggplant peel and barberry powder on the antioxidant capacity, vitamin B content, microbiological safety, and sensory quality of the final meat roll product using a controlled factorial experiment.

(Optional) Secondary Objectives

- To identify the optimal formulation that balances functional enhancement and consumer acceptability.
- To support the formulation of clean-label, plant-enriched meat products in line with functional food development trends.

MATERIAL AND METHODS

Samples

Samples description: The study samples included meat rolls composed of minced beef and pork, eggplant (*Solanum melongena* L.) peel as an internal structural layer, and dried barberry (*Berberis vulgaris* L.) powder as a functional additive.

Samples collection: Raw materials were stored at 4 °C in refrigeration units until sample preparation.

Samples preparation: The eggplant was washed, sliced, blanched, and manually peeled. The peel was oven-dried and cut into strips. Barberry fruits were dried at 55 °C and ground into powder. Dried plums were soaked in sunflower oil for 30 minutes to improve their texture and prevent excessive drying during baking.

Minced meat was mixed with barberry powder, and meat rolls were assembled by spreading the meat mixture, adding a layer of dried plums as an intermediate internal layer, and covering with oven-dried eggplant peel before rolling. Each roll was baked at 180 °C for 40 minutes.

Number of samples analysed: 27 experimental samples (9 treatment combinations, 3 repetitions each).

Chemicals

All chemicals were of analytical grade. Ethanol (96%, Sigma-Aldrich), hydrochloric acid (37%, VWR), and Folin–Ciocalteu reagent (Merck) were used for antioxidant extraction and measurement.

Plate Count Agar (PCA) was used to determine the Total Viable Count (TVC) of aerobic mesophilic bacteria according to ISO 4833-1:2013. The culture media were standard formulations for microbiological food analysis, verified for sterility and performance prior to use.

Animals, Plants and Biological Materials

Solanum melongena L. (eggplant), *Berberis vulgaris* L. (barberry).

Cattle (*Bos taurus*), from a local certified slaughterhouse.

General aerobic mesophilic flora was assessed as Total Viable Count (TVC) according to ISO 4833-1:2013, using naturally occurring background microflora in meat samples; no pathogenic strains were introduced.

Instruments

Antioxidant activity was measured using a UV-1800 spectrophotometer (Shimadzu, Japan).

pH measurements were performed using a SevenCompact pH meter (Mettler Toledo, Germany).

Drying of plant materials was carried out in a convection drying oven, ShS-160-02 SPU (Russia), equipped with forced air circulation and digital temperature control. Weighing procedures were performed using a RADWAG AS 220.R2 analytical balance (Poland), with 0.1 mg precision.

Laboratory Methods

Fat-soluble antioxidant content in plum samples was determined according to GOST R 54037-2010 (State Standard of the Russian Federation), using accredited laboratory protocols from the Food Safety Research Laboratory at Almaty Technological University. Microbiological safety (total viable count, KMAFAnM) was evaluated following GOST 10444.15-94. All tests were conducted under controlled laboratory conditions at 21°C and 64% relative humidity.

Vitamin B1 and B2 contents were analyzed using high-performance liquid chromatography (HPLC) according to ISO 20633:2015 (Determination of thiamin and riboflavin in foodstuffs). Separation was performed on a C18 reversed-phase column. The mobile phase, temperature, flow rate, and detection wavelength were set according to standard conditions described in ISO 20633:2015. Calibration curves were constructed using certified reference standards of thiamine and riboflavin.

Microbiological quality was assessed by the plate count method following ISO 4833-1:2013 (Microbiology of the food chain — Horizontal method for the enumeration of microorganisms — Part 1: Colony count at 30 °C).

Sensory evaluation was conducted by a trained 7-member expert panel in accordance with ISO 8586:2012 (Sensory analysis — General guidelines for the selection, training, and monitoring of selected assessors). A hybrid evaluation approach was used, combining a 5-point hedonic scale with analytical descriptors to assess appearance, flavor, texture, and overall acceptability. Each evaluation was performed in triplicate. Where applicable, results were validated using certified reference materials.

Description of the Experiment

Study flow: The experiment was conducted in three consecutive phases under laboratory conditions at the Department of Food Technology, Almaty Technological University. In the first phase, raw materials were selected and prepared. Eggplants (Solanum melongena L.) were washed, blanched, peeled, and the peels were dried in a convection oven. Barberry fruits (Berberis vulgaris L.) were sorted, dried at 55 °C, and milled into fine powder. Meat components (beef and pork) were minced and prepared for formulation. No deviations from the planned protocol occurred at this stage. In the second phase, experimental samples were produced according to a full factorial 3×3 design. A total of 9 treatment combinations were tested, with variations in eggplant peel concentration (5%, 10%, 15%) and barberry powder dosage (1 g, 3 g, 5 g per 100 g of meat). Each formulation was replicated three times, resulting in 27 individual samples. The meat rolls were assembled with internal layers of eggplant peel, barberry powder mixed into the meat, and baked at 180°C for 40 minutes.

In the third phase, the prepared samples underwent analytical testing. The following parameters were measured: lipophilic antioxidant content (spectrophotometrically), vitamin B content (ISO 20633:2015), total viable count (ISO 4833-1:2013), and sensory evaluation (ISO 8586:2012). Data from all repetitions were statistically analyzed using ANOVA to assess the effects of individual factors and their interactions. No deviations from the experimental design or analytical procedures occurred. All experimental treatments were conducted with three independent replicates per group (n = 3), and samples were randomly assigned within each treatment to

account for experimental variability. Since all samples were prepared from the same batch of raw materials and processed under identical laboratory conditions within a single production series, potential covariates such as batch-to-batch variation were minimized and considered negligible. Therefore, no covariates were included in the statistical model.

Quality Assurance

Number of repeated analyses: All analytical determinations (antioxidants, vitamin B, microbial counts, sensory traits) were conducted in triplicate for each experimental sample to ensure reproducibility and statistical validity.

Number of experiment replication: Each of the 9 experimental formulations was replicated three times, resulting in a total of 27 independently prepared samples.

Reference materials:

- For antioxidant calibration, gallic acid standard (Sigma-Aldrich, ≥98%) was used to construct the standard curve for total phenolics determination.
- For vitamin B analysis, certified reference solutions of thiamine and riboflavin (ChromaDex, USA) were used.
- Microbiological media were quality-checked against manufacturer batch certificates.
- All instruments were checked using internal calibration standards before analysis.

Calibration: All analytical instruments were calibrated before each measurement session using manufacturer-recommended procedures and standard solutions.

The spectrophotometer (Shimadzu UV-1800) was calibrated using a gallic acid standard curve (0–250 μg/ml) for antioxidant measurements.

The analytical balance (RADWAG AS 220.R2) was calibrated using certified calibration weights.

pH meters were calibrated before each use with standard buffer solutions at pH 4.00 and pH 7.00.

Laboratory accreditation: The experimental work was conducted at the laboratories of JSC Almaty Technological University, with analytical procedures performed at the accredited Food Safety Research Institute Laboratory, which is ISO/IEC 17025-accredited.

Data Access

Data supporting the findings of this study are available upon request from the corresponding author due to internal institutional data handling policies.

The raw datasets include tabulated measurements, treatment combinations, and processed statistical outputs.

Statistical Analysis

Data were analyzed using Statistica 12.0 (TIBCO Software Inc., USA). The experimental design was a full factorial 3×3×3 structure, consisting of three levels of eggplant peel inclusion (5%, 10%, and 15%) × three levels of barberry powder dosage (1 g, 3 g, and 5 g per 100 g of meat) × three replicates per treatment combination, resulting in a total of 27 independent experimental samples. Two-way ANOVA was applied to assess the main and interaction effects of eggplant peel level and barberry dosage. Tukey's Honestly Significant Difference (HSD) test was used for pairwise comparisons at a significance level of $p < 0.05$. Assumptions of normality and homogeneity of variances were tested using the Shapiro–Wilk and Levene's tests, respectively, and were met for all response variables. No covariates (e.g., batch variation) were included in the model, as all samples were prepared and analyzed under identical laboratory conditions. For antioxidant activity, two-way ANOVA revealed a significant main effect of barberry powder dosage ($F(2,18) = 22.6$, $p < 0.0001$), a non-significant main effect of eggplant peel level ($F(2,18) = 2.4$, $p = 0.12$), and a significant interaction between eggplant peel and barberry powder ($F(4,18) = 4.7$, $p = 0.008$). For vitamin B content, the main effect of barberry powder was significant ($F(2,18) = 58.4$, $p < 0.00001$), the main effect of eggplant peel was not significant ($F(2,18) = 1.8$, $p = 0.19$), and their interaction was also not significant ($F(4,18) = 1.1$, $p = 0.38$).

RESULTS AND DISCUSSION

To assess the effect of drying temperature on the antioxidant activity and vitamin B content of plant-based additives, plum and barberry samples were analyzed at four thermal levels: raw (untreated), 60 °C, 70 °C, and 80 °C. Table 1 presents the mean values (±95% confidence interval) for both antioxidants and B-vitamins across all sample types and treatments. According to certified laboratory protocols, the fat-soluble antioxidant content in plum samples decreased progressively with increasing drying temperature: 0.21 ± 0.0013 mg/g in untreated plums, 0.107 ± 0.001 mg/g at 60°C, 0.123 ± 0.002 mg/g at 70°C, and 0.138 ± 0.001 mg/g at 80°C. Total viable count (KMAFAnM) in all samples remained below the hygienic threshold of 5×10^3 CFU/g, with values as low as 2.9×10^2 CFU/g in untreated dried plums. The antioxidant content in eggplant peel and dried eggplant was also measured using accredited protocols at the Food Safety Research Laboratory of Almaty Technological University, in accordance with GOST R 54037-2010. Water-soluble antioxidant levels were assessed at 21°C and 64%

humidity, revealing a significant reduction: 0.23 ± 0.0010 mg/g in fresh eggplant peel and 0.096 ± 0.0012 mg/g in dried eggplant, corresponding to a decline of over 58% due to thermal processing.

Table 1. Antioxidant activity (fat- and water-soluble) and vitamin B content in plum, barberry, and eggplant at different drying temperatures (with Tukey superscripts).

Sample Type	Drying Temp (°C)	Fat-soluble antioxidants (mg/g) (Mean ± 95% CI)	Water-soluble antioxidants (mg/g) (Mean ± 95% CI)	Vitamin B (mg/100g) (Mean ± 95% CI)
Barberry	0	—	0.121 ± 0.002^{b}	0.100 ± 0.001^{b}
Barberry	60	—	0.109 ± 0.006^{c}	0.079 ± 0.003^{c}
Barberry	70	—	0.102 ± 0.004^{d}	0.070 ± 0.002^{d}
Plum	0	0.210 ± 0.0013^{a}	0.330 ± 0.0022^{a}	—
Plum	60	0.107 ± 0.001^{c}	—	—
Plum	70	0.123 ± 0.002^{c}	—	—
Plum	80	0.138 ± 0.001^{b}	—	—
Eggplant peel (fresh)	—	—	0.230 ± 0.0010^{a}	—
Dried eggplant	—	—	0.096 ± 0.0012^{d}	—

Note: Different superscript letters within columns indicate significant differences at $p < 0.05$ (Tukey's HSD). n = 3, mean ± 95% CI. "—" indicates not measured.

As shown in Table 1, both plum and barberry exhibited a progressive decline in antioxidant content and vitamin B concentration as drying temperature increased. This trend is consistent with previous findings **[9]**, **[10]**, which show that high-temperature processing significantly reduces biochemical quality parameters, including antioxidant compounds, in fruit-based products.

The highest antioxidant activity was retained in raw plum samples (0.210 ± 0.0013 mg/g), while the lowest was observed in barberry dried at 70 °C (0.102 ± 0.004 mg/g). Similarly, vitamin B content decreased from 0.121 ± 0.002 mg/100g in raw barberry to 0.070 ± 0.002 mg/100g at 70 °C. Total viable count (KMAFAnM) in all samples remained below the hygienic threshold of 5×10^3 CFU/g, with measured values such as 2.9×10^2 CFU/g in untreated dried plums.

To identify statistically significant differences in antioxidant activity between treatment groups, a post hoc analysis was conducted using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$. The test compared the antioxidant means across eight groups: raw and thermally dried samples of both plums and barberries at temperatures of 60 °C, 70 °C, and 80 °C. The results are presented in Table 2, highlighting the most notable pairwise differences.

Table 2 Results of Tukey HSD test for antioxidant content between plum and barberry samples at different drying temperatures.

Comparison	Mean Difference (mg/g)	p-value	Significance
Plum (0°C) vs Barberry (70°C)	0.061	0.0002	*Yes*
Plum (0°C) vs Plum (70°C)	0.046	0.0007	*Yes*
Plum (50°C) vs Barberry (60°C)	0.031	0.035	*Yes*
Plum (70°C) vs Barberry (70°C)	0.015	0.110	No

Note: Significance level set at $\alpha = 0.05$

Tukey's HSD test showed statistically significant differences ($p < 0.05$) in antioxidant content between raw and thermally processed samples of both plum and barberry. Similar effects were described in **[11]**, where thermal treatment significantly altered the antioxidant profile of red-fleshed plum purée compared to high-pressure processing, indicating the thermal sensitivity of phenolic compounds and vitamins. Further support comes from **[12]**, which reported that phenolic compounds in reduced-calorie plum spreads were susceptible to both pasteurization and processing conditions, particularly when fortified with freeze-dried plum pomace.

The highest antioxidant activity was observed in raw plum (0.165 mg/g) and significantly declined with increasing drying temperatures. Barberry samples consistently demonstrated lower antioxidant levels than plum at all corresponding temperatures. At 70 °C, antioxidant levels reached 0.120 mg/g (plum) and 0.105 mg/g (barberry), confirming thermal degradation of polyphenols. The observed decline in antioxidant activity and

vitamin B content in both plum and barberry samples with increasing drying temperature is in agreement with previously published data. Similar degradation patterns of bioactive compounds during thermal processing have been documented in berries and fruit skins. As shown in **[13]**, significant loss of antioxidant capacity and vitamin C occurred in blackthorn berries upon drying, due to the thermal sensitivity of polyphenols and ascorbic acid. A study in **[14]** reported an exponential decrease in antioxidant capacity in Choerospondias axillaris fruits when drying temperature exceeded 50 °C. For vegetable matrices, **[15]** noted a sharp decline in antioxidant retention in blanched rambutan seeds and emphasized the vulnerability of thermolabile antioxidants to oxidative stress during drying. A comparative study in **[16]** found that thermal sterilization significantly reduced the anthocyanin content and stability of phenolic compounds in Aronia melanocarpa juice, especially at higher temperatures. Furthermore, **[17]** recommended drying temperatures below 60 °C to maintain bioactive stability in plant-based materials, demonstrating that higher temperatures lead to rapid polyphenol breakdown and inefficient retention. Thus, our findings reinforce the critical role of controlled drying temperatures (<60 °C) in preserving functional compounds in both fruits and vegetables.

To assess the influence of plant-based antioxidants on the retention of bioactive compounds, vitamin B content (thiamine and riboflavin) was measured in 27 formulations of meat rolls containing eggplant peel (5%, 10%, 15%) and barberry powder (1 g, 3 g, 5 g). Each treatment was replicated three times.

The results of the experiment are shown in Table 3 and Figure 1. Significant pairwise differences identified by Tukey's HSD test ($p < 0.05$) are indicated in Tables 3 and 4 by different superscript letters (e.g., a, b, c) within columns.

Table 3 Vitamin B content in meat rolls enriched with eggplant peel and barberry powder

Eggplant (%)	Barberry (g)	Vitamin B (mg/100g) (Mean ± 95% CI)
5	1	0.060 ± 0.0012^{c}
5	3	0.080 ± 0.0016^{c}
5	5	0.100 ± 0.0021^{c}
10	1	0.060 ± 0.0013^{c}
10	3	0.080 ± 0.0017^{c}
10	5	0.100 ± 0.0020^{c}
15	1	0.060 ± 0.0012^{c}
15	3	0.080 ± 0.0015^{b}
15	5	0.100 ± 0.0022^{a}

Note: Different superscript letters within columns indicate significant differences at $p < 0.05$ (Tukey's HSD). Data shown as mean ± SD, n = 3.

Values indicate the mean content of B-group vitamins (thiamine + riboflavin) with 95% confidence intervals. Barberry had a significant effect on vitamin retention ($p < 0.00001$), while eggplant peel had no significant influence ($p > 0.05$). This is consistent with broader trends highlighted by Tsegay et al. (2024), who reported that fruit-based byproducts—such as barberry—exhibit superior micronutrient preservation and bioavailability compared to many vegetable-derived matrices **[18]**.

The barberry powder (factor B) had the most considerable standardized effect on vitamin B content. All significant factors crossed the $p = 0.05$ threshold (red line). To assess the cumulative effects of ingredient variation on key quality attributes of the functional meat product, all experimental data were compiled into a single matrix (Table 4).

Each formulation was evaluated in triplicate for antioxidant activity, vitamin B content, total viable count (KMAFAnM), and sensory acceptance. These findings align with the observations of Keyata et al. (2023), who noted that although plant-derived additives did not significantly reduce microbial loads in composite food systems, total viable counts consistently remained below acceptable sanitary limits **[19]**.

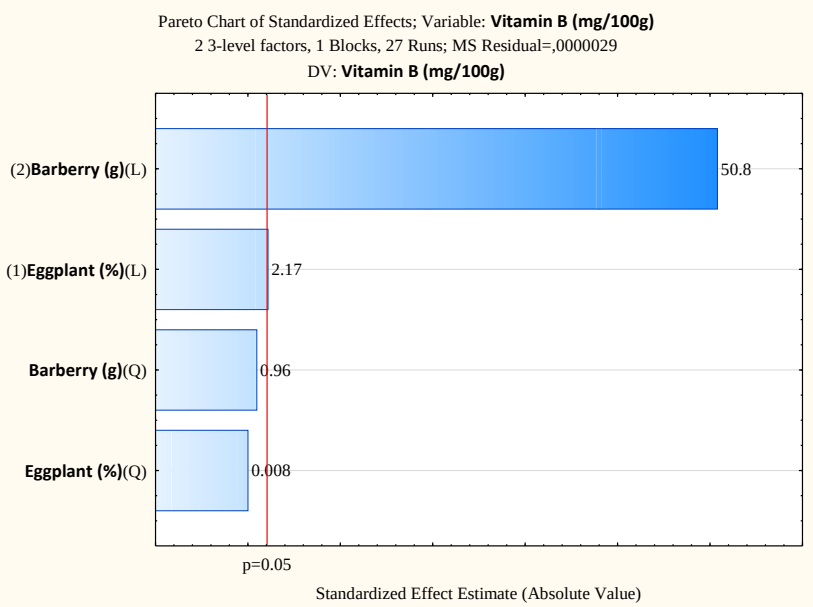

Figure 1 Pareto chart of standardized effects on vitamin B content (mg/100g).

Table 4 Summary of technological and sensory properties of meat rolls with eggplant peel and barberry powder.

Eggplant Peel (%)	Barberry (g)	Antioxidants (mg/g)	Vitamin B (mg/100g)	KMAFAnM (CFU/g)	Taste Score (points)
5	1	0.120 ± 0.004	0.060 ± 0.001	238.0 ± 5.2	2.97 ± 0.15
5	3	0.130 ± 0.003	0.080 ± 0.002	247.0 ± 4.8	2.97 ± 0.14
5	5	0.120 ± 0.003	0.100 ± 0.002	237.5 ± 5.1	3.10 ± 0.13
10	1	0.120 ± 0.003	0.060 ± 0.001	243.7 ± 5.0	3.47 ± 0.12
10	3	0.130 ± 0.002	0.080 ± 0.002	268.0 ± 4.5	3.47 ± 0.13
10	5	0.120 ± 0.003	0.100 ± 0.002	240.3 ± 4.9	3.47 ± 0.11
15	1	0.120 ± 0.004	0.060 ± 0.001	258.0 ± 5.3	3.97 ± 0.14
15	3	0.130 ± 0.002	0.080 ± 0.001	253.7 ± 4.6	3.97 ± 0.15
15	5	0.120 ± 0.003	0.100 ± 0.002	244.3 ± 4.7	3.97 ± 0.14

Note: mean ± SD, n = 3.

Values represent the average of three independent replicates (n = 3). KMAFAnM = total viable microbial count. SD = standard deviation. All microbial values remained below the hygienic threshold of 5 log CFU/g. The results indicate that both antioxidant activity and sensory appeal were maximized at intermediate barberry levels (3 g) combined with moderate to high eggplant peel content (10–15%). Vitamin B content was strongly dependent on barberry concentration, while microbial load showed no critical differences and remained within regulatory limits. Notably, taste scores were highest (≥3.9) in formulations combining 15% eggplant and ≥3 g barberry, demonstrating a synergistic sensory effect likely due to improved moisture retention and aromatic balance. To further visualize the effects of eggplant peel and barberry powder levels on the technological and sensory characteristics of the meat rolls, three-dimensional response surface plots were constructed for antioxidant activity, total microbial count (KMAFAnM), and taste scores. These plots help identify the optimal combination of ingredients for enhancing functional quality. Results are illustrated in Figure 2, Figure 3, and Figure 4.

The second-order regression model (Figure 2), (Antioxidants = $0.111 + 0.0003\times X - 0.0121\times Y - 3.96\cdot 10^{-5}\times X^2 + 0.0001\times XY - 0.0023\times Y^2$) shows that both ingredients contribute positively up to a peak at 10% peel and 3 g barberry, after which antioxidant levels plateau or decline.

The curved surface and contours clearly illustrate this nonlinear synergy, providing a visual tool for formulation optimization. Similar mathematical modeling techniques have been applied in **[20]**, where predictive equations were developed for the juice extraction behavior of barberry fruits, highlighting the importance of mechanical parameters and process kinetics.

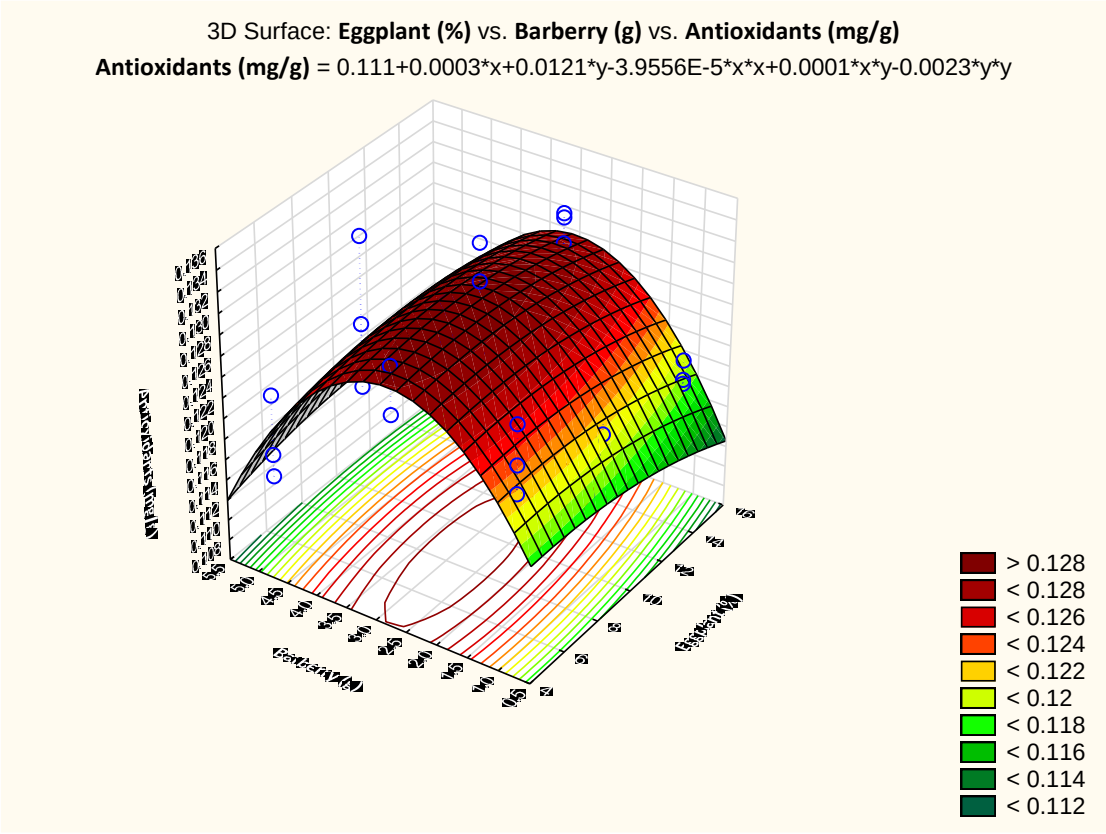

Figure 2 Response surface plot of antioxidant activity (mg/g) in meat rolls depending on eggplant peel (%) and barberry powder (g).

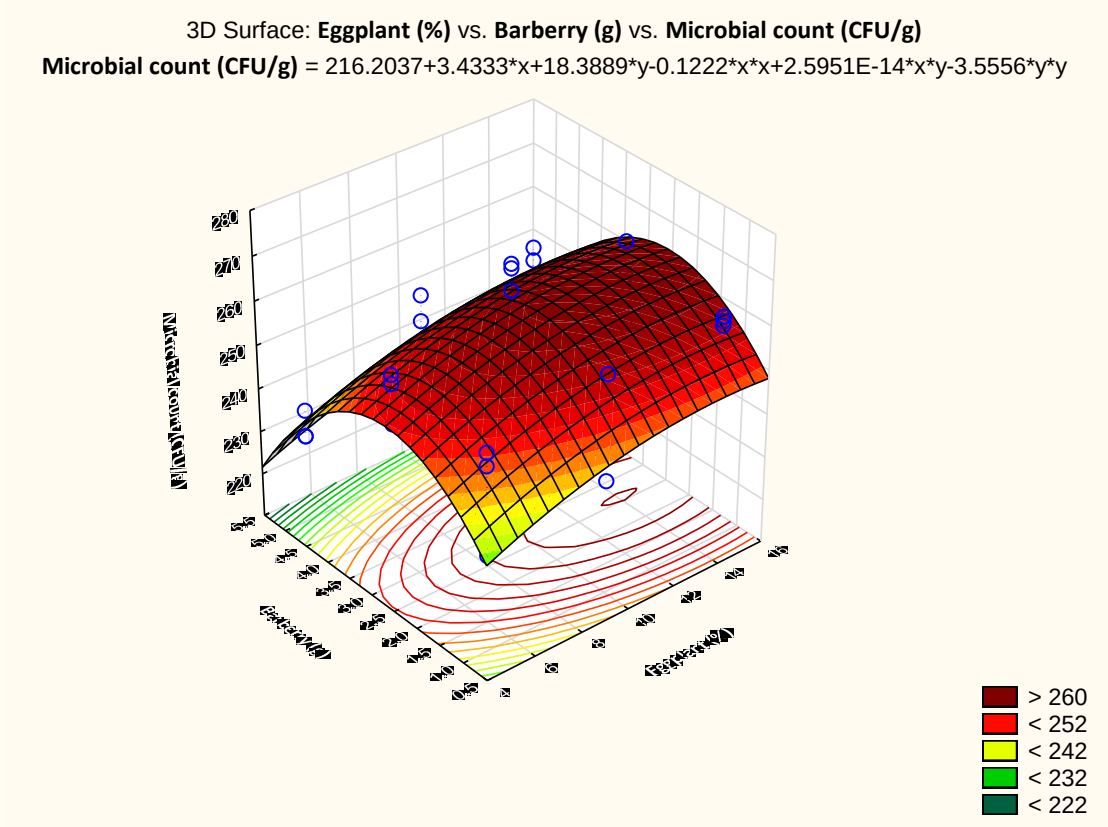

Figure 3 Response surface plot of microbial count (CFU/g) as influenced by eggplant peel (%) and barberry powder (g).

Despite slight increases at high levels of both ingredients, microbial counts remained below the hygienic threshold of 5 log CFU/g. The regression model (Figure 3), ($CFU = 216.2 + 3.43 \times X + 18.39 \times Y - 0.1222 \times X^2 - 3.56 \times Y^2$) indicates that while both factors contributed to microbial variation, no statistically significant antimicrobial effect was observed at the tested concentrations. Importantly, although microbial count slightly increased with higher dosages of eggplant peel and barberry, all values remained within acceptable sanitary limits (<5 log CFU/g).

While both eggplant peel and barberry powder are known to contain polyphenolic compounds with potential antimicrobial activity, our data did not reveal a statistically significant reduction in total microbial load. This observation is consistent with findings reported in **[21]**, which emphasize that the efficacy of polyphenols against foodborne pathogens depends strongly on compound type, dosage, and interaction with food matrix components.

Similarly, **[22]** emphasized that although many natural polyphenolic extracts exhibit antimicrobial properties in vitro, their activity in complex food systems may be attenuated or inconsistent, particularly under moderate concentrations. This suggests that the potential antimicrobial effect of plant-based additives requires further study, possibly with alternative dosing or extraction strategies.

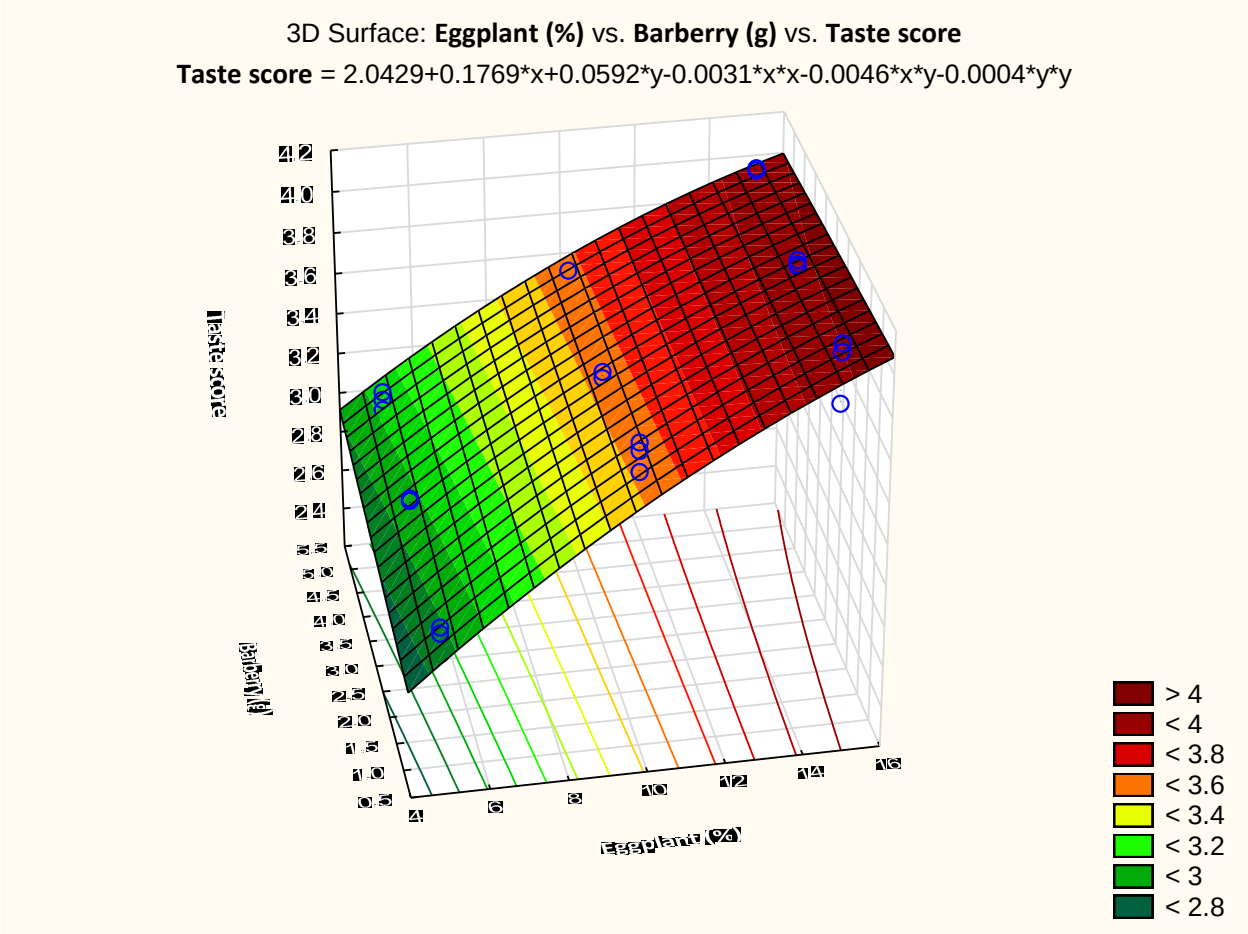

Figure 4 Response surface plot of sensory taste score in meat rolls based on eggplant peel (%) and barberry powder (g).

The fitted second-order model (Figure 4), ($Taste\ score = 2.0429 + 0.1769 \times X + 0.0592 \times Y - 0.0031 \times X^2 - 0.0046 \times X \times Y - 0.0004 \times Y^2$) demonstrates that both variables positively influence flavor, but with diminishing returns at higher levels. The maximum predicted score (> 4.2 points on a 5-point hedonic scale) was achieved at 15% eggplant peel and 3 g barberry powder.

This suggests a synergistic effect in flavor enhancement and visual appeal at intermediate levels of plant-derived additives. Similar sensory benefits of aubergine-derived fiber have been reported by Fong-In et al. (2023), who demonstrated that dietary fiber extracted from purple eggplant improved the palatability and textural balance of formulated food matrices, supporting its use in meat-based product development **[23]**.

Stability of Antioxidants and B-Vitamins During Drying

The experimental results clearly demonstrated a consistent decline in both antioxidant activity and vitamin B content in plum and barberry samples with increasing drying temperatures above 50 °C. The highest concentrations of bioactive compounds were observed in untreated (0 °C) samples, while the most substantial losses occurred at 70 °C.

These findings are consistent with those of **[24]**, and **[25]**, who reported significant degradation of phenolic compounds and antioxidant activity in blueberries dried using far-infrared radiation and vacuum-assisted heating, particularly at temperatures exceeding 60 °C. Similar degradation patterns were noted by other authors, who found that even gentle drying and sieving steps led to reduced levels of biologically active compounds in blackthorn berries **[13]**. As shown in **[26]**, thermal degradation of antioxidants follows predictable kinetic patterns and can be significantly mitigated through formulation strategies and precise control of drying parameters. This highlights the importance of temperature optimization in the processing of functional ingredients. Thus, our results reinforce the importance of carefully controlling drying parameters in the production of plant-based functional ingredients, as even moderate thermal exposure may compromise their bioactive potential.

Antioxidant Activity and Ingredient Dosage in Meat Products

Among the meat roll formulations, the highest antioxidant activity was observed at 10% eggplant peel and 3 g of barberry powder. The response surface plot (Figure 2) indicated a nonlinear effect: increasing the dosage beyond this optimal range did not yield proportional gains in antioxidant levels, possibly due to matrix saturation or thermal instability of phenolic compounds. These observations are supported by findings in **[27]**, where a mixture design approach was employed to optimize the recovery of phenolic and flavonoid compounds. The study showed that maximal antioxidant activity was achieved at specific ingredient ratios, beyond which no further improvement was observed.

This outcome aligns with current approaches to developing functional meat products, as shown in **[28]**, where moderate dosages of plant-based additives enhance nutritional and technological quality without compromising product balance or sensory acceptance.

Microbiological Safety

Across all formulations, total viable counts (KMAFAnM) remained well below the hygienic threshold of 5 log CFU/g, regardless of the levels of eggplant and barberry added. Although a slight increase in microbial counts was observed with higher additive concentrations, the differences were not statistically significant. This suggests that the selected dosages of plant-based ingredients did not exert a strong antimicrobial effect under the tested conditions. Similar findings were reported in studies reviewed in **[29]**, which concluded that the product matrix, polyphenol type, and processing conditions often limit antimicrobial efficacy of polyphenol-rich plant extracts in meat products. Nevertheless, further enhancement might be possible through the use of concentrated extracts, encapsulation, or edible coatings. As shown in **[28]**, microalgae-based coatings enriched with bioactive compounds significantly slowed spoilage in fresh berries. Although a slight increase in microbial counts was observed with higher additive concentrations, the differences were not statistically significant. This suggests that the selected dosages of plant-based ingredients did not exert a strong antimicrobial effect under the tested conditions. These results are consistent with the findings of Oulahal and Degraeve (2022), who emphasized that although phenolic compounds possess notable in vitro antimicrobial activity, their effectiveness in food systems is often reduced due to interactions with proteins and lipids, diffusion barriers, and instability during processing **[30]**.

Sensory Acceptability

The highest sensory scores (≥4.2 out of 5) were recorded in formulations containing 15% eggplant peel and 3 g of barberry powder, as shown in both Figure 4 and the ANOVA results. This combination appeared to optimize flavor and visual appeal, likely due to the synergy of plant acids and phenolics with the meat matrix. Similar improvements in flavor, color intensity, and overall acceptability were observed when purple eggplant flour was incorporated into low-fat beef patties, confirming the suitability of eggplant-derived ingredients in meat formulations **[31]**. These findings position the identified formulation as a promising candidate for the development of functional meat products with enhanced consumer acceptance and no compromise to safety or processing feasibility.

This aligns with recent trends in sustainable product development, where eggplant by-products are increasingly valorized as functional components in food systems **[32]**. In line with our results, **[33]** reported that incorporating eggplant flour into Frankfurt-type sausages significantly improved product texture, flavor profile, and consumer preference ratings, further validating the functional and sensory contribution of eggplant derivatives in meat formulations. Notably, the observed synergistic effect aligns with previous findings by **[34]**, who reported that incorporating eggplant flour into Frankfurt-type sausages improved oxidative stability and added functional benefits through natural bioactive compounds.

The final appearance of the developed meat roll enriched with functional plant ingredients is presented in Figure 1. The cross-section shows a well-structured roll with visible layers of meat and filling, ensuring even distribution of the added functional components, including eggplant peel and barberry powder. The accompanying garnish of cooked beets complements the meat roll both visually and nutritionally.

Figure 5 Visual presentation of the final product: meat roll with functional plant-based ingredients and a side dish of oil-cured plums.

This figure illustrates the potential consumer appeal of the formulated product, confirming its acceptable structure and stability after preparation. The product retains its integrity, indicating successful technological incorporation of the plant-based additives without compromising texture or appearance.

CONCLUSION

This study demonstrated that both barberry powder and eggplant peel significantly influenced the antioxidant activity and vitamin B content of meat rolls, with barberry at the highest dosage exhibiting the greatest effect. The significant interaction between eggplant peel and barberry powder indicated that combining plant-based ingredients with different functional roles can enhance the nutritional properties of meat products. These results confirm the initial hypothesis that integrating multiple plant-derived antioxidants in meat formulations increases their functional value. Notably, incorporating eggplant flour into Frankfurt-type sausages improved oxidative stability and conferred additional functional benefits through its natural bioactive compounds. This supports the growing trend of using fruit and vegetable by-products as clean-label additives in meat products to enhance nutritional quality and extend shelf life.

The findings have practical applications in developing functional meat products with improved oxidative stability and enriched nutritional profiles. Such formulations can help create healthier meat options made with natural ingredients, supporting dietary recommendations to increase intake of antioxidant- and vitamin-rich foods.

However, the study has limitations, including a relatively small sample size (n=3 per treatment), the use of raw materials from a single geographic source, and the absence of a detailed sensory evaluation with a large consumer panel. Future research should expand sample sizes, include materials from multiple regions, and conduct comprehensive sensory studies to confirm the feasibility of large-scale production and consumer acceptance of these functional meat products.

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Funds:

This research received no external funding. Please do not delete this part.

Acknowledgments:

The authors would like to thank the staff and laboratory technicians of the Department of Food technology, Almaty Technological University, for their support with analytical equipment and sample preparation.

We also acknowledge the contributions of the Sensory Evaluation Committee for conducting the taste tests, and the Scientific Research Institute of Food Safety for providing access to accredited laboratory facilities.

Competing Interests:

No potential conflict of interest was reported by the author(s).

Ethical Statement:

This article does not contain any studies that would require an ethical statement.

AI Statement:

AI tools (e.g., ChatGPT-4o, OpenAI, May 2025 release) were used to language editing. All data interpretation, scientific analysis, and final content approval were conducted and verified by the authors.

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