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Effect of Hydroponic Fodder Supplementation on Physicochemical Properties and Nutritional Profile of Bull Meat

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Simple Summary

Bulls were fed hydroponically sprouted seeds in a controlled feeding trial conducted at Vytautas Magnus University to investigate the effects of sprouted feed on meat quality. Wheat, barley, alfalfa, and peas were germinated in a hydroponic system for seven days, and dairy–meat crossbred bulls were subsequently fed these sprouts for a period of 18 months. The chemical composition of the sprouted seeds, including protein, fat, fiber, mineral elements, and amino and fatty acids, was analyzed. Samples of the Longissimus dorsi (LD) muscle were collected from the carcasses for comprehensive meat quality assessment. The results demonstrated that supplementation with sprouted alfalfa seeds and peas led to a 2.86% increase in the content of essential amino acids in bull meat. Furthermore, the inclusion of sprouted grains resulted in a 13.78–15.70% reduction in saturated fatty acids compared with meat from the control group. Additionally, meat from bulls receiving sprouted alfalfa exhibited a lighter color and lower water content, indicating improved physicochemical properties. These findings suggest that hydroponically sprouted seeds can enhance the nutritional and sensory quality of beef.

Abstract

Hydroponic fodder production can be applied to a wide range of forage crops, optimizing the use of water, arable land, and other resources in a sustainable manner. This study aimed to evaluate the effects of hydroponically sprouted seeds on bull meat quality. Wheat, barley, alfalfa, and peas were germinated in a hydroponic system for seven days, and dairy–meat crossbred bulls were fed these sprouts for 18 months. The chemical composition of the sprouted seeds, including proteins, fats, fiber, mineral elements, and amino and fatty acids, was analyzed. Samples of the Longissimus dorsi (LD) muscle were collected from the carcasses for comprehensive meat quality assessment. The study revealed that while sprouted grains did not significantly alter the chemical composition of meat, they influenced its physical characteristics, depending on the type of grain. Meat from bulls fed sprouted alfalfa seeds was significantly lighter in color and contained less water. The inclusion of sprouted grains also positively affected the amino acid and fatty acid profiles. The content of undesirable saturated fatty acids was 13.78–15.70% lower compared with meat from the control group. Furthermore, meat from bulls receiving sprouted alfalfa seeds contained 2.86% more essential amino acids, while meat from bulls fed sprouted peas contained 0.58% more than the control. Overall, the addition of sprouted grains enhanced the biological value of beef protein, with alfalfa seeds demonstrating the greatest effect on protein integrity indicators.

Keywords: green fodder; beef; meat quality; sprouted seeds; physicochemical composition; amino acids; fatty acids

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1. Introduction

The technology of sprouting seeds for human consumption has been known and used in Eastern countries for over a century [1]. Since the mid-19th century, hydroponic fodder technology has evolved, and in 1939, Leitch reviewed various experiments using hydroponic fodder for different types of livestock and poultry [2].In recent years, there has been renewed interest in hydroponic fodder due to the shortage of agricultural land and the adverse effects of climate change.

Hydroponic green fodder production systems can operate year-round, producing pesticide-free green fodder with minimal water consumption due to recirculation systems, and without soil-borne contaminants [3].

Sprouting 1 kg of seeds can produce 7 to 10 kg of green fodder during the short production period of 7–10 days, depending on seed type. In a study conducted by Al-Karaki and Al-Hashimi [4], five forage crops (alfalfa, barley, cowpea, sorghum, and wheat) were compared in terms of green fodder yield and water-use efficiency under hydroponic conditions. The results indicated that barley provided a high fodder yield while using water efficiently. Nevertheless, low dry matter content remains the dominant concern for sustainable fodder production in controlled environments.

Significant nutritional changes occur during seed sprouting, primarily due to the breakdown of complex compounds into simpler forms [5]. The sprouting process influences enzyme activity, increases total protein content, and alters the amino acid profile. It can also increase soluble sugars, crude fiber, certain vitamins, and minerals, while reducing starch content and contributing to a loss of total dry matter [1]. Furthermore, germination decreases phytic acid levels, which would otherwise form insoluble complexes with minerals. Additionally, enzymes generated during sprouting can mitigate other anti-nutritional factors [6].

Previous studies report, that using hydroponic fodder for feeding improves animal productivity and has the potential to be used for producing value-added products from livestock [7].

Beef is a valuable source of amino acids, minerals, and vitamins, and thus plays an essential role in human nutrition. According to nutritionists, beef and veal should constitute a major proportion of meat consumed by humans [8,9]. Along with these essential nutrients, meat also provides fats that serve as a major energy source and facilitate the absorption of fat-soluble vitamins, including A, D, E, and K [10]. Intramuscular fat is considered one of the key determinants of meat quality [11]. Beef quality encompasses both its chemical composition and physical properties [12]. The chemical composition of meat includes complex biochemical compounds that determine its nutritional value [13,14]. The composition of muscle proteins affects texture, water-holding capacity, color, and other physicochemical characteristics of meat [12].

Research indicates, that supplementing a corn grain/cob-based beef diet with hydroponic fodder increased weight gain in 7.5% and decreased feed consumption by 23% [15]. Study involving small livestock indicate that Awassi ram lambs fed barley hydroponic fodder showed significantly higher feed intake, average daily gain, and feed efficiency than those fed barley grain [16].

Since it is known that diets based on fresh forages offer several advantages over grain-based feeding for producing healthier meat, including a more favorable ω-3 to ω-6 fatty acid ratio, higher concentrations of conjugated linoleic acid, and increased levels of fat soluble vitamins [17]. Therefore, incorporating hydroponic fodder in beef cattle rations could improve the concentration of the ω-3 fatty acid, its ratio, and vitamins in meat.

This study was conducted in response to increasing feed costs, limited availability of feedstuffs, and the need for more sustainable feed production methods. The aim of this study was to evaluate how sprouting different types of seeds affects the quality of bull meat, with a focus on its physical and chemical characteristics.

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2. Materials and Methods

2.1. Seeds Sprouting

Alfalfa (Medicago sativa L.), peas (Pisum sativum L.), and a mixture of wheat (Triticum aestivum L.) and barley (Hordeum vulgare L.) at a ratio of 1:1 were sprouted in a 4 × 1.4 × 2 m (length × width × height, respectively) hydroponic unit.

This unit contained 20 plastic shelves, each measuring 4 m in length, 0.23 m in width, and 0.08 m in height. The total area available for sprouting in the unit was 18.4 m^2.

Prior to sprouting, the seeds were disinfected in a solution of 5000 ppm sodium hypochlorite for 30 min. After disinfection, the seeds were thoroughly rinsed with tap water and soaked for 12 h in water at a seed-to-water ratio of 1:4. The water was continuously aerated with oxygen during soaking. Any floating debris or plant residues that appeared on the surface of the water were carefully removed. The imbibed seeds were then distributed evenly in a 2 cm thick layer on the sprouting shelves and sprouted for seven days under controlled environmental conditions of a temperature of 21 °C and relative humidity of 65%, following a day/night light regime.

The seeds were irrigated four times every 24 hours with a hydroponic nutrient solution. The pH and electrical conductivity (EC) of the solution were automatically monitored and regulated to maintain these values of 6.3–6.5 and 1.8 mS cm^{-1}, respectively. The nutrient solution was prepared using calcium nitrate ($Ca(NO_3)_2$), potassium nitrate (KNO_3), and magnesium sulfate heptahydrate ($MgSO_4{\cdot}7H_2O$), supplemented with micronutrients. Dry crystalline phosphoric acid was used to adjust and stabilize the pH of the nutrient solution.

2.2. Determination of Seed Chemical Composition

The chemical composition of the sprouts was determined after seven days of sprouting. Dry matter (DM) content was determined by drying samples to a constant weight at 105 °C. Crude protein content was determined using the Kjeldahl method [18]. Crude fat content was measured by extracting the sample with diethyl ether in a Soxhlet apparatus [19]. Ash content was determined by dry ashing the samples at 500 °C. Crude fiber was analyzed according to a modified Henneberg–Stohmann method [20].

For amino acid analysis, the samples were hydrolyzed using acetonitrile and analysed with a Shimadzu LCMS High-Speed Amino Acid Analysis System UF-Amino Station (Shimadzu Corporation, Japan) [21]. Fatty acid composition was analyzed using a gas chromatograph–mass spectrometer (GC–2010, Shimadzu Corporation, Japan) equipped with a flame ionization detector and a 120 m BPX–70 column. Seed samples were prepared according to the procedure described in LST EN ISO 12966-2:2011. Fatty acids were methylated with anhydrous NaOH in methanol [22].

The mineral content of the sprouted seeds was determined using an atomic absorption spectrometer (AA 1200, Aurora Instruments Ltd., Vancouver, Canada). In brief, 1 g of the sample was heated in a muffle furnace at 450 °C overnight and then mixed with 5 mL of 6 M HCl. The crucibles containing the samples were charred on a hot plate, cooled, and dissolved in 10 mL of 5% HNO_3. The samples were allowed to stand for 2 hours, transferred to 50 mL volumetric flasks, diluted with Milli-Q water, and analysed subsequently [23].

2.3. Study for Fattening Bulls

Four groups of crossbred dairy–beef bulls were formed: three experimental groups and one control group, each comprising 10 bulls, aged 7 months. The animals were selected based on body development and live weight. Before the start of the trial, all bulls were weighed using a metrologically verified mobile scale. The bulls were allocated to groups to ensure that average live weight (422,9 kg) and developmental level were as uniform as possible across groups. To determine average daily gain, all animals were weighed monthly throughout the experimental period, and daily live-weight gain was calculated from monthly weight changes (control and experimental groups 22.9-25.3 kg). All bulls were fed the same basal diet consisting of 45% grass silage, 25% barley grain, and

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30% alfalfa hay. The experimental groups were supplemented with 2 kg of sprouted seeds per animal per day (approximately 25% of the ration): experimental group 1 received sprouted alfalfa; experimental group 2 received a mixture of sprouted wheat and barley 1:1; and experimental group 3 received sprouted peas.

Before the experiment began, bulls in the experimental groups were gradually adapted to the new feed over a one-week period. After adaptation, all groups were weighed and the feeding trial was initiated. The total duration of the trial was 12 months. At the end of the trial, four bulls from each group (those with body weights closest to the group mean, 654 kg) were selected for control slaughter and meat-quality evaluation. All selected animals were slaughtered at the same slaughterhouse under identical conditions. Prior to slaughter, the animals were rested for 12 hours with free access to water but no feed. All procedures were conducted in accordance with European Union regulations on animal welfare during slaughter (Council Regulation (EC) No. 1099/2009). Carcass yield, lean-to-fat ratio, and fat cover class were determined during slaughter. Afterwards, a 600 g sample of meat was collected from the longissimus dorsi muscle at the level of the last ribs. The meat was matured for 48 hours at +4 °C, and then its physicochemical properties, amino acid profile, and fatty acid composition were determined.

2.4. Determination of the physical properties of meat

The pH value was measured using a Hanna HI-2002-02 pH meter (Hanna Instruments Inc., Woonsocket, Rhode Island, USA), which was equipped with a glass electrode standardized at pH 4.6 and 7.0. The meat color was determined after a 30-minute bloom period, using a Minolta CR-400 colorimeter (Minolta Inc., Osaka, Japan) in the CIE Lab color space* (Commission Internationale de l'Éclairage, 1976), where lightness (L*), redness (a*), and yellowness (b*) were recorded. Drip loss was measured according to the standard bag method, which determines the weight loss of a standardized muscle sample (40–50 g, approximately 30 × 60 × 25 mm) suspended in an airtight container at 4 °C for 48 h [24]. Drip loss was expressed as a percentage of the initial sample weight.

Cooking loss was determined using the Shiling method. A muscle sample of approximately 30 g was cut perpendicular to the muscle fibers and its initial weight was recorded. Each sample was sealed in a boilable plastic bag and heated in a water bath at 72 °C until the core temperature reached 70 °C. After heating, the meat was cooled to room temperature, blotted dry with filter paper, and weighed again. Cooking loss was calculated as a percentage of the initial weight [25].

Water-holding capacity (WHC) was measured using the Hamm pressing method [26].

Shear force (SF) was measured using the Warner–Bratzler method. The meat samples were sealed in airtight plastic bags and cooked in a water bath (IKA IB 20 pro, IKA®-Werke GmbH & Co. KG, Germany) until the temperature at the geometric centre of the sample reached 80 °C. The cooked samples were then cooled at 4 °C. After cooling, cylindrical cores (1 cm in diameter) were cut parallel to the muscle fibers using a punch. Shear force was then measured using a TA.XTplus Texture Analyzer (Stable Micro Systems Ltd., Surrey, England), which was equipped with a stainless-steel Warner–Bratzler blade. The crosshead speed was set at 250 mm/min, and the results were expressed in N/cm^2. The shear force value was obtained from the mechanical force–deformation curves as the maximum force applied, using Exponent software version 6.1.4.0 (Stable Micro Systems Ltd., Surrey, England).

2.5. Determination of the Chemical Composition of Meat

The dry matter content was determined using an MA 50.R automatic moisture analyser (RADWAG, Poland).

The intramuscular fat content of the beef samples was determined using the Soxhlet extraction method [19]. Crude protein content was analysed using the Kjeldahl method, while the ash content was determined by incinerating the organic matter at 600–800 °C to constant weight [18,27].

The fatty acid composition of the intramuscular fat was determined using gas chromatography with the Shimadzu GC-2010 PLUS system (Shimadzu Corporation, Japan), after converting the fatty

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acids into their methyl esters. The amino acid composition was analysed using a UF-Amino Station amino acid analyser (Shimadzu Corporation, Japan) [24].

2.6. Statistical Analysis

The chemical composition of sprouted seeds and meat-quality parameters were analyzed using one-way analysis of variance (ANOVA) in Statistica 10 software (StatSoft Inc., USA). Fisher's least significant difference (LSD) test was applied to assess significant differences ($p < 0.05$) among sprouted-seed samples. All analyses of sprouted-seed chemical composition were performed in triplicate. Meat-quality data were also subjected to one-way ANOVA to calculate the arithmetic mean ($\bar{X}$) and standard error of the mean ($S\bar{x}$) and to evaluate differences among groups. Statistical significance was interpreted as: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, and **** $p < 0.001$ (compared with the control group).

The meat quality data were also subjected to one-way ANOVA (Stat 1.1 StatSoft) to calculate the arithmetic mean ($\bar{X}$), the standard error of the mean ($S\bar{x}$), and to evaluate the statistical significance between experimental groups. The reliability of the indicators was evaluated based on probability values by using the statistical analysis software Stat 1: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, and **** $p < 0.001$, and was compared with animals of the control group.

3. Results and Discussion

Chemical Content of Sprouted Seeds

After seven days of sprouting, 1 kg of alfalfa seeds produced 8.37 kg of green fodder, while the wheat and barley mixture yielded 5.25 kg, and the peas yielded 4.59 kg.

This fresh-weight yield (4.59–8.37 kg green fodder per kg seed) is comparable to the typical 6–10 kg kg^{-1} range reported for hydroponically sprouted forage; importantly, most of the apparent yield increase reflects water uptake rather than net dry matter gain, which has implications for ration formulation and cost-effectiveness [4,28,29].

The chemical composition of the sprouted seeds is presented in Table 1. The highest dry matter content was observed in seven-day-sprouted peas (24.10%), whereas the lowest content was found in alfalfa sprouted seeds (6.54%). These results suggest that alfalfa produces a large amount of green biomass. However, its low dry matter content reflects the high moisture level of the sprouts.

The very low dry matter in alfalfa sprouts (6.54%) is consistent with systematic evidence that hydroponic sprouts are typically characterized by high moisture (often ~8–12% DM), with dry matter losses during germination being a recurrent limitation of the technology [28,29].

Table 1. Chemical content of seven days sprouted seeds, % of DM.

Parameter	Alfalfa	Peas	Wheat:barley (1:1)
Dry matter	6.54±0.27a	24.10±0.70c	16.70±0.36b
Proteins	37.43± 0.30c	26.00± 0.10 b	14.5± 0.16a
Fat	3.52±0.01 c	1.70± 0.04 a	2.50± 0.18 b
Fiber	19.95±0.20 c	8.60± 0.01 a	11.18 ±0.09b
Ash	5.38± 0.27c	4.00±0.03 b	3.08± 0.03a
Nitrogen free extractives	33.73±0.33 a	59.73± 0.19 b	68.76± 0.14c
Ca mg/100 g DM	0.33 ± 0.10a	0.30 ± 0.04a	0.39 ± 0.05a
Fe mg/100 g DM	2.09 ± 0.10a	2.20 ± 0.31a	2.54 ± 0.79a
Mg mg/100 g DM	79.49 ± 1.34a	78.43 ± 0.78a	65.70 ± 4.06b

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Cu mg/100 g DM	38.48 ± 0.83a	28.14 ± 0.51b	35.42 ± 3.45a

*Note. Means ± standard deviations marked with different lower letters (a, b, c…) in the rows are significant different at $p<0.05$;.

The sprouted alfalfa seeds had the highest protein content, whereas the wheat–barley mixture had the lowest (Table 1). In contrast, the wheat–barley mixture contained the highest amount of nitrogen-free extractives. Sprouted alfalfa seeds were also rich in fat, ash, and fiber. Proteins provide essential amino acids necessary for animal growth, muscle development, and overall health. A high level of nitrogen-free extractives indicates a greater proportion of readily digestible carbohydrates, which are an important energy source for animals. Therefore, feeds that are rich in both protein and nitrogen-free extractives play a key role in ensuring balanced animal nutrition [3,5].

Across hydroponic forage studies, crude protein values for sprouts vary widely with seed type, sprouting duration, and growing conditions; barley-based sprouts are often reported around the mid-teens (% of DM), while legume-based sprouts can be higher, supporting our observation of comparatively higher protein content in sprouted alfalfa [28].

The mineral content of the sprouted seeds varied slightly between samples. There were no statistically significant difference in the calcium (Ca) and iron (Fe) content, while the highest magnesium (Mg) content was observed in alfalfa and peas, and the highest copper (Cu) content in alfalfa and the wheat-barley mixture (Table 1).

The fatty acid profile shows that palmitic, linoleic, and alpha-linolenic acids were predominant, regardless of the seed type, whereas gamma-linolenic, eicosanoic, lauric, and eicosadienoic acids were present in much lower amounts (Table 2). Sprouted alfalfa seeds contained significantly higher amounts of palmitic, stearic, and eicosadienoic acids, whereas sprouted peas contained significantly higher amounts of polyunsaturated fatty acids (linoleic, gamma-linolenic, and alpha-linolenic acids).

A predominance of palmitic, linoleic, and oleic/α-linolenic acids is typical for cereal and legume grains and their sprouts; sprouting can shift individual fatty acids depending on germination time and temperature, often increasing the relative contribution of polyunsaturated fatty acids while reducing some saturated fatty acids [30,31].

Table 2. Fatty acids profile of seven days sprouted seeds, % from total amount of fatty acids.

Systematic (Trivial) Name	Fatty acid type	Alfalfa	Peas	Wheat:barley (1:1)
Saturated fatty acids				
Dodecanoic (Lauric) acid	*(C12:0)*	0.22±0.03a	0.21±0.02a	0.25±0.07a
Tetradecanoic (Myristic) acid	*(C14:0)*	0.75±0.10a	0.82±0.05a	0.68±0.17a
Pentadecanoic (Pentadecylic) acid	*(C15:0)*	0.66±0.03a	0.74±0.04a	0.65±0.08a
Hexadecanoic (Palmitic) acid	*(C16:0)*	24.25±0.44a	20.36±0.48b	18.63±1.65b
Margaric (Heptadecanoic) acid	*(C17:0)*	0.23±0.01a	0.22±0.03a	0.17±0.05a
Octadecanoic (Stearic) acid	*(C18:0)*	5.02±0.67a	4.36±0.12ab	3.24±0.79b
Eicosanoic (Arachidic) acid	*(C20:0)*	1.03±0.04a	1.23±0.02a	1.55±0.44a
Docosanoic (Behenic) acid	(C22:0)	1.54±0.05b	1.78±0.16a	1.76±0.02a
Monounsaturated fatty acids				
cis-9-Hexadecenoic (Palmitoleic) acid	*Omega-7 (C16:1)*	0.20±0.01a	0.25±0.03a	0.19±0.06a
cis-9-oleic acid	*Omega-9 (C18:1)*	9.98±0.17a	10.70±0.04a	9.38±1.49a

11-Eicosenoic acid	*Monounsaturated (C20:1)*	0.22±0.04b	0.28±0.03a	0.24±0.02ab
Polyunsaturated fatty acids				
9,12-Octadecadienoic (Linoleic) acid	*Omega-6 (C18:2)*	25.56±0.07c	30.15±0.05a	29.21±0.95b
6,9,12-Octadecatrienoic (gamma-linolenic) acid	*Omega-6 (C18:3)*	0.15±0.02a	0.19±0.02a	0.12±0.03b
9,12,15-Octadecatrienoic (alpha - linolenic) acid	*Omega-3 (C18:3)*	13.36±0.07b	16.21±0.03a	12.66±1.51b
cis-11,14-eicosadienoic (Eicosadienoic) acid	*Omega-6 (C20:2)*	0.26±0.02a	0.24±0.02c	0.19±0.05b
cis-8,11,14-eicosatrienoic (Dihomo-g-linolenic) acid	*Omega-6 (C20:3)*	1.25±0.06a	1.36±0.11a	1.24±0.13a
cis-4,7,10,13,16,19-docosahexaenoic (Docosaheptaenoic) acid	*Omega-3 (C22:6)*	1.48±0.12b	1.78±0.15a	1.63±0.15ab

*Note. Means ± standard deviations marked with different lower letters (a, b, c…) in the rows are significant different at $p<0.05$;.

Isoleucine was the predominant essential amino acid in alfalfa and the wheat–barley mixture, whereas lysine was the predominant essential amino acid in peas (Table 3). Isoleucine plays a key role in protein synthesis, muscle development, and metabolic regulation in animals. Pea sprouts also contained an exceptionally high amount of aspartic acid, demonstrating their potential to enhance the overall balance of amino acids and support energy metabolism, immune function, and the synthesis of other amino acids [5].

Table 3. Amino acid composition of seven-days sprouted seeds, % from total amount of amino acids.

Amino acid	Alfalfa	Peas	Wheat:barley (1:1)
Essential amino acids			
Histidine	0.40±0.03b	0.61±0.05a	0.38±0.14b
Isoleucine	**24.77±1.17a**	11.31±0.12c	**22.34±0.26b**
Leucine	17.80±0.83b	2.97±0.30c	19.76±0.01a
Lysine	7.26±0.05b	**13.39±0.43a**	4.29±0.09c
Methionine	5.20±0.05a	4.51±0.11b	5.46±0.25a
Phenylalanine	12.59±0.5b	5.32±0.11c	13.70±0.16a
Tryptophan	2.39±0.01c	5.38±0.08a	2.82±0.05b
Valine	8.00±0.17b	7.62±0.13b	9.88±0.72a
Threonine	0.61±0.1a	0.55±0.03b	0.44±0.03c
Partially replaced amino acids			
Glycine	0.46±0.05b	2.17±0.73a	0.73±0.29b
Glutamine	1.34±0.03ab	1.40±0.05a	1.13±0.18b

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Arginine	0.21±0.01c	0.99±0.04a	0.61±0.01b
Proline	0.72±0.02b	2.01±0.07a	0.80±0.08b
Tyrosine	2.66±0.15c	4.01±0.23a	3.36±0.18b
Other amino acids			
Aspartic	6.17±0.65b	**20.32±0.59a**	6.17±0.85b
Glutamic	3.81±0.32b	8.39±0.72a	4.55±0.85b
Asparagine	0.43±0.05b	0.80±0.02a	0.46±0.01b
Serine	4.73±0.05a	5.32±0.58a	3.75±0.15b
Alanine	0.45±0.08b	2.92±0.08a	0.18±0.01c

*Note. Means ± standard deviations marked with different lower letters (a, b, c…) in the rows are significant different at p<0.05;.

Chemical and Physical Content of Meat

The chemical composition of the meat from the control and experimental bulls is presented in Table 4.

Table 4. Chemical content of bull's meat, %.

Parameter	Bulls group			
	Control	Alfalfa	Peas	Wheat: barley (1:1)
Dry matter	25.39 ± 0.35	25.83 ± 0.51	25.67 ± 0.57	25.76 ± 0.50
Fat	3.25 ± 0.25	3.17 ± 0.49	3.36 ± 0.24*	3.28 ± 0.35
Ash	1.02 ± 0.00	1.10 ± 0.04	1.05 ± 0.03	1.05 ± 0.03
Protein	21.12 ± 0.59	21.56 ± 0.70	20.83 ± 0.27	21.16 ± 0.53

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

As shown in Table 4, dry matter content was similar across all groups. The highest intramuscular fat content was observed in bulls receiving sprouted peas, although the difference from the control group was small (0.11 percentage points) and not statistically significant (p > 0.05). Field pea grain is highly digestible; however, starch fermentation and ruminal protein degradation rates are slower than for several other common feeds. Increased dry matter intake (DMI) has been observed in some studies when field pea grain is included in the ration [32]. The lowest intramuscular fat content was observed in bulls receiving sprouted alfalfa. Protein content was similar among all groups.

The physical characteristics of the meat from the control and experimental bulls are presented in Table 6. The lowest meat pH was observed in the bulls that received sprouted wheat: barley and sprouted peas, although the differences were not statistically significant (p > 0.05).

From a technological standpoint, pH and drip loss are tightly linked: lower ultimate pH generally reduces water-holding capacity, whereas moderate pH values support improved water-holding capacity (WHC) and tenderness. Therefore, the reduced drip loss observed in the alfalfa-sprout group is consistent with improved functional properties of meat and aligns with established relationships between post-mortem acidification and water retention in beef [33].

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Table 6. Physical parameters of bulls meat.

Index	Group			
	Control	Wheat: barley (1:1)	Alfalfa	Peas
pH value	6.29 ± 0.08	5.98 ± 0.19	6.16 ± 0.07	5.98 ± 0.26
Colorfulness (L)	32.49 ± 3.20	34.72 ± 3.55	33.97 ± 1.61	34.21 ± 0.95
Colorfulness (a*)	17.36 ± 2.88	20.06 ± 2.31	18.96 ± 0.84	18.83 ± 1.81
Colorfulness (b*)	4.89 ± 0.84	7.20 ± 1.89*	6.06 ± 0.87	6.65 ± 1.72
Drip loss, %	1.24 ± 0.28	1.07 ± 0.99	0.41 ± 0.19	0.90 ± 0.18
Water-holding capacity, %	61.78 ± 5.24	62.55 ± 3.54	62.8 ± 5.15	64.26 ± 3.21*
Cooking losses, %	29.76 ± 4.66	26.25 ± 6.67	24.12 ± 6.89	26.76 ± 6.10*
Hardness, kg cm²	2.08 ± 0.22*	1.86 ± 0.43	1.35 ± 0.37	1.94 ± 0.24

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

The pH of the bulls' meat was too high and did not meet the requirements for export-quality beef. Acceptable beef pH should not exceed 5.5. Meat color, measured by the L* value, differed insignificantly between groups (p > 0.05). There were also no significant differences between the groups in the a* (redness) color parameter. The b* (yellowness) value was highest in the meat of bulls fed wheat-barley grain mixtures, showing a 47.2% increase compared to the control group (p > 0.05). The least watery meat was found in bulls fed sprouted alfalfa grains, while the control group's meat was the most watery. The highest water-binding capacity was observed in bulls fed sprouted pea grains, which was 2.48% higher than that of the control group (p > 0.05). There was a tendency toward lower cooking losses (p > 0.05) and reduced meat hardness in bulls fed sprouted seeds. The tenderest meat came from bulls fed sprouted alfalfa grains, with a difference of 0.73 kg/cm² compared to the control group (p > 0.05). Meat from other groups fed sprouted seeds was also slightly softer than that of the control group, although the differences were very small.

The fatty acid levels in the meat of control and experimental bulls are presented in Figure 1.

From the data presented in the Figure 1, it is seen that the use of sprouted seeds for feeding bulls led to a decrease in the amount of unwanted saturated fatty acids in their meat. Saturated fatty acids were 14.82% in the meat of bulls fed sprouts of wheat and barley, 16.39% in the meat of bulls germinated with alfalfa seeds, and 13.78% in the meat of bulls fed with sprouted peas, less than in the meat of control bulls.

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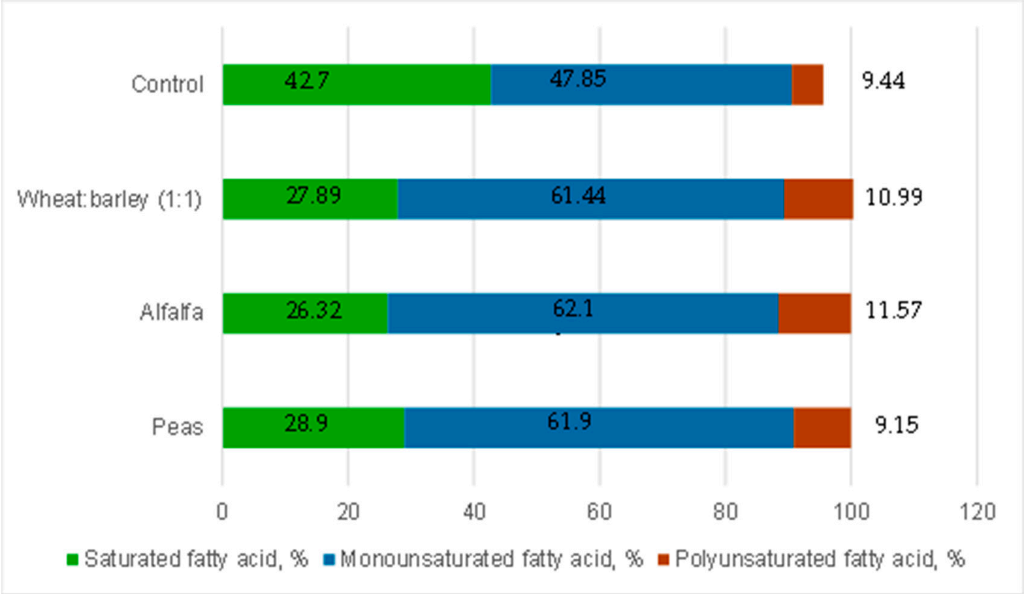

Figure 1. Intramuscular fat fatty acid structure of the loin meat (*musculus longissimus dorsi*), %.

The use of sprouted seeds resulted in a significant increase in the content of monounsaturated fatty acids. The meat of bulls that received a mixture of sprouted wheat and barley contained 13.59% monounsaturated fatty acids, sprouted alfalfa seeds - 14.26%, and sprouted peas - 14.07%, more than in the meat of control bulls. The content of polyunsaturated fatty acids in the meat of all groups of cattle differed very insignificantly. The structure of saturated fatty acids in the meat of the studied groups of bulls is presented in Table 7.

Table 7. Saturated fatty acids in the meat, %of the total amount of fatty acids.

Index		Group			
Fatty Acid	Fatty Acid Type	Control	Wheat:barley (1:1)	Alfalfa	Peas
Butanoic acid	*(C4:0)*	0.015 ±0.00	0.028 ± 0.02	0.019 ± 0.00	0.022 ± 0.01
Hexanoic acid	*(C6:0)*	0.018 ± 0.01	0.028 ± 0.01	0.021 ± 0.00	0.023 ± 0.00
Octanoic (caprylic) acid	*(C8:0)*	0.141 ± 0.05	0.053 ± 0.01	0.033 ± 0.01	0.046 ± 0.01
Decanoic acid	*(C10:0)*	0.688 ± 0.19*	0.266 ± 0.12	0.274 ± 0.06	0.253 ± 0.15
Undecanoic acid	*(C11:0)*	0.019 ± 0.00	0.022 ± 0.01	0.014 ± 0.00	0.016 ± 0.00
Dodecanoic acid	*(C12:0)*	0.420 ± 0.03	0.342 ± 0.16	0.329 ± 0.06	0.318 ± 0.20
Tridecanoic acid	*(C13:0)*	0.123 ± 0.03	0.101 ± 0.04	0.081 ± 0.04	0.082 ± 0.04

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Tetradecanoic (myristic) acid	*(C14:0)*	4.499 ± 0.29*	1.503 ± 0.68	1.274 ± 0.81	1.415 ± 0.98
Pentadecanoic acid	*(C15:0)*	1.713 ± 0.00	1.357 ± 0.58	1.278 ± 0.56	1.217 ± 0.77
Palmitic acid	*(C16:0)*	14.026 ± 2.69*	7.406 ± 5.83	6.076 ± 1.97	3.877 ± 2.49
Heptadecanoic (margaric) acid	*(C17:0)*	6.057 ± 0.36*	2.007 ± 0.34	1.777 ± 0.69	2.439 ± 0.52
Stearic acid	*(C18:0)*	13.759 ± 4.09	13.427 ± 1.86	14.381 ± 3.46	18.364 ± 11.35*
Arachic acid	*(C20:0)*	0.667 ± 0.07	0.481 ± 0.15	0.329 ± 0.06	0.355 ± 0.14
Heneicosanoic acid	*(C21:0)*	0.128 ± 0.03	0.136 ± 0.06	0.097 ± 0.05*	0.120 ± 0.03
Behenic acid	*(C22:0)*	0.200 ± 0.03	0.380 ± 0.43*	0.151 ± 0.07	0.160 ± 0.05
Tricosanic acid	*(C23:0)*	0.108 ± 0.03	0.214 ± 0.25*	0.079 ± 0.04	0.096 ± 0.03
Lignoceric acid. - tetracosanoic acid	*(C24:0)*	0.131 ± 0.03	0.138 ± 0.02	0.101 ± 0.04	0.128 ± 0.03

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

The use of sprouted seeds for fattening bulls had varied effects on the content of individual fatty acids. The content of decanoic acid (C10:0) in the fat of control group bulls was 2.51 to 2.58 times higher than in the meat fat of the experimental groups. An even greater difference was observed for tetradecanoic acid (C14:0), which was 2.99 to 3.53 times lower in the meat of bulls from the experimental groups compared to controls (Table 7).

A substantial difference between groups was also found in the amount of palmitic acid (C16:0). Bulls fed sprouted peas had 3.62 times less palmitic acid in their meat fat compared to control bulls. Bulls fed a mixture of sprouted wheat and barley, as well as those fed sprouted alfalfa grain, had 1.83 to 2.30 times lower levels of palmitic acid than the control group. Excess palmitic acid (C16:0) in the human body is linked to various vascular diseases, including atherosclerosis, heart attack, stroke, and others (Table 7). The content of monounsaturated fatty acids in the meat is presented in Table 8.

Table 8. Monounsaturated fatty acids in meat, % of total fatty acids.

Index		Group			
Fatty Acid Names	Fatty Acid Type	Control	Wheat:barley (1:1)	Alfalfa	Peas
Myristoleic acid	*Omega-5 (C14:1)*	6.230 ± 0.53	4.642 ± 1.84*	4.646 ± 0.50	4.091 ± 2.57
Cis-10-pentadecenoic acid	*Omega-5 (C15:1)*	0.198 ± 0.07	0.250 ± 0.08*	0.235 ± 0.06*	0.227 ± 0.07
Palmitoleic acid	*Omega-7 (C16:1)*	16.326 ± 3.96	17.988 ±2.64*	22.379 ± 6.72*	14.653 ± 8.64

Cis-10-heptadecanoic acid	*Omega-7 (C17:1)*	2.156 ± 0.08*	1.549 ± 0.65	1.480 ± 0.62	1.556 ± 0.90
Cis-9-oleic acid	*Omega-9 (C18:1)*	17.563 ± 4.91	21.329 ±1.12*	19.542 ± 4.42*	27.710 ± 10.81*
Trans-9-elaidic acid	*Omega-9 (C18:1) Trans*	4.100 ± 0.27	13.223 ±1.24*	12.585 ± 3.49*	11.964 ± 4.61*
Eicosanic acid	*Monounsaturated (C20:1)*	0.633 ± 0.00	0.795 ± 0.53*	0.409 ± 0.13*	0.597 ± 0.25
Erucic acid	*Omega-9 (C22:1)*	0.156 ± 0.09	0.784 ± 0.43*	0.607 ± 0.74*	0.581 ± 0.53*
Nervonic acid	*Omega-9 (C24:1)*	0.485 ± 0.21	0.881 ± 0.72*	0.230 ± 0.22*	0.539 ± 0.56*

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

The content of cis-9-oleic and trans-9-elaidic acids in the meat of control and experimental bulls differed the most. The levels of these fatty acids were significantly higher in the meat of bulls that received sprouted seeds. Cis-9-oleic acid was highest in bulls fed sprouted peas, with a difference of 10.15% compared to the control group. A slightly smaller difference was observed in bulls that received sprouted barley and wheat (Table 8). A very large difference between the groups was also found in the amount of trans-9-elaidic acid. The highest content of this fatty acid was observed in bulls fed the mixture of sprouted wheat and barley. Compared to the control group, the difference reached 9.11%. Bulls receiving sprouted alfalfa or sprouted pea seeds also had 7.86–8.48% higher levels of this fatty acid than the control group (Table 8). This increase can be explained by the biochemical composition of sprouted grains, which contain higher levels of readily available lipids, enzymes, and metabolic precursors that enhance the synthesis and deposition of monounsaturated fatty acids in muscle tissue.

As a result, bulls fed sprouted peas, alfalfa, wheat, and barley accumulated significantly more cis-9-oleic and trans-9-elaidic acids compared with the control group, indicating a favorable modification of the meat's fatty-acid profile.

It was determined that the meat of bulls that received sprouted seeds contained higher levels of Omega-3 fatty acids compared to the meat of control bulls. Omega-3 fatty acids were most abundant in the meat of bulls that received sprouted alfalfa, and slightly lower in those fed sprouted barley–wheat. Differences in other fatty acids were not statistically significant (Table 9).

Table 9. Polyunsaturated fatty acids in meat, % of total fatty acids.

Index		Group			
Fatty Acid Names	Fatty Acid Type	Control	Wheat:barley (1:1)	Alfalfa	Peas
Gamma-linolenic acid	*Omega-6 (C18:3)*	0.109 ± 0.02	0.146 ± 0.05*	0.079 ± 0.02*	0.110 ± 0.04
Linoleic acid	*Omega-6 (C18:2)*	3.343 ± 0.53	4.345 ± 2.52*	6.160 ± 2.92*	3.798 ± 3.74
Linoleic acid	*Omega-6 (C18:2)Trans*	3.636 ± 0.35*	2.590 ± 0.85	2.307 ± 0.80	2.408 ± 1.27

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Cis-5.8.11.14.17-Eicosapentaenoic acid (EPA)	*Omega-3 (C20:5)*	0.231 ± 0.02	0.491 ± 0.38*	0.242 ± 0.07	0.267 ± 0.12
Cis-8.11.14-eicosatrienoic acid	*Omega-6 (C20:3)*	0.738 ± 0.11	0.876 ± 0.59*	0.503 ± 0.19*	0.678 ± 0.38
Cis-11.14-eicosadienoic acid	*Omega-6 (C20:2)*	0.358 ± 0.07	0.577 ± 0.20*	0.283 ± 0.16*	0.469 ± 0.18
Linoleic acid	*Omega-3 (C18:3)*	0.125 ± 0.13	**0.208 ± 0.08***	**0.137 ± 0.10***	**0.137 ± 0.04***
Cis-5.8.11.14-eicatosetraenoic acid	*Omega-6 (C20:4)*	0.591 ± 0.17	0.616 ± 0.27*	0.553 ± 0.27	0.542 ± 0.34
Cis-4.7.10.13.16.19-docosahexaenoic acid	*Omega-3 (C22:6)*	0.184 ± 0.05	0.444 ± 0.46*	0.676 ± 1.06*	0.149 ± 0.08
Cis-13.16-docosadienoic acid (DHA)	*Omega-6 (C23:2)*	0.126 ± 0.05	0.695 ± 0.449*	0.630 ± 0.686*	0.592 ± 0.68*

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

Sprouted-seed treatments altered several polyunsaturated fatty acid–related markers (PUFA) in intramuscular fat. All sprout-fed groups exhibited higher α-linolenic acid (C18:3 n-3) concentrations than the control, with the wheat:barley mixture showing the greatest increase. This finding aligns with current evidence that germination remodels grain and legume lipids and can increase the relative contribution of unsaturated fatty acids on a dry-matter basis. In contrast, hydroponic production typically yields biomass with high moisture content and, therefore, results should be interpreted on a dry-matter basis [33–35].

Although ruminal biohydrogenation limits the direct transfer of dietary PUFA into tissues, modest improvements in the n-3 fraction and its related long-chain derivatives have been reported in ruminants receiving sprouted feeds. For example, hydroponic wheat seedling supplementation in fattening sheep modified the meat fatty-acid profile in a manner consistent with improved n-3 status [36]. Similarly, finishing steers fed sprouted barley at moderate inclusion levels showed no deterioration in conventional meat-quality traits, although metabolomic differences were detected [37].

From a human-nutrition perspective, even small increases in EPA and DHA, along with a more favorable n-6:n-3 ratio, are frequently regarded as desirable outcomes in ruminant meat lipids [38]. However, between-treatment differences may also reflect changes in dietary energy density, fiber supply, and passage rate, all of which can influence biohydrogenation and de novo lipogenesis. These factors should therefore be considered before attributing observed changes solely to sprout composition.

The effect of bull feeding on the amino acid profile of meat is presented in Tables 10, 11, 12, and 13.

Table 10. Quantity of amino acids in the meat of control and experimental young bulls.

Index	Group			
	Control	Wheat:barley (1:1)	Alfalfa	Peas
Tryptophan, mg/100 g	281.10 ± 57.59	**300.82 ± 28.95***	**332.37 ± 81.60***	279.40 ± 50.05
Hydroxyproline, mg/100 g	79.32 ± 26.42	**65.49 ± 10.42***	**59.30 ± 14.95***	**64.44 ± 12.23***
Protein-sufficiency rate	3.62 ± 0.48	4.64 ± 0.42*	**5.82 ± 1.87***	4.33 ± 0.03
Essential amino acids per cent of the total amino acid content	16.96 ± 4.07	15.4 ± 3.90	**19.82 ± 4.84***	17.54 ± 0.92

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

The essential amino acid concentrations (mg/100 g) were broadly stable across diets, with some targeted differences. Tryptophan levels were higher in the wheat:barley and sprouted-alfalfa groups, suggesting a modest improvement in the supply of metabolizable protein and/or alterations in microbial protein synthesis. Mechanistically, sprouted feeds may modify rumen fermentation patterns and microbial ecology. In growing lambs, graded replacement with sprouted barley increased digestibility and altered volatile fatty acid profiles and bacterial abundance, illustrating a plausible pathway for downstream changes in absorbed amino acids [39].

Additionally, hydroponic wheat seedling supplementation in fattening sheep has been reported to influence nitrogen-related parameters and meat composition in a manner consistent with improved nutrient utilization [36]. Hydroxyproline concentrations were lower in all sprout-fed groups relative to the control. Because hydroxyproline is commonly used as a marker of collagen content, this finding may reflect a reduced connective-tissue contribution within the sampled muscle fraction or altered collagen turnover.

Recent finishing studies indicate that diet and growth rate can influence connective-tissue characteristics and, consequently, tenderness-related outcomes; however, responses are not universal and depend strongly on overall ration formulation [37]. Overall, this pattern supports the broader view that sprouted-feed inclusion tends to fine-tune nitrogen metabolism rather than substantially remodel the core muscle amino acid profile.

It was established that the tryptophan content in the meat of bulls receiving sprouted alfalfa seeds was 18.24% higher, and in bulls receiving the sprouted wheat–barley mixture 7.0% higher than in the control group (p > 0.05). Feeding sprouted peas to bulls did not significantly influence the tryptophan content in the meat. The meat of bulls that received sprouted seeds contained less incomplete connective-tissue protein, which was confirmed by a lower hydroxyproline concentration. The hydroxyproline level in the meat of control bulls was 25.33% higher than in bulls fed sprouted alfalfa, 18.80% higher than in those fed sprouted peas, and 18.42% higher than in bulls receiving the sprouted wheat–barley mixture.

The inclusion of sprouted grains had a positive effect on the meat protein wholeness (protein-sufficiency) factor. Bulls receiving sprouted alfalfa seeds exhibited the highest coefficient of protein wholeness, meeting the requirements for high biological value beef. Sprouted wheat–barley mixture and sprouted peas also improved the protein wholeness factor, although the values remained below the threshold for high biological value; therefore, the meat of these bulls is classified as having medium biological value. The meat of bulls in the control group met only the minimum requirements for beef of average biological value.

Feeding bulls with sprouted seeds had a distinctly positive effect on the amino acid composition and biological value of the meat compared to the control group. Sprouted alfalfa seeds demonstrated the strongest improving effect: the meat of these bulls contained the highest levels of essential amino acids, including a remarkable increase in tryptophan, and showed the lowest concentration of hydroxyproline, indicating a reduced proportion of incomplete connective-tissue proteins. As a result, the protein wholeness coefficient in this group reached the threshold for high biological value meat.

The highest proportion of essential amino acids was observed in bulls receiving sprouted alfalfa seeds. In this group, the essential amino acid content was 2.86% higher than in the control group.

Table 11. Essential amino acids in the meat of control and experimental bulls, % of total amino acids content.

Essential amino acids	Group			
	Control	Wheat:barley (1:1)	Alfalfa	Peas
Histidine	0.736 ± 0.31	0.684 ± 0.19	0.835 ± 0.15	0.862 ± 0.19
Threonine	0.401 ± 0.08	0.594 ± 0.41	0.625 ± 0.17	0.513 ± 0.25
Valinas	0.552 ± 0.01	0.735 ± 0.36	0.842 ± 0.26	0.655 ± 0.16
Methionine	0.581 ± 0.11	0.585 ± 0.18	1.567 ± 1.09	0.713 ± 0.12
Lysine	0.763 ± 0.19	1.075 ± 0.56	1.117 ± 0.08	0.966 ± 0.26
Isoleucine	0.524 ± 0.06	0.420 ± 0.20	0.542 ± 0.46	0.423 ± 0.07
Leucine	0.653 ± 0.09	0.726 ± 0.29	0.880 ± 0.46	0.797 ± 0.22
Phenylalanine	0.367 ± 0.07	0.419 ± 0.29	0.449 ± 0.37	0.450 ± 0.19
Tryptophan	0.768 ± 0.27	0.849 ± 0.11	1.166 ± 0.18	1.027 ± 0.33

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

From the data presented in Table 11 we can see that in the meat of bulls that received sprouted seeds, the content of almost all essential amino acids was more or less higher than in the meat of control bulls. Compared to the control group, the mixture of sprouted wheat and barley had the least effect on the content of some amino acids. The meat of this group of bulls contained less isoleucine and histidine than the meat of the control group of bulls. The inclusion of sprouted seeds in the diet of bulls resulted in negligible changes in the concentrations of isoleucine and phenylalanine in their muscle tissue. However, a significant increase in lysine content was observed, which enhanced the overall amino acid profile, improving the protein completeness and nutritional quality of the meat. These modifications potentially increase the nutritional value and health benefits of the beef.

Expressing essential amino acids as a percentage of total amino acids results in only minor between-treatment differences, which is biologically expected in ruminants. Post-absorptive metabolism and the conserved composition of major contractile proteins generally buffer dietary effects on proportional amino acid patterns in muscle, unless diets induce substantial differences in growth rate or muscle fiber characteristics.

Recent datasets examining beef amino acid profiles across breeds and production systems likewise indicate that the essential amino acid (EAA) pattern is largely stable, with variation more strongly attributable to intrinsic muscle biology than to individual dietary ingredients [40,41].

In this context, our findings suggest that sprouted-seed supplementation can be implemented without compromising beef protein quality, and that any improvements in protein completeness indices likely reflect small, coordinated shifts across multiple amino acids.

The data presented in Table 12 indicate that the extent of amino acid modification is greater in the meat of bulls fed sprouted seeds compared to the control group. The meat from bulls supplemented with alfalfa sprouted seeds showed a significant increase in glycine content, which was 3.75 times higher than that of the control group ($p < 0.01$). Glutamine content was predominantly elevated in the meat of bulls fed a mixture of sprouted wheat and barley, with a 1.55-fold increase relative to the control group. Additionally, the meat of bulls receiving arginine-rich sprouted seeds exhibited an increase of 1.12–2.29% compared to controls. Similarly, proline levels in the meat of bulls fed sprouted seeds were elevated by 0.198–0.226% relative to the control group. This enhancement in the amino acid profile of the meat not only improves its nutritional value but also positively impacts quality attributes such as flavor and tenderness.

Table 12. Percentage of amino acids partially replaced in relation to total amino acid content.

Partially replaced amino acids	Group			
	Control	Wheat:barley (1:1)	Alfalfa	Peas
Glycine	1.327 ± 0.45	1.502 ± 0.23	**4.974 ± 0.15***	1.451 ± 0.21
Glutamine	11.107 ± 0.18	**17.216 ±0.43***	13.646 ± 0.91	13.545 ± 0.51
Arginine	0.984 ± 0.24	1.076 ± 0.26	1.213 ± 1.56	1.156 ± 0.08
Proline	**0.514 ± 0.43**	**0.740 ± 0.14***	**0.712 ± 0.05***	**0.712 ± 0.15***
Tyrosine	0.715 ± 0.17	0.848 ± 0.13	0.945 ± 0.28	0.982 ± 0.32

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group.

Glycine concentrations were markedly higher in the sprouted-alfalfa group. Glycine is a major constituent of collagen and also plays a role in one-carbon metabolism and antioxidant buffering via glutathione-related pathways. A higher glycine proportion could therefore indicate: a greater relative contribution of collagenous proteins in the analyzed muscle fraction; differences in free amino acid pools; or normalization effects, depending on how the partially replaced fraction was calculated.

Because hydroxyproline levels were lower in the sprout-fed groups, the glycine signal should be interpreted cautiously and ideally validated using an independent estimate of collagen content (e.g., collagen calculated from hydroxyproline concentration or histological assessment). Germination is known to activate proteolytic and transamination pathways in cereals and legumes, increasing free amino acids and related nitrogenous metabolites, which could plausibly contribute to the observed pattern [33,34]. Future studies combining free amino acid profiling with direct collagen quantification would help clarify whether the elevated glycine reflects structural differences in connective tissue or primarily shifts in soluble nitrogen fractions.

The content of other amino acids in the meat of control and experimental bulls is given in Table 13.

Table 13. Percentage of other amino acids relative to total amino acid content.

Amino acids	Group			
	Control	Wheat:barley (1:1)	Alfalfa	Peas
Glutamic acid	7.742 ± 0.32	7.189 ± 0.82	6.669 ± 0.68	7.993 ± 0.75
Hydroxyproline	0.217 ± 0.01	0.185 ± 0.03	0.208 ± 0.24	0.237 ± 0.88
Asparagine	0.416 ± 0.03	0.562 ± 0.33	0.670 ± 0.75	0.606 ± 0.34
Serinas	1.231 ± 0.04	1.340 ± 0.13	1.589 ± 0.87	1.326 ± 0.25
Sarcosine	2.347 ± 0.09	2.815 ± 0.16	**7.873 ± 0.24****	2.703 ± 0.25
Taurine	1.260 ± 0. 08	1.357 ± 0.18	1.581 ± 0.23	1.714 ± 0.53
Alanine	3.302 ± 0.33	3.118 ± 0.11	3.208 ± 0.36	3.173 ± 0.85
Carnosine	52.655 ± 0.14	47.164 ± 0.32	**40.790 ± 0.12****	48.856 ± 0.87
Anserine	10.195 ± 1.34	8.122 ± 1.56	7.236 ± 1.80	8.483 ± 1.27
Theanine	0.152 ± 0.41	0.303 ± 0.24	0.231 ± 0.07	0.182 ± 0.01

Ornithine	0.491 ± 0.32	0.377 ± 0.06	0.431 ± 0.02	0.475 ± 0.15

** $p < 0.1$, ** $p < 0.05$, and **** $p < 0.001$—compared to the animals with the control group

The other amino acids varied only modestly, with glutamic acid remaining the predominant component, ranging from 6.67% in the alfalfa group to 7.99% in the peas group, as is typical for beef and reflective of the abundance of glutamate-rich muscle proteins and metabolites. Numerical increases in asparagine, serine, taurine, and theanine in the sprout-fed groups are directionally consistent with the biochemistry of sprouting: germination activates endogenous enzymes and reallocates nitrogen toward free amino acids and related compounds, particularly in legumes.

Interestingly, sarcosine and carnosine exhibited the most notable changes. Sarcosine increased markedly in the alfalfa group (7.873%), while carnosine decreased from 52.655% in the control to 40.790% in alfalfa-fed animals. Such changes could reflect specific modulation of histidine-containing dipeptides, which have functional roles in muscle buffering and antioxidative capacity [40,41].

Comparable subtle shifts in nitrogenous fractions have been reported in ruminants supplemented with hydroponic sprouts [36]. Taken together with the results presented in tables 9–12, these findings reinforce the view that sprouted-feed inclusion is more likely to influence beef quality through adjustments in the lipid fraction and specific taste-active or functional metabolites, while leaving the core muscle protein amino acid profile largely intact.

Compared to the control group, the meat of bulls fed hydroponically sprouted seeds showed higher concentrations of asparagine, serine, taurine, and theanine, while most other amino acids varied only marginally. Notably, sarcosine was comparable among treatments except in the sprouted-alfalfa group, where it increased markedly relative to the control. Similar enrichment of free and non-protein nitrogenous compounds during germination has been described for cereals and legumes, where activation of endogenous proteases and transamination pathways increases the pool of free amino acids (including asparagine in legumes) and related metabolites available to the animal [5,42,43]. From a meat quality perspective, higher taurine and theanine may be relevant because both compounds contribute to taste-active nitrogenous fractions and antioxidant buffering in muscle, although the magnitude of change observed here suggests a subtle compositional shift rather than a wholesale remodeling of muscle proteins.

Mechanistically, germination increases protein digestibility and releases peptides and free amino acids through proteolysis, while also shifting carbohydrate metabolism toward respiration. These biochemical changes can alter rumen-fermentable substrates and the profile of absorbed amino acids, providing a plausible route for the targeted differences we observed in the sprout-fed groups [5,42].

Overall, our results support the view that hydroponically sprouted seeds primarily influence beef quality through modifications in lipid fractions and specific nitrogenous compounds, rather than through substantial changes in proximate composition. This aligns with recent findings in finishing steers, where the inclusion of sprouted barley at moderate levels did not materially affect instrumental color, drip loss, cooking loss, or shear force, even when metabolomic differences between diets were detected [33].

Taken together, these findings suggest that sprouted feeds can be used as a partial replacement for concentrate without consistently compromising conventional meat-quality indicators, provided that diets are properly balanced on a dry matter and energy basis [28,29].

From a practical standpoint, our fresh-weight yields and the low dry matter of sprouts are consistent with the broader hydroponic fodder literature: increases in green mass largely reflect water uptake, while dry matter can decline due to respiratory losses during germination. Systematic evidence indicates that hydroponic barley sprouts typically contain only about ~10% dry matter on a fresh basis, meaning that ration formulation and performance interpretation must be done on a dry matter basis to avoid overestimating the nutritional contribution of sprouts [28,29].

The ultimate pH values observed in this trial were relatively high. In beef, normal ultimate pH is typically in the ~5.5–5.8 range, whereas elevated pH is commonly associated with pre-slaughter glycogen depletion driven by stressors such as transport, fasting, handling, and mixing. High pH

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predisposes meat to darker color, reduced shelf-life, and greater variability in tenderness; intermediate pH values (approximately 5.8–6.2) have also been linked to tougher meat due to slower proteolysis and altered myofibrillar degradation kinetics [44–46]. Therefore, management factors before slaughter should be evaluated alongside dietary interventions when interpreting the meat quality outcomes of sprout-based feeding strategies.

The improvements in the fatty acid profile, particularly the reduction in palmitic acid (C16:0) and the higher proportions of monounsaturated fatty acids (MUFA) in sprout-fed groups, are directionally consistent with reports showing that dietary management can shift ruminant lipid profiles toward lower proportions of hypercholesterolemic saturated fatty acids (SFA) and higher MUFA, even in the presence of ruminal biohydrogenation [33,47–49]. Germination itself can modify the lipid fraction of grains through lipase-driven hydrolysis and remodeling of fatty acids, which may partially explain the higher cis-9-oleic acid observed in the sprout-supplemented treatments [50]. Moreover, the higher omega-3 fraction in sprout-fed bulls agrees with broader evidence that forage-leaning diets tend to yield beef with a more favorable n-6:n-3 ratio and higher long-chain n-3 fatty acids compared with concentrate-heavy finishing systems [44,45,49].

Finally, the interpretation of dietary effects should consider: the inherently low dry matter content of hydroponic sprouts; potential variation in sprout composition across batches and growth stages; and the strong confounding influence of pre-slaughter handling on pH-driven quality traits.

Future research should combine controlled pre-slaughter management with ration formulation on a dry matter basis and link rumen fermentation responses to downstream changes in muscle lipid oxidation and nitrogenous metabolites to clarify the biological pathways underlying the observed shifts in MUFA and selected amino acids [39,40,51,52].

4. Conclusions

- The chemical composition of the meat was not affected by the inclusion of sprouted seeds in the diet. However, sprouted seeds influenced the physical characteristics of the meat to varying degrees, depending on their type. The meat of bulls fed sprouted alfalfa seeds was significantly lighter and showed lower drip loss ($p > 0.05$ and $p < 0.05$, respectively). This indicates an improvement in the functional and technological properties of the meat, including enhanced water-holding capacity and tenderness, which are important indicators of overall meat quality.
- The inclusion of sprouted grains in the bulls' diet had a positive effect on the fatty acid profile of intramuscular fat. Meat from animals receiving this supplement contained 13.78–15.70% fewer saturated fatty acids (SFA), which are generally considered undesirable and potentially detrimental to human health, compared with meat from control bulls. The reduction in saturated fatty acids and the shift toward a more favorable fatty acid profile are directionally consistent with the broader literature comparing forage-based and concentrate-based feeding systems, in which greater forage inclusion is commonly associated with lower proportions of hypercholesterolemic SFA (e.g., C14:0 and C16:0) and an improved n-6:n-3 balance in beef lipids [44,45].
- The amino acid composition of the meat was most strongly affected by the addition of sprouted alfalfa seeds and sprouted peas. The meat of bulls fed sprouted alfalfa contained 2.86% more essential amino acids, while the meat of bulls receiving sprouted peas contained 0.58% more than that of the control animals. The mixture of sprouted wheat and barley did not influence this parameter.
- The addition of sprouted alfalfa seeds had the strongest impact on the meat protein integrity index. The meat of bulls receiving this supplement reached a level of biological value equivalent to that of the highest-quality beef. Although the protein completeness of bulls fed other types of sprouted grains was higher than that of the control group, it still did not meet the requirements for beef of the highest biological value.

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