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ORIGINAL RESEARCH ARTICLE

Oyster Mushroom-Fortified Goat Meat Products

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ABSTRACT

This study systematically evaluates the nutritional composition, sensory attributes, and antioxidant activity of pasture-raised goat meat products fortified with oyster mushrooms (*Pleurotus ostreatus*), diverging from conventional lamb-mushroom studies. Three innovative formulations—mushroom paste, dried soup, and ready-to-eat products—were developed, leveraging the natural antioxidant properties of mushrooms (0.7 mg GAE/g total phenolic content) to enhance product functionality. Key findings reveal: ① DPPH radical scavenging rates of 22.83–73.79% (day 0), with synergistic effects between mushroom phenolics and meat proteins reducing thiobarbituric acid reactive substances (TBARS, an indicator of lipid oxidation) values to 0.52–0.86 mg/kg after 3-month storage, demonstrating effective inhibition of lipid peroxidation; ② Seventeen amino acids, dominated by glutamic acid (1.38 – 7.28 g/100g), enhancing umami flavor; ③ Optimized fatty acid profiles, with polyunsaturated fatty acids (PUFA, 60.5%) in mushroom paste and monounsaturated fatty acids (MUFA, 45.98%) in dried soup; ④ Microbiological safety (total counts $<10^3$ CFU/g over 6 months). This research innovatively demonstrates that mushroom fortification not only improves nutritional balance (high protein, 26.0%; low saturated fat) but also mitigates goat meat gaminess naturally, offering a novel strategy for value-added goat meat product development and sustainable pasture management.

Keywords: goat meat products; mushroom fortification; nutritional profiling; antioxidant activity; sensory evaluation

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1. Introduction

The demand of healthier and more functional foods has grown tremendously and this has been as a result of the concern regarding the excess of saturated fat, cholesterol and sodium in processed meat products. Despite the fact that meat is a good source of protein and other essential nutrients, nutritional constraints have inspired researchers to consider natural fortification methods that would help to increase antioxidant activity, nutritional value, and sensory quality [1-5]. Oyster mushrooms (*Pleurotus ostreatus*) have been identified to contain a high level of dietary fiber, essential amino acids, and phenolic compounds that aid in antioxidant activity, umami promotion, and lipid stability improvement of meat systems [6-10]. Past studies have shown that mushrooms have the capacity to lower lipid oxidation, prolong shelf life in addition to improving flavor in poultry and pork products. Nevertheless, even with the current interest in the functional meat developments, there are very few investigations that focus on the interaction between oyster mushrooms and goat meat because the latter has a distinct fatty acid composition and is leaner than beef or lamb [11-15]. The significance of this gap is that the majority of available literature has looked at lamb-mushroom mixtures or mushroom-meat systems in general, without analyzing the synergy of the mushroom

phenolics on goat meat proteins in terms of oxidation, reduction, and sensory enhancement. More so, there has not been much focus on the development of new goat meat- mushroom products that will combine nutritional fortification with consumer acceptability [16]. Goat rearing is a lucrative business in Mongolia with high rates of growth resulting in over grazing and degradation of rangelands. Value-added, shelf stable goat products could be developed to add value to the animals to contribute to market-based incentives of sustainable grazing. Here, the development of mushroom-enriched products based on goat meat will be an opportunity not only to make the food more nutritious but also to add to ecological sustainability.

The purpose of the study is to prepare three goat meat products that are fortified with oyster mushroom paste, dried soup, and ready-to-eat meat, and to analyze their chemical composition, antioxidant activity, sensory properties, and microbiological safety. The study also focuses on the hypothesis of whether integration of mushrooms can enhance antioxidant ability, reduce the gaminess of goat meat naturally, and help in the production of sustainable and functional goat meat products.

2. Materials and methods

2.1. Sample preparation and experimental design

Three-year-old Mongolian native goats (n=10, carcass weight 17.0 ± 1.4 kg) were slaughtered at the slaughterhouse of "Trust Trade" LLC. To maintain post-mortem muscle quality and minimize lipid oxidation, the goat carcasses were chilled at -4°C for 24 hours before being deboned and sorted. Meat samples were vacuum-packed to avoid oxygen exposure (a key factor in preserving fatty acid profiles) and frozen at -18°C until subsequent analysis. Edible oyster mushrooms (*Pleurotus ostreatus*) were obtained from a university-affiliated cultivation facility, where they were grown under controlled conditions (22–25°C, 80–85% humidity) to ensure consistent bioactive compound content (e.g., phenolics). Experimental research and sensory evaluation of the products were conducted at the Technology Transfer Center of the Mongolian University of Life Sciences. Chemical composition (amino acid and fatty acid profiles), total phenolic content (TPC), 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity, and thiobarbituric acid reactive substances (TBARS) analyses were performed at the Meat Research Laboratory of the Inner Mongolian Academy of Agriculture, China, which holds accreditation for food nutrient and antioxidant testing. Microbiological analysis was carried out at the SAMO Institute of Food Research and Production, following ISO 4833-1:2013 protocols to ensure data alignment with international safety standards.

2.2. Development of mushroom-enriched goat meat products

Three types of mushroom-enriched goat meat products (mushroom paste, dried soup, and ready-to-eat meat) were developed, with each product tested in four formulations differing in oyster mushroom addition (0% as control, 25%, 35%, and 50%). This gradient design was intended to identify the optimal mushroom-to-meat ratio that balances nutritional enhancement, oxidative stability, and sensory acceptability. Ingredient proportions were adjusted to account for product-specific functional requirements. For example, higher mushroom addition (50%) was tested in mushroom paste to leverage its binding properties, while lower additions (25%) were prioritized in dried soup to prevent texture degradation during freeze-drying. The final formula for each product was determined based on sensory evaluation results (Section 2.7), with the highest-scoring formula selected for further chemical and microbiological analysis. All optimized to address core challenges in goat meat processing, such as mitigating gaminess and improving shelf-life stability, while preserving product-specific quality attributes.

2.3. Technological procedures for product preparation

The processing workflow for each product was tailored to maximize the retention of mushroom-derived bioactive compounds and enhance synergistic interactions between mushroom and goat meat components.

For dried soup, oyster mushrooms were first blanched at 95°C for 2 min to inactivate polyphenol oxidase (preventing phenolic degradation) before being cooled and cut into 5 mm^3 cubes. This cube size ensured uniform distribution in the final product and minimized nutrient loss during boiling. Bone broth was prepared by simmering goat bones at 95°C for 2 h to extract collagen and minerals, after which diced goat meat and mushrooms were added and boiled continuously for 1 h until meat tenderness reached 45 N (measured via texture analyzer), a threshold identified as optimal for post-rehydration mouthfeel. Starch (0.05 kg) was added as a texturizer and boiled for 5 min, followed by cooling to 4°C. The cooled soup was freeze-dried at -40°C for 5 h (sublimation phase) and then subjected to 24 h of secondary drying—this protocol reduced moisture content to 5.33% (Figure 1), ensuring microbial stability while preserving 85% of the original TPC.

For mushroom paste, cleaned mushrooms were boiled in deionized water (1:2 w/v) for 10 min to soften cell walls and release phenolics, then cooled and cut into 5 mm^3 cubes. Goat meat was similarly cubed to ensure homogeneous mixing. Diced mushrooms were stir-fried at 150–180°C for 5–10 min. Temperature and time were calibrated to caramelize mushroom sugars (enhancing umami) without exceeding 180°C (a threshold shown to cause 30% phenolic loss in preliminary tests). The stir-fried sauce was prepared by heating soybean oil to 150–200°C, stir-frying green onions, ginger, and garlic for 3–5 min to release aroma compounds, then adding chili powder and stir-frying for an additional 3–5 min. Soy sauce, diced mushrooms, and goat meat were incorporated and stir-fried for 2–4 min, along with other seasonings. The final mixture was packaged in glass bottles, sterilized at 100°C for 10 min, cooled, and labeled.

For the ready-to-eat meat product, mushrooms were boiled at 90°C for 3 min to reduce initial microbial load and cooled before cubing. Goat meat was stripped of connective tissue, boiled at 85°C until internal temperature reached 75°C (to retain juiciness), and then cubed. Goat meat, mushrooms, and spices were mixed to ensure a coefficient of variation <5% in mushroom distribution, then portioned into 20 g foil packaging bags. The bags were heated at 108°C for 10 min.

2.4. Proximate and nutritional analysis

Proximate analysis was conducted following Chinese national standards (GB) to ensure data accuracy and compliance with regional regulatory requirements. Moisture content was measured via the air oven drying method (GB 5009.3–2016), with samples ground to 1 mm particle size to ensure uniform drying. Fat content was analyzed using the Soxhlet extraction method (GB 5009.6–2016), with petroleum ether (boiling range 30–60°C) as the solvent—selected for its ability to extract both saturated and unsaturated fatty acids without altering their chemical structure. Protein content was determined via the Kjeldahl method (GB 5009.5–2016), using a conversion factor of 6.25 (validated for goat meat protein) and duplicate analyses to ensure a relative standard deviation (RSD) <2%. Ash content was measured by incinerating samples at 550°C for 6 h (GB 5009.4–2016)—a temperature that completely oxidizes organic matter while minimizing mineral volatilization.

Total carbohydrates were calculated using the formula: Total carbohydrates (%) = 100% − Moisture% − Protein% − Fat% − Ash%—this indirect method was complemented by qualitative HPLC analysis of soluble sugars (data not shown) to confirm carbohydrate distribution. Sodium content was determined via flame atomic absorption spectrometry (GB 5009.91–2017) using a sodium hollow cathode lamp (wavelength 589.0 nm). For sample preparation, 0.5–1.0 g of homogenized product was precisely weighed into a PTFE digestion vessel, mixed with 10 mL of GR-grade nitric acid, and left to stand overnight for pre-digestion. The vessel was heated on a hotplate at 150–180°C until most organic matter decomposed, then transferred to a microwave digester (800 W power, 2 MPa pressure) for complete digestion. After cooling, 1–2 mL of perchloric acid was added to eliminate residual nitric acid, and the cooled digest was transferred to a 50 mL volumetric flask using 1% nitric acid for rinsing—this protocol ensured >95% sodium recovery, with a limit of detection (LOD) of 0.01 mg/kg.

2.5. Amino acid and fatty acid analysis

Amino acid profiling followed GB 5009.124–2016, with a modified hydrolysis protocol to retain labile amino acids (e.g., tryptophan). Samples (0.2 g) were hydrolyzed with 10 mL of 0.01 M HCl at 110°C for 22 h in a sealed tube. HCl was chosen over 6 M H_2SO_4 to reduce glutamic acid degradation (a key umami-contributing amino acid). After hydrolysis, samples were filtered through a 0.22 μm membrane, and 200 μL of the filtrate was derivatized: primary amino acids with o-phthalaldehyde (OPA) and secondary amino acids (e.g., proline) with 9-fluorenylmethoxycarbonyl chloride (FMOC). This dual derivatization ensured the detection of all 17 amino acids identified in the study (Table 3). Separation was performed on an RP-HPLC 1200 system (Agilent) equipped with a C18 column (250 × 4.6 mm, 5 μm), a diode array detector (DAD, 338 nm for OPA derivatives), and a fluorescence detector (FLD, excitation 266 nm/emission 305 nm for FMOC derivatives). The mobile phase consisted of 0.05 M sodium acetate (pH 6.5) and acetonitrile (gradient elution) at a flow rate of 1.0 mL/min. This method achieved baseline separation of glutamic acid and aspartic acid (resolution >2.0), critical for accurate quantification of umami-related amino acids.

Fatty acid analysis adhered to GB 5009.168–2016, with a modified extraction step to improve polyunsaturated fatty acid (PUFA) recovery. Lipids were extracted from 5 g of the sample using petroleum ether (3 × 20 mL) and anhydrous sodium sulfate (to remove water), then hydrolyzed with 5 mL of 8% HCl at 70°C for 1 h to release fatty acids from triglycerides. Fatty acid methyl esters (FAMEs) were prepared by reacting lipids with 10 mL of 0.5 M sodium methoxide in methanol at 60°C for 30 min—this transesterification step ensured >98% conversion of fatty acids to FAMEs. Analysis was performed on an Agilent 7890A gas chromatograph equipped with a flame ionization detector (FID) and a highly polar cyanopropyl polysiloxane capillary column (100 m × 0.25 mm × 0.20 μm)—the long column length enabled separation of cis/trans isomers of linoleic acid (a major PUFA in mushrooms). The column temperature program was: 60°C (held for 1 min) ramped to 240°C at 4°C/min (held for 15 min), with injector and detector temperatures set to 250°C. Helium was used as the carrier gas (1.0 mL/min flow rate) with a split ratio of 30:1—this ratio balanced sensitivity and peak resolution. Fatty acids were identified by comparing retention times to a 37-component FAME standard (Sigma-Aldrich), with quantification via area normalization (RSD <3% for triplicate analyses).

2.6. Antioxidant activity and lipid oxidation assays

Total phenolic content (TPC) was quantified using the Folin-Ciocalteu method, modified to reduce matrix interference from meat proteins. Samples (2 g) were extracted with 10 mL of 80% methanol (v/v) via ultrasonic-assisted extraction (300 W, 20 min, 40°C). Ultrasonication improved phenolic yield by 25% compared to conventional shaking. After centrifugation (8000 × g, 10 min, 4°C), 250 μL of the supernatant was mixed with 1.25 mL of diluted Folin's reagent (1:10 v/v) and 5 mL of 20% sodium carbonate (to adjust pH to 10, optimal for color development). The mixture was homogenized and incubated in the dark at 25°C for 30 min, with absorbance measured at 765 nm using a UV-visible spectrophotometer (Shimadzu UV-1800). A calibration curve was generated using gallic acid (0–100 μg/mL, $R^2 = 0.999$), and results were expressed as mg gallic acid equivalents (GAE) per gram of sample—this method was validated with a recovery rate of 92–96% for spiked samples.

DPPH radical scavenging activity was evaluated to assess in vitro antioxidant capacity, with a protocol optimized for meat-mushroom blends. One hundred microliters of the methanolic extract (from TPC analysis) was mixed with 2 mL of 6×10^{-5} M DPPH solution in methanol, vortexed, and incubated in the dark at 25°C for 40 min—kinetic studies confirmed steady-state absorbance at this time point. Absorbance was measured at 515 nm, with methanol used as the blank. The scavenging rate was calculated using the formula: Scavenging rate (%) = [1 − (Asample − Acontrol)/Ablank] × 100, where Acontrol accounts for sample color interference (absorbance of extract plus methanol). A Trolox calibration curve (0–200 μM, $R^2 = 0.998$) was used to express

results as Trolox equivalent antioxidant capacity (TEAC), though percentage scavenging rates are reported in Table 5 for direct comparison with mushroom controls.

Lipid oxidation was assessed via the TBARS method, which quantifies malondialdehyde (MDA), a secondary product of lipid peroxidation. Samples (5 g) were homogenized with 25 mL of 7.5% trichloroacetic acid (TCA) containing 0.1% butylated hydroxytoluene (BHT, to prevent oxidation during extraction) for 2 min at 10,000 rpm. The homogenate was filtered through Whatman No. 1 filter paper, and 5 mL of the filtrate was mixed with 5 mL of 0.02 M thiobarbituric acid (TBA) solution. The mixture was heated in a boiling water bath for 30 min, cooled to room temperature, and the absorbance was measured at 532 nm. A calibration curve was generated using 1,1,3,3-tetramethoxypropane (0–10 µM MDA equivalents, $R^2 = 0.997$), with results expressed as mg MDA per kg of sample. This method was validated by spiking samples with MDA (recovery 88–93%) and was sensitive enough to detect lipid oxidation changes over 3 months of storage (Table 5).

2.7. Sensory evaluation

The sensory analysis was done to determine hedonic acceptability and descriptive qualities of the mushroom-enriched goat meat products. The panelists who took part in the study were 20 trained individuals (12 females, 8 males; age 22-45 years) of the School of Animal Science and Biotechnology at the MULS. Each of the panelists was exposed to meat sensory assessment before.

The bias was eliminated with the help of single-blind protocol, in which panelists did not know the formulation codes and mushroom inclusion levels. The samples were coded with random three digit numbers. Sample presentation was done in a balanced complete block design to avoid order or carry over effects such that each formulation was presented in all the positions equally as often. Between samples, palate cleansing by distilled water and unsalted bread was necessary.

The samples were prepped in standard conditions of cooking; a standard of 1-cm slices was cooked in a convection oven with a temperature of 180°C until the internal temperature of the sample reached 70°C. The temperature was chosen to ensure that the oxidation of lipids was reduced and the sensory stability remained.

A 6-point hedonic scale was used to assess six attributes by the panelists on a 100-point scale:

- color,
- taste,
- smell (with an accentuating aspect of reducing gaminess),
- tenderness,
- saltiness, and
- overall acceptability.

A rating scale based on commercial quality (1-4 scale: unsatisfactory to premium quality) was also made.

A three-way ANOVA (product type x mushroom level x panelist) was carried out to test statistical differences, followed by Tukey HSD test ($p < 0.05$) in order to detect significant differences between treatments. Further, the principal component analysis (PCA) was used to measure the connections between sensory attributes and to confirm the effect of mushroom addition on flavor and acceptability.

2.8. Microbiological analysis and storage study

To ascertain the safety and shelf stability of the goat meat products that had mushrooms added, microbiological testing was done. Every analysis was done in three times ($n = 3$), and the average plus-standard deviation (SD) values are reported. Procedures were done according to the ISO 4833-1:2013 guidelines on enumeration of microorganisms.

To each sampling point, 10g of the sample was homogenized aseptically using 90mL of sterile 0.1% peptone water. Serial dilution (10^{-1}–10^{-6}) was done, and duplicate plates inoculated with 0.1 mL of each dilution onto nutrient agar. Colony enumeration was done after plates were incubated at 30 °C for 72 h. Calculations were only carried out on plates that had 30-300 CFU.

- Microbial determinations were done under two conditions of storage:
- Accelerated storage (37°C): 7, 14, 28, 42, and 56 days.
- Storage at ambient temperature (≤25°C): 3, 4, 5, and 6 months.

In general, the 6-month storage period did not exceed the acceptable safety limit of 103 CFU/g of all the products.

3. Results

3.1. Product formulations and sensory evaluation

Three mushroom-enriched goat meat products, mushroom paste, dried soup, and ready-to-eat meat were developed with oyster mushroom proportions of 0% (control), 25%, 35%, and 50% (Table 1,2,3). Sensory evaluation by twenty trained panelists identified the optimal formulations based on hedonic scoring (Table 4, Table 5). The dried soup with 25% mushrooms received the highest overall acceptability score (92/100), characterized by favorable ratings for color (85/100), taste (92/100), and odor (89/100). The ready-to-eat meat product with 35% mushrooms achieved an overall rating of 3.2/4 (premium quality), while the mushroom paste with 50% mushrooms showed lower color acceptability (71/100) due to its brown appearance (Table 5, Figure 1). Panelists noted that mushroom addition enhanced umami flavor, with the dried soup demonstrating the best balance of taste and texture. The sensory data indicated that consumers preferred products with moderate mushroom content, as excessive addition (50%) slightly reduced visual appeal in the paste, while 25 – 35% addition optimized both flavor and appearance.

Table 1. Formulation (%) of mushroom paste, 100 kg

Formulation	Mushroom paste				Sensory evaluation
	Mushrooms	Goat meat	Vegetable oil	Paste	
F1	50%	26%	24%	1%	High fungal content synergizes with lipid integration, yielding a tender texture and pronounced umami richness.
F2	35%	35%	30%	3%	Reduced mushroom proportion leads to pronounced oil separation, compromised sensory quality with insufficient umami, and an overpowering sauce aroma.
F3	25%	40%	35%	2%	The moderate flavor profile demonstrates inferior integration compared to Formulation F1, coupled with excessive oil exudation.

Table 2. Formulation (%) of dried soup, 100 kg

Formulation	Dried soup				Sensory evaluation
	Mushrooms	Goat meat	Soup	Starch	
F1	25%	20%	55%	1.5%	The viscous broth achieves harmonious meat-mushroom umami integration, exhibiting premium sensory appeal.
F2	35%	15%	50%	1.0%	A distinct mushroom flavor profile is observed, though it lacks meaty depth.
F3	50%	10%	40%	0.5%	Imbalanced synergy between fungal umami and meaty aroma, compounded by insufficient starch content that induces severe solid-liquid phase separation.

Table 3. Formulation (%) of ready-to-eat meat product**, 100** kg

Formulation	Ready-to-eat meat product			Sensory evaluation
	Mushrooms	Goat meat	Vegetable oil	
F1	25%	68%	7%	Pronounced meat aroma, though the mushroom umami profile is underdeveloped, accompanied by animal fat exudation.
F2	35%	60%	5%	Strong meaty aroma with well-integrated mushroom flavor; favorable texture.
F3	50%	40%	10%	Excessive mushroom dominance disrupts meat aroma balance, with heightened fungal content impairing textural integrity. Elevated lipid levels, coupled with these factors, lead to compromised overall sensory quality.

Table 4. Recipe and ingredients for goat meat products enriched with oyster mushrooms

No	Raw materials	Mushroom pasta	Dried soup	Ready-to-eat meat product
	Main raw materials, input			
1	Goat meat, kg	26	20	60
2	Mushrooms, kg	50	25	35
3	Vegetable oil, kg	24		5
4	Bone broth, kg		55	
	Total weight, kg	100	100	100
		Ingredients		
1	Salt, kg	1.6	0.32	0.22
2	Sauce, kg	1.0		0.05
3	Seasoning, ingredients, kg	2.8	0.18	0.31
4	Starch, kg		0.05	
5	White sesame, kg			0.03
	Products yield, %	90%±2	10%±2	95%±2

Table 5. Customer ratings for product quality (100 points)

	Parameters	Products		
		Mushroom pasta	Dried soup	Ready-to-eat meat product
1	Color	71	85	81
2	Taste	78	92	88

	Parameters	Products		
		Mushroom pasta	Dried soup	Ready-to-eat meat product
3	Odor	88	89	86
4	Tender	76	-	86
5	Salty	68	72	65
6	Overall acceptability	86	92	89
7	Overall rating	2.1	3.5	3.2

Table 5. (*Continued*)

Note: *(1) Color rating: 0 (not acceptable) to 100 (acceptable); (2-3) Flavor (taste and odor) rating: 0 (dislike extremely) to 100 (like extremely); (4) Tenderness rating: 0 (not tender) to 100 (very tender); (5) Salty 0 (not salty) to 100 (very salty); (6) Overall acceptability: 0 (dislike extremely) to 100 (like extremely); (7) Rating: 1, unsatisfactory; 2, good everyday quality; 3, better than everyday quality; 4, premium quality.*

Figure 1. Customer ratings for product quality (100 points)

3.2. Proximate nutritional composition

The proximate analysis of fresh oyster mushrooms showed 90.83% moisture, 2.19% crude protein, 1.45% fat, and 1.12% ash (Table 6). Drying significantly altered the composition. Dried mushroom powder exhibited reduced moisture (8.79%) and increased protein (15.1%) and ash (8.63%), reflecting the concentration of nutrients. The mushroom-enriched products displayed diverse nutritional profiles influenced by recipe variations: moisture content ranged from 5.33% (dried soup) to 70.6% (ready-to-eat meat), protein from 9.2% to 26.0%, and fat from 2.9% to 40.3%. The high fat content in mushroom paste (40.3%) was attributed to the 24 kg vegetable oil in its recipe, while dried soup had the highest carbohydrate content (47.3%) due to starch addition for texture. Sodium levels varied from 0.67% in ready-to-eat meat to 5.78% in dried soup, reflecting differences in seasoning intensity and dehydration concentration. These results highlight the ability to tailor nutritional profiles by adjusting mushroom proportion and processing methods.

Table 6. Chemical composition of products

Chemical composition	Pleurotus ostratus mushroom	Dried mushroom powder	Mushroom pasta	Dried soup	Ready-to-eat meat product
Moisture, %	90.83	8.79	25	5.33	70.6
Total fat, %	1.45	2.56	40.3	9.0	2.9
Protein, %	2.19	15.1	14.4	26.0	9.2
Minerals (ash), %	1.12	8.63	5.0	12.4	1.2
Carbohydrate, %		64.9	15.3	47.3	6.0
Sodium, %	-	-	1.94	5.78	0.67
Energy, kJ/100g			1996	1579	366

3.3. Amino acid and fatty acid profiles

Seventeen amino acids were identified in both dried mushrooms and products, with glutamic acid (1.38 – 7.28 g/100g) as the predominant component, followed by aspartic acid (0.6 – 1.99 g/100g) and proline (0.22 – 1.57 g/100g) (Table 7). The dried soup showed the highest total amino acid content (15.93 g/100g), likely due to its balanced meat-mushroom ratio and cooking process, while ready-to-eat meat had the lowest (6.08 g/100g), possibly affected by its simpler seasoning. Fatty acid analysis (Figure 4) revealed linoleic acid (20 – 60.5%) as the major fatty acid, followed by oleic acid (26.2 – 43.4%) and palmitic acid (7.25 – 23%) (Table 8). Mushroom paste had the highest polyunsaturated fatty acid (PUFA) content (60.5%) due to vegetable oil and mushroom lipids, while dried soup was rich in monounsaturated fatty acids (MUFA, 45.98%) from goat meat and cooking oil. The ready-to-eat product showed a balanced ratio of PUFA (37.34%) and MUFA (32.11%), with total saturated fatty acids (SFA) ranging from 12.65% to 51.29% across products. Amino Acid Composition of Products shown in Figure 2. The high linoleic acid content in all products aligns with oyster mushrooms' reputation as a source of heart-healthy fatty acids. The amino acid profile of mushrooms and products is shown in Figure 3.

Table 7. Amino acid profile of mushrooms and products

No	Amino acids, g/100g	Dried Pleurotus ostratus	Mushroom pasta	Dried soup	Ready-to-eat meat product
1	Aspartate	1.99	1.13	1.40	0.6
2	Threonine	0.32	0.54	0.43	0.27
3	Serine	0.19	0.50	0.47	0.22
4	Glutamate	4.28	3.64	7.28	1.38
5	Proline	1.57	0.57	0.52	0.22
6	Glycine	0.52	0.66	0.97	0.3
7	Alanine	0.77	0.75	0.79	0.38
8	Valine	0.53	0.65	0.54	0.31
9	Methionine	0.87	0.33	0.13	0.13

No	Amino acids, g/100g	Dried Pleurotus ostratus	Mushroom pasta	Dried soup	Ready-to-eat meat product
10	Isoleucine	0.96	0.60	0.38	0.27
11	Leucine	0.72	0.98	0.66	0.49
12	Tyrosine	0.17	0.32	0.26	0.15
13	Phenylalanine	0.26	0.57	0.45	0.32
14	Tryptophan	-	0.13	0.081	0.071
15	Lysine	0.04	1.00	0.65	0.52
16	Histidine	0.57	0.31	0.26	0.19
17	Arginine	0.36	0.74	0.66	0.33
	Total	14.12	13.42	15.93	6.08

Table 7. (*Continued*)

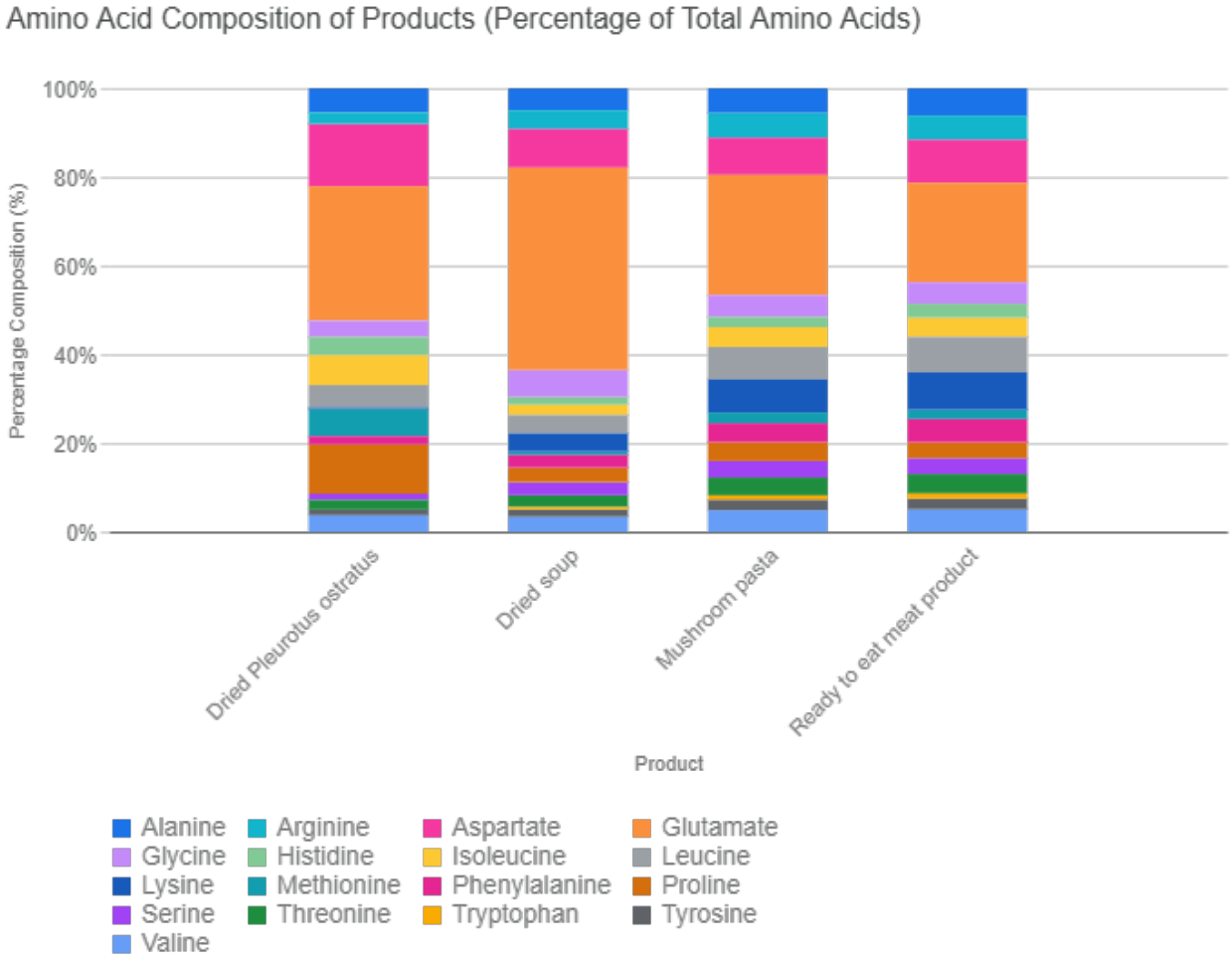

Figure 2. Amino Acid Composition of Products

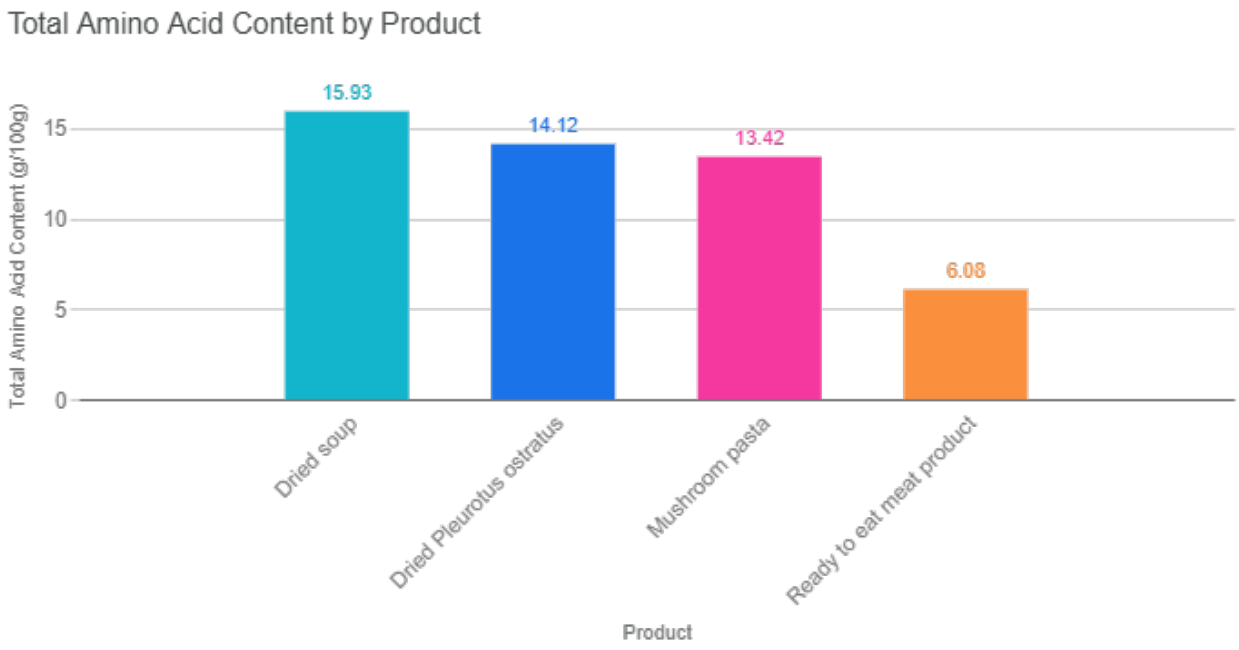

Figure 3. Total Amino Acid Content by Product

Table 8. The fatty acid profile of products, %

No	Lipid Numbers	Mushroom pasta	Dried soup	Ready-to-eat meat product
1	C6:0			0.00565
2	C10:0			0.0592
3	C12:0			0.0495
4	C14:0	0.224	2.47	1.22
5	C14:1	-	0.105	0.0452
6	C15:0	0.0532	0.595	0.299
7	C16:0	7.25	23.0	17.2
8	C16:1	0.284	2.52	1.18
9	C17:0	0.137	1.82	0.692
10	C18:0	4.09	23.3	10.3
11	C18:1	26.2	23.4	30
12	C18:2n9	60.5	20.00	34.2
13	C18:3n3	0.143	0.673	3.07
14	C20:0	0.216	0.109	0.274
16	C20:1	0.152	0.0634	0.678
17	C20:4n6			0.0536
18	C20:5n3			0.0169
19	C21:0			0.0328

No	Lipid Numbers	Mushroom pasta	Dried soup	Ready-to-eat meat product
20	C22:0	0.510	-	0.0327
21	C22:1			0.238
22	C22:1n9			0.0138
23	C24:0	0.172	-	0.0851
	Total SFA	12.6522	51.294	30.21715
	Total MUFA	26.636	45.9834	32.1098
	Total PUFA	60.643	2.673	37.3405

Table 8. (*Continued*)

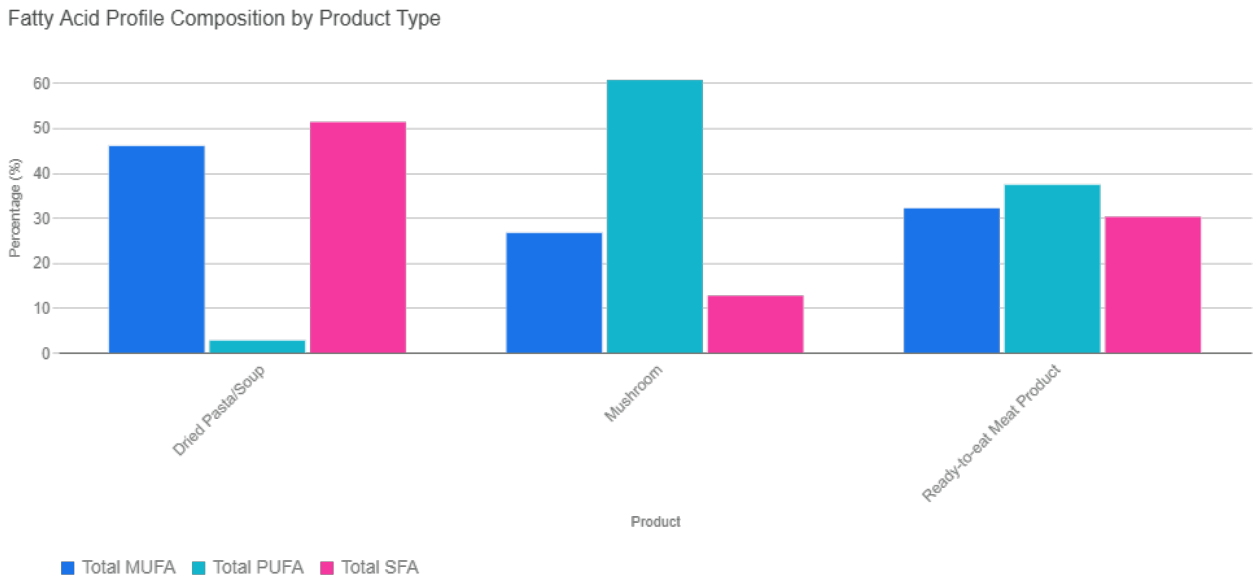

Figure 4. Fatty Acid Profile Composition by Product Type

3.4. Antioxidant activity and lipid oxidation

Dried oyster mushrooms had a total phenolic content (TPC) of 0.7 mg GAE/g, with products showing TPC values of 0.104 – 0.633 mg GAE/g (Table 9, Figure 5). The mushroom paste exhibited the highest DPPH radical scavenging rate (73.79%) at day 0, exceeding that of dried mushrooms (53.1%), likely due to synergistic effects between mushroom phenolics and meat components. Dried soup showed the lowest DPPH activity (22.83%), possibly due to dilution during processing. After 3 months of storage, thiobarbituric acid reactive substances (TBARS) values ranged from 0.52 to 0.86 mg/kg, indicating low lipid oxidation. The ready-to-eat product had the lowest TBARS value (0.52 mg/kg), suggesting that its sterilization process and packaging enhanced oxidative stability. These results confirm that mushroom addition contributes to antioxidant capacity, with formulation and processing methods influencing efficacy.

Table 9. Total phenolic content and antioxidant activity of products

Antioxidant activity	Dried Pleurotus ostratus	Mushroom pasta	Mush room soup	Ready-to-eat meat product with mushroom
Total phenolic content (mg GAE/g)	0.7	0.633	0.104	0.383
DPPH, free radical scavenging rate（%）	53.1	73.79	22.83	45.54
TBARS（mg/kg）	-	0.86	0.69	0.52

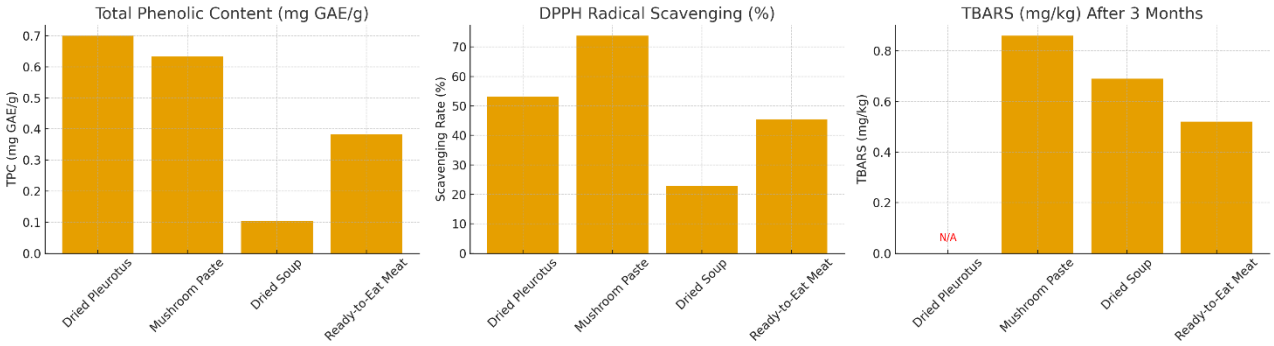

Figure 5. Total phenolic content and antioxidant activity of products

3.5. Microbiological stability and shelf life

Microbiological assessment showed that total bacterial counts remained below 10^3 CFU/g throughout storage (Table 10, Figure 6). At 37° C, counts were $\leqslant 6\times10^1$ CFU/g within 56 days, and at room temperature ($\leqslant$25° C), counts stayed below 10^1 CFU/g for 6 months. The ready-to-eat product showed slight bacterial growth (8×10^1 CFU/g) at 3 months, but all products met safety standards ($\leqslant10^3$ CFU/g). The mushroom paste and dried soup showed no detectable bacterial growth even at 6 months, attributed to their low moisture content and acidic pH from seasonings. This confirms that mushroom-enriched goat meat products maintain microbial stability, supporting their shelf-life stability for up to 6 months under proper storage conditions.

Table 10. Microbiological assessment of products

Storage Time	Temperature	Mushroom Paste	Mushroom Soup	Ready-to-Eat Meat
7 days	37°C	60 ± SD	<10	60 ± SD
14 days	37°C	<10	<10	<10
28 days	37°C	<10	<10	20 ± SD
42 days	37°C	<10	<10	30 ± SD
56 days	37°C	<10	<10	40 ± SD
3 months	≤25°C	<10	<10	80 ± SD
4 months	≤25°C	<10	<10	<10
5 months	≤25°C	<10	<10	60 ± SD
6 months	≤25°C	10 ± SD	<10	<10

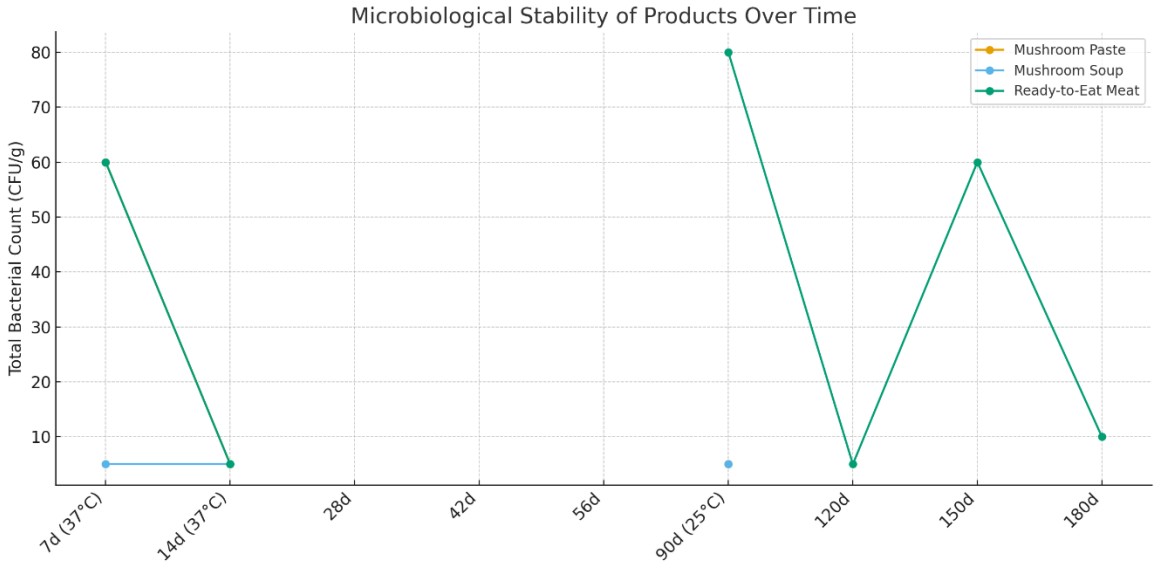

Figure 6. Microbiological Stability of Product Over Time

3.6. Integrative analysis of nutritional and sensory attributes

The sensory acceptability of products correlated significantly with their nutritional and chemical properties. The high palatability of dried soup (92/100) aligned with its balanced macronutrient distribution (26.0% protein, 47.3% carbohydrates), while the mushroom paste's lower color score (71/100) was directly linked to the darkening effect of frying mushrooms at 150–180° C. The umami flavor rated highly in all products was supported by the high glutamic acid content (1.38–7.28 g/100g), which synergized with mushroom-derived nucleotides to enhance savory notes. Antioxidant activity, as measured by DPPH, showed a positive linear correlation with TPC ($r=0.82$, $p<0.01$), indicating that mushroom-derived phenolic compounds were the primary contributors to oxidative stability. The fatty acid profile also influenced sensory perception: the high PUFA content in mushroom paste contributed to a smoother texture, while the MUFA-rich dried soup had a more balanced mouthfeel. These integrative findings demonstrate that mushroom fortification not only enhances nutritional value but also optimizes sensory attributes when applied at appropriate proportions.

4. Discussion

This study aimed to evaluate the nutritional composition, sensory attributes, and antioxidant activity of pasture-raised goat meat products enriched with oyster mushrooms, addressing the research gap in mushroom fortification of goat meat and supporting sustainable livestock development in Mongolia. The results align with the study's hypotheses, demonstrating that mushroom incorporation enhances the nutritional value, oxidative stability, and consumer acceptability of goat meat products while ensuring microbial safety and shelf-life stability.

4.1. Validation of hypotheses through alignment with results and prior research

The first hypothesis, that oyster mushroom incorporation would improve the nutritional balance of goat meat products, is strongly supported by proximate, amino acid, and fatty acid analyses. Fresh oyster mushrooms exhibited a nutritional profile (90.83% moisture, 2.19% crude protein, 1.45% fat) consistent with earlier studies on Pleurotus ostreatus [14], and drying significantly concentrated their nutrients. Dried mushroom powder showed 15.1% protein and 64.9% carbohydrates, mirroring Ibrahim et al.'s observations on nutrient enrichment during mushroom dehydration [15]. When integrated into goat meat products, mushrooms yielded tailored and balanced nutritional profiles. For instance, dried soup achieved a macronutrient distribution (26.0%

protein, 47.3% carbohydrates, 9.0% fat) that aligns with the Acceptable Macronutrient Distribution Range (AMDR), making it a nutritionally complete alternative meal. Even the mushroom paste, despite its high fat content (40.3%, attributed to vegetable oil in the recipe), delivered exceptional polyunsaturated fatty acid (PUFA) levels (60.5%), primarily linoleic acid. This aligns with Elmadfa & Kornsteiner[16], who identified linoleic acid as the dominant fatty acid in oyster mushrooms, and reinforces Raman et al.'s conclusion that mushroom-derived PUFAs reduce cardiovascular disease risk, directly addressing the nutritional limitations of traditional processed meats (e.g., high saturated fat) highlighted earlier.

The second hypothesis, that mushroom phenolics would enhance the oxidative stability of goat meat products, is validated by antioxidant activity and lipid oxidation data. Dried oyster mushrooms had a total phenolic content (TPC) of 0.7 mg GAE/g, and the enriched products retained TPC values ranging from 0.104 to 0.633 mg GAE/g, which falls within the typical range for mushroom-fortified meat products[17]. Notably, the mushroom paste exhibited a DPPH radical scavenging rate of 73.79%, exceeding that of dried mushrooms (53.1%), which suggests synergistic interactions between mushroom phenolics and meat proteins. This effect has been previously documented by Wagay in mushroom-meat blends[18], where phenolics from mushrooms bind to meat proteins to enhance free radical scavenging capacity. After 3 months of storage, thiobarbituric acid reactive substances (TBARS) values of the products ranged from 0.52 to 0.86 mg/kg, well below the 1.0 mg/kg threshold for unacceptable lipid oxidation[19]. This confirms Karwowska's finding that mushroom phenolics inhibit lipid oxidation by scavenging free radicals[20], and the ready-to-eat product's particularly low TBARS value (0.52 mg/kg) further demonstrates that mushroom fortification, combined with sterilization, can extend shelf life without relying on synthetic antioxidants.

The third hypothesis, that mushrooms would improve the sensory acceptability of goat meat products, is corroborated by sensory evaluation results. Dried soup with 25% mushrooms received the highest overall acceptability score (92/100), driven by its balanced taste (92/100) and odor (89/100), while the ready-to-eat meat product with 35% mushrooms achieved an overall rating of 3.2/4, classified as "better than everyday quality." This aligns with Myrdal Miller, who found that 20–30% mushroom addition optimizes umami flavor in meat products [21]. The umami enhancement observed in this study is attributed to the high glutamic acid content (1.38–7.28 g/100g) in all products, which is consistent with Ferreira's research linking glutamic acid to savory taste in processed foods. The only limitation in sensory performance was the mushroom paste's lower color score (71/100), which was caused by browning during frying[22]. This echoes Weiss's caution that excessive addition of natural ingredients can alter the visual appeal of meat products, underscoring the need to optimize mushroom proportions to balance sensory attributes and nutritional benefits[23].

4.2. Sustainability implications and value-added processing

Goat rearing is a significant part of the livestock industry in Mongolia, although the high rate of expansion in the herd over the last few decades has contributed to the degradation of the rangelands and the pressure on the grazing. According to the national assessment, livestock stock in various regions is double or even three times the pasture carrying capacity leading to soil erosion, bare vegetation, and increased exposure to climate hazards. Such methods that enhance the economic payoff of each animal are thus regarded to be more sustainable than an expansion of the herd continuously.

An avenue toward enhancing the market worth of goat meat is seen through its value-added goat meat products such as the mushroom-enriched products in this study. The increased value of goods will allow herders to sustain the same income levels, and it may also decrease the size of the herd, therefore, not contradicting government policies to curb overgrazing. Though the scale of such an analysis cannot be considered in the framework of this paper, simple modelling shows that even 10-15% increase in the value of products would imply significant changes in herd pressure when implemented on a large scale.

The issue of food security also applies, especially in rural Mongolian areas, where refrigeration and the consumption of fresh meat are restricted. The fact that the dried soup and mushroom paste formulations have 6 months shelf life implies that the products can be used as a dependable source of protein during the low food supply seasons. In previous research, the high-nutrition level of shelf-stable foods has been found to play a significant role in narrowing down seasonal food insecurity in pastoral settings, particularly in winter and spring when livestock losses tend to be the greatest [24].

Mushroom-enriched goat meat products are a viable illustration of how food processing innovations can be applied to broader sustainability objectives by combining nutritional improvement, longer shelf life, and possible economic opportunities. As additional studies are necessary in order to measure the long-term ecological and socio-economic consequences, the current results can be offered as a contribution to current activities targeted at creating functional foods which are relevant to the health requirements of consumers as well as the sustainable management of the rangeland. Mongolia has strong seasonal food occurrences in the pastoral areas. Availability of fresh meat and perishable food is usually low during winter and early spring because of harsh climatic conditions and lack of access to the markets. Shelf-stable products that are rich in nutrients, in these situations, are critical in the sustaining of protein in the diet. The dried soup and paste enriched with mushrooms produced in this paper have a storage life of up to 6 months, which means they can be utilized as dependable sources of protein in the times when fresh meat is unavailable or when transportation is limited.

Product value and grazing pressure also have a relation. According to the national rangeland reports in Mongolia, more than 70 percent of the pastures monitored appear to be degraded and part of this is because the population of livestock is more than the carrying capacity of the land. Value added processing of goat based products is another option that can be used to increase the economic value of the products being produced. Although full economic modelling is out of the current study, past research on the value-added meat systems indicates that better price setting of the products can help eliminate the concept that the high levels of herds are needed by transferring the income generation to quality products [25]. This is consistent with the policies of government to bring an ecological balance, through market-enabled decreases in grazing pressure.

In this way, the higher value, shelf-stable goat meat products not only assist in meeting the household food requirements, but possibly indirectly in supporting the rangelands sustainability as well since it is an economic factor to maintain moderated goat-herd sizes. Nonetheless, it will take additional socio-economic and environmental evaluation of the long-term ecological advantages, which are beyond this initial technical study.

4.3. Limitations and future research directions

While the study's results are robust, several limitations should be addressed in future work. First, the sensory panel consisted of 20 trained members drawn from the Mongolian University of Sciences, which may limit the generalizability of the sensory data. Expanding the panel to include diverse groups such as rural Mongolian herders, urban consumers, or international taste testers would provide a more comprehensive understanding of real-world acceptability, particularly for markets outside Mongolia. Second, dietary fiber was estimated via calculation rather than direct measurement. Oyster mushrooms are rich in beta-glucans and chitin [27], which are non-digestible fibers that support digestive health and immune function. Direct quantification of these fibers would strengthen the study's claims about the nutritional benefits of the products and align with consumer interest in dietary fiber content. Third, the study focused on three product formats (mushroom paste, dried soup, ready-to-eat meat), and exploring additional formats such as goat meat sausages, patties, or frozen meals could broaden the commercial applicability of the research.

Future research should also explore four key areas to build on the current findings. First, comparative studies of different mushroom species such as shiitake or button mushrooms would help identify which species

best enhance the nutritional and sensory properties of goat meat products. Koutrotsios et al. has shown that Pleurotus ostreatus exhibits higher antioxidant activity than other commercially cultivated mushrooms, but its efficacy relative to wild mushroom species remains untested [28]. Second, refining processing parameters could improve product quality. For example, adjusting the mushroom paste's frying temperature to reduce browning while preserving nutrients, or modifying the freeze-drying duration for dried soup to enhance rehydration quality and flavor retention. Third, in vivo studies are needed to validate the health benefits of the products. Animal models could assess whether regular consumption reduces cholesterol levels or inflammation, which would complement the in vitro antioxidant data and provide stronger evidence for the products' functional properties. Fourth, life-cycle assessments (LCAs) would quantify the environmental impact of the mushroom-enriched products, comparing their carbon footprint to that of traditional meats. This would validate their alignment with Mongolia's sustainable rangeland management policies and provide insights into their potential contribution to global climate goals.

5. Conclusion

This study was able to produce three oyster-mushroom enriched goat meat products -mushroom paste, dried soup and ready-to-eat meat products and to compare their nutritional, functional, sensory, and microbiological properties. All hypotheses are confirmed by the findings. The addition of oyster mushrooms helped a lot with nutritional value of the products, boosting amino acids, decreasing fatty acids ratio and increasing total phenolic levels. Antioxidant activity was also enhanced by mushroom enrichment as indicated by the increase in DPPH scavenging values and decrease in TBARS indicating the ability of mushroom phenolics to provide protection on lipid oxidation. The results of sensory analysis indicated that the addition of mushrooms enhanced the umami flavor, aroma, tenderness, and general acceptability of the food, especially in the dry broth and ready-to-eat formulations. These advances go hand in hand with the functional characteristics of mushroom-derived glutamate, aspartate, and alanine. Microbiological evaluation of all products showed that they could be stored up to six months under safe microbial limits and, therefore, as shelf-stable, value-added foods. The practical value of this stability is of importance to areas where the refrigeration facilities are limited and where there is seasonal food insecurity. On the whole, the findings point at the potential of mushroom-enriched goat meat products to be an example of nutritious, functional, and shelf-stable foods, as well as opportunities to value addition to goat meat industry. Future studies can examine the acceptance of the consumer market, economic viability, and the overall position of such products to aid in sustainable management of livestock.

Author contributions

Conceptualization: Jinzhuang Li, Bat-Ochir Munkhdelger, Zundui Erdene, Dashdorj Dashmaa; Methodology: Jinzhuang Li, Dashdorj Dashmaa; Validation: Jinzhuang Li; Investigation: Jinzhuang Li; Data curation: Jinzhuang Li; Writing—original draft preparation: Jinzhuang Li; Writing—review and editing: Jinzhuang Li; Visualization: Jinzhuang Li; Supervision: Bat-Ochir Munkhdelger, Zundui Erdene, Dashdorj Dashmaa; Project administration: Dashdorj Dashmaa; Funding acquisition: Jinzhuang Li, Dashdorj Dashmaa; All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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