Kirkuk University Journal for Agricultural Sciences
ISSN:2958-6585
https://kujas.uokirkuk.edu.iq

RESEARCH ARTICLE
https://doi.org. 10.58928/ku26.17211

Effect of Dietary Fennel (*Foeniculum vulgare* L.) Seed Powder on Meat Quality and Oxidative Stability in Karadi Male Lambs during Refrigerated Storage

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Received:10/11/2025 **Revised: 18/01/2026** **Accepted: 07/05/2026** **Published: 08/06/2026**

ABSTRACT

Farmers are also turning to natural substitutes for synthetic growth promoters to enhance the performance and quality of their livestock's meat. The aim of the present study was to investigate the effects of fennel seed powder (FSP) on the meat quality and oxidative stability of Karadi lambs. A total of 20 male lambs were divided into three dietary treatment groups over a span of 90 days: a control group receiving 0% FSP (n=6), a treatment group with 1.4% FSP (T1, n=7), and another with 2.8% FSP (T2, n=7). At the end of the study, the lambs were slaughtered, after which samples from the Longissimus dorsi muscle were collected for analysis, focusing on chemical composition, sensory evaluation, and oxidative stability. Additionally, measurements of carcass cut percentages were recorded. The findings demonstrated that T2 (2.8% FSP) significantly enhanced the intramuscular fat content and improved sensory evaluations concerning flavor, tenderness, juiciness, and overall acceptability ($P<0.05$). Compared to the control group, T1 demonstrated a higher fat deposition in the leg (15.75%) and loin (28.85%), while T2 exhibited intermediate values for these cuts. The control group had a higher proportion of bone in the leg (29.04%) compared to T2 (23.47%), with T1 presenting similar results to T2. T1 produced a higher neck meat percentage compared to T2, with the control group showing results similar to T1. In antioxidant activity within the meat, T1 demonstrated the strongest results. No significant differences were found in supplement levels affecting carcass composition. Overall, FSP is an effective natural feed additive for improving lamb meat quality, with 2.8% optimal for sensory quality and 1.4% for oxidative stability, depending on production goals. Farmers are also turning to natural substitutes for synthetic growth promoters to enhance the performance and quality of their livestock's meat. The objective of the current study was the effects of fennel seed powder (FSP) on the meat quality and oxidative stability of Karadi lambs.

***Keywords*:** Fennel seed powder, Karadi lambs, Meat quality, Sensory characteristics, Antioxidant activity.

INTRODUCTION

The livestock sector is facing significant challenges in meeting the demand for animal protein while addressing consumer concerns regarding food safety, animal welfare, and environmental sustainability. Historically, synthetic growth promoters and antimicrobial agents have been used to improve dietary efficiency and productivity [1]. However, the emergence of antibiotic-resistant bacteria and chemical residue risks has prompted a shift towards natural and environmentally friendly alternatives [2, 3]. Plant-based feed additives are gaining attention as a potential substitute for synthetic substances, leveraging the vast diversity of bioactive compounds in plants [4, 5].

Fennel (Foeniculum vulgare L.) is an herb from the Apiaceae family known for its rich bioactive compounds and historical use in herbal medicine as a carminative, digestive aid, and galactagogue [6]. Phytochemical studies have identified important constituents like trans-anethole, estragole, fenchone, and limonene [7, 8], which exhibit strong antioxidant, antimicrobial, anti-inflammatory, and hepatoprotective properties [8, 9]. These antioxidants scavenge free radicals and bind pro-oxidant metals, protecting cells from oxidative injury [9, 10]. Additionally, fennel's antimicrobial properties influence gut microbiota positively, enhancing digestive efficiency and overall animal health [4, 11]. Several studies indicate that dietary supplementation with fennel seed or its extracts enhances nutrient digestibility and optimal rumen fermentation in lambs. For instance, Hajalizadeh et al. [12] reported increased digestibility of dry and organic matter, along with improved ruminal volatile fatty acid levels in fattening lambs fed fennel seed powder. These improvements contribute to better growth performance and carcass traits [13]. Additionally, fennel supplementation is linked to enhanced meat quality, specifically in terms of water-holding capacity and tenderness, which are crucial for consumer preference and satisfaction [12, 14].

Mohammadabadi et al. [15] demonstrated that fennel seed powder upregulates the expression of the DLK1 gene in the liver and muscle tissues of growing lambs, which is crucial for adipocyte differentiation and lipid metabolism. This finding is corroborated by Masoudzadeh et al. [16], who noted tissue-specific increases in DLK1 expression in Kermani lambs on fennel supplementation, indicating fennel's role in regulating metabolic pathways. Additionally, fennel has been shown to enhance appetite and growth performance in calves by improving feed intake and conversion ratios [17]. One major challenge in the meat industry is maintaining meat quality and extending shelf life due to oxidative degeneration of post-mortem muscle tissue [18, 19], resulting in rancidity and degradation of color, texture, and nutritional value [10, 18]. Such changes worsen during storage, leading to poor quality and economic losses [18]. While synthetic antioxidants mitigate these issues, rising consumer demand for clean-label products drives interest in natural alternatives [2, 3], like fennel extracts, which are effective against lipid and protein oxidation due to their phenolic compounds [10, 11, 19]. Incorporating these natural antioxidants into animal diets enhances meat's oxidative stability by integrating bioactive compounds into muscle tissues [3, 20].

Research indicates a gap in the use of fennel seed powder in lamb production systems in Kurdistan, particularly concerning the Karadi breed, which is economically important due to its adaptation to regional environmental conditions, desirable meat characteristics preferred by consumers, and its moderate growth rate and high quality of meat. While previous studies have examined fennel's effects on growth and gene expression [13, 15, 16], there is limited data on its influence on the sensory attributes (flavor, odor, juiciness, tenderness) and oxidative stability of meat in refrigerated conditions within these systems. This study was therefore meant to fill such a knowledge gap. Its objective is to critically analyze the impacts of diet supplementation with fennel seed powder on the physicochemical and sensory attributes and oxidative stability of meat stored in refrigeration for Karadi male lambs.

Materials and methods

Experimental Animals and Diets

Twenty male Karadi lambs aged about 4 months and with an average body weight of 25 kg were bought in the local markets in the Kurdistan Region. Following a 14-day introduction period—the lambs were given a basic meal during the acclimatization period and provided the opportunity to acclimatize in relation to the experimental environment—they were randomly divided into three of the dietary treatment regimens depending on their initial body weights (control, n=6 lambs, and T1 and T2, n=7 lambs for each treatment). A single lamb was kept in a pen of 1 × 1.5 m² area to allow the accurate observation of an individual's feed consumption. The control diet is without the addition of fennel seed powder (0% supplementation). The first treatment (T1) included 1.4% fennel seed powder, while the second treatment (T2) included 2.8% fennel seed powder. Fennel seed powder was added to the total mixed ration (TMR) as a DM basis, which was replaced with barley grain. The experimental diet was designed as the TMR to fulfill the nutrient needs of developing lambs according to the available nutrient standards. It was 60% concentrate and 40% roughage. Table 1 presents the detailed formulation and chemical composition of the experimental diets. The feeding experiment was 90 days. Each lamb was fed twice a day, at 08.00 and 16.00 hours. The daily dry matter intake of the experimental diet at the rate of 3.5% on a DM basis of the body weight of the lambs was recommended by NRC [22] for moderately growing lambs and was therefore changed after every week based on the measurements of the body weights.

Diet Analysis and Chemical Composition

To find out the content of dry matter (DM), the feed samples were dried in a forced-air oven at 60℃ over a 48-hour period. Crude protein (CP), ether extract (EE), ash, and fiber (neutral detergent fiber (NDF) and acid detergent fiber (ADF)) fractions were then conducted in accordance with official procedures of the AOAC [21]. The values of metabolizable energy (ME) were estimated according to the NRC [22]. All nutrient composition values are expressed on a DM basis as shown in Table (1).

Table 1: Formulation and Chemical Composition of the Experimental Diet.

Ingredient %	Control	T1	T2
Wheat straw	12	12	12
Alfalfa hay	28	28	28
Barley grain	23	21.6	20.2

Fennel seed powder	0	1.4	2.8
Soybean meal	10	10	10
Wheat bran	12	12	12
Corn grain	12	12	12
Minerals and vitamins mixture	1	1	1
Salt	1	1	1
Sodium bicarbonate	0.5	0.5	0.5
Limestone	0.5	0.5	0.5
Chemical composition%			
Dry Matter	90.1	90.1	90.1
Crude Protein	14.4	14.5	14.6
Organic matter	93.61	93.41	93.05
Ether Extract	2.15	2.21	2.45
Nonstructural carbohydrate*	45.46	45.0	44.56
Neutral Detergent Fiber	31.6	31.7	31.8
Acid Detergent Fiber	20.3	20.3	20.3
Ash	6.39	6.59	6.95
Metabolizable Energy (Mcal/kg DM)	2.57	2.57	2.57

* Nonstructural carbohydrate was calculated by using the equation 100-(NDF%+CP%+EE%+Ash%).
Control: basal diet without the addition of fennel seed powder; T1: contained 1.4% fennel seed powder replaced with barley grain; T2: contained 2.8% fennel seed powder replaced with barley grain.

Slaughtering Process and Collection of Meat Samples

At the end of the trial (90 days), the Karadi male lambs were fasted for 12 hours with access to water and quickly weighed before slaughter. The lambs in each treatment group were slaughtered according to Islamic law in the slaughterhouse's carcass section without anesthesia in the Animal Science Department, College of Agricultural Engineering Sciences, University of Sulaimani. Blood was drained by cutting the jugular vein fold at the occipital-atlantic joint, with the carotid artery and jugular vein, and sometimes the trachea, being resected at a point near the head that separates the throat from the spine. After slaughter, the head was severed at the occipital-atlantic joint, and the foreshank and hindlegs were separated at the wrist and ankle joints, respectively. The carcass was mostly cleaned on the ground, then hung on racks by its hind legs, and the cleaning was completed. The weight of the hot carcass was noted immediately after evisceration. Carcasses were chilled at 4°C for 24 h. Carcass weight after chilling was recorded as cold carcass weight, and the *Longissimus dorsi* (LD) muscle was removed on the left side of the carcass between the 12th and 13th ribs. Three duplicate samples of the *Longissimus dorsi* muscle were taken from each individual carcass of lamb. After collection, the LD sample was carefully cleaned to remove subcutaneous fat, peripheral muscle tissue, and muscle membrane, then stored in plastic zipper bags and marked by using a marker for each sample and replication. All LD samples were carefully prepared and stored until specialized analysis was carried out. The LD muscle was then further subdivided into sub-samples to conduct physical property analysis, chemical composition, oxidative stability analysis, and sensory analysis.

Carcass Cuts Measurement

The left carcasses, after which the weight of the chilled carcass was measured. The kidney and pelvic fat were then removed and weighed separately. The carcass was partially cut along the vertebrae into two parts using a handsaw; the left half of the carcass was then cut into nine whole parts, including the leg, loin, rack, neck, breast, flank, shoulder, foreshank, and neck. All the whole parts were weighed separately at the same time. After that, each part is dissected into lean, bone, and fat and calculated as a percentage for each cold carcass cut.

Chemical Analysis of Meat

The chemical analysis of the meat samples (LD muscles) was done on moisture according to the method AOAC (934.01), protein according to the method AOAC (981.10), fat (ether extract) according to the method AOAC (920.39), and ash content using AOAC standard methods (942.05) [21].

Oxidative Stability Assessment

To determine the stability of meat on oxidative degradation after storage, meat samples were refrigerated (4℃). The antioxidant activity of meat was computed as indicated by Echegaray et al. [23] and Lateef et al. [24]. Fat oxidation was determined by measuring the concentration of malondialdehyde (MDA) as an indicator of oxidative damage. Antioxidant capacity was calculated based on the inhibition of fat peroxidation during refrigerated storage.

All analyses were performed in triplicate, and results are expressed as means for each treatment group.

Sensory Evaluation

The muscle samples of the LD were evaluated by a trained sensory panel regarding the sensory quality characteristics. The samples of each treatment were cooked to a temperature of 70℃ and served to the panelists in a randomized sequence. A panel of 5 scored color, flavor, tenderness, juiciness, and acceptability with a structured 5-point hedonic scale, which was based on the approach of Qadir et al. [25].

Statistical Analysis

A one-way analysis of variance (ANOVA) was used to analyze all the collected data designed under a completely randomized design. The general linear model (GLM) SAS (9.4) procedure was used, in which dietary treatment was used as the fixed effect. In the event that any significant differences (p equal to or less than 0.05) were established, the use of the Multiple Range Test of Duncan [26] was adopted to compare the means of treatment. The findings are reported in mean values with the standard error of the mean (SEM). The data analysis of the current experiment follows the model:

$Y_{ij} = \mu + t_i + eij$

Where Y_{ij}= the dependent variable, μ= overall mean, $t_{i=}$ effect of treatments (i= control, T1=1.4% fennel seed powder, T2= 2.8% fennel seed powder), and eij= random residual error.

Results

Physical Dissection of the carcass

The effect of fennel seed powder on physical dissection of different carcass cuts is provided in Table 2. The statistical analysis indicated that the 1.4 percent (T1) and 2.8 percent (T2) supplementation of fennel seed powder did not bring any significant ($p > 0.05$) difference in the proportional weights of the meat, fat, or bone in all primal cuts measured. However, the trend of higher fat deposition in the leg and loin was 15.75% and 28.85% for T1 compared to the control group (9.54% and 12.74%), respectively, while T2 showed intermediate values between T1 and the control group for both fat depositions in carcass cuts. In contrast, the higher percentage of bone in the leg was shown in control groups (29.04%) compared to T2 (23.47%), and T1 was similar between them. On the other hand, the fat deposition in the rack showed a higher percentage in T2 (24.53%) compared to the control group (17.43%); at the same time, T1 was similar between them. T1 showed a higher meat percentage in the neck compared to T2, while the control group did not differ from the others.

Table 2 : Effect of dietary fennel seed powder on carcass cut percentages of Karadi male lambs

Carcass cuts	Physical Dissection%	Control	T1	T2	SEM	*P-Value*
Leg	Lean	61.42	58.83	62.86	1.71	0.310
	Fat	9.54^{b}	15.75^{a}	13.67^{ab}	1.67	0.093
	Bone	29.04^{a}	25.42^{ab}	23.47^{b}	1.31	0.060
Loin	Lean	44.43	40.91	41.41	1.87	0.408
	Fat	12.74^{b}	23.85^{a}	20.43^{ab}	2.76	0.071
	Bone	42.83	35.24	38.16	3.02	0.276
Rack	Lean	38.03	39.63	36.15	6.06	0.922
	Fat	17.43^{b}	22.56^{ab}	24.53^{a}	1.77	0.069
	Bone	44.54	37.81	39.32	4.75	0.746
Breast	Lean	31.04	29.01	38.87	5.04	0.401
	Fat	36.99	41.98	27.86	4.89	0.199
	Bone	31.97	29.01	33.27	2.09	0.393
Flank	Lean	64.18	58.79	60.73	5.34	0.778
	Fat	35.82	41.21	39.27	5.34	0.778
Shoulder	Lean	52.99	62.64	43.93	6.47	0.204
	Fat	6.08	10.63	12.25	2.74	0.324
	Bone	40.93	26.73	43.82	8.03	0.340
Foreshank	Lean	47.52	46.23	50.28	3.35	0.698
	Fat	6.07	5.74	6.73	1.92	0.934
	Bone	46.41	48.03	42.99	2.99	0.515

	Lean	51.88^{ab}	53.43^{a}	41.21^{b}	3.28	0.075
Neck	Fat	4.72	8.53	10.76	2.08	0.197
	Bone	43.40	38.04	48.03	3.24	0.174

Control: basal diet without the addition of fennel seed powder; T1: contained 1.4% fennel seed powder replaced with barley grain; T2: contained 2.8% fennel seed powder replaced with barley grain. SEM: standard error of the mean.
$^{a, b}$ Means with different superscripts letters within same raw are not significant (P>0.05).

Chemical Composition of Meat

Table 3 shows the significant impact of dietary fennel seed powder supplementation on the chemical composition of the longissimus dorsi muscle. The moisture, fat, and protein contents had significant differences ($p \leq 0.05$), whereas the ash content did not differ significantly ($p > 0.05$).

Table 3: Effect of dietary fennel seed powder on the chemical composition of the *Longissimus dorsi* muscle in Karadi male lambs.

Treatment	Control	T1	T2	SEM	*P-Value*
Moisture%	70.19^{a}	69.15^{b}	69.28^{b}	0.098	0.001
Fat%	4.58^{c}	5.66^{b}	6.90^{a}	0.197	0.000
Protein%	22.47^{a}	21.79^{a}	20.71^{b}	0.224	0.004
Ash%	1.77	2.33	1.90	0.248	0.313

Control: basal diet without the addition of fennel seed powder; T1: contained 1.4% fennel seed powder replaced with barley grain; T2: contained 2.8% fennel seed powder replaced with barley grain. SEM: standard error of the mean.
$^{a, b}$ Means with different superscripts letters within same raw are significant (P≤0.05).

The moisture content was the greatest in the control group (70.19), which was significantly higher than the moisture content in both fennel-supplemented groups. In contrast, the intramuscular fat (IMF) content exhibited a significant and evident dose-dependent increase with increased levels of fennel supplementation as the percentage of IMF fat content increased to 4.58, 5.66, and 6.90 in control, T1, and T2, respectively. Protein content showed an opposite pattern with respect to fat, where it declined drastically in the control, T1, and T2, to 22.47% and 20.71%, respectively. The content of ash was statistically equal between groups.

Sensory Evaluation

Table 4 presents the summary of the sensory evaluation done by the trained panel. Fennel seed powder dietary supplementation had a strong ($p \leq 0.05$) and distinctive impact on all the evaluated sensory attributes, except meat color.

Table 4: Effect of dietary fennel seed powder on the sensory evaluations of *Longissimus dorsi* meat in Karadi male lambs.

Treatment	Control	T1	T2	SEM	*P-Value*
Color	4.00^{ab}	3.66^{b}	4.67^{a}	0.27	0.098
Flavor	3.67^{b}	3.33^{b}	5.00^{a}	0.27	0.011
Tenderness	3.33^{b}	3.67^{b}	5.00^{a}	0.27	0.011
Juiciness	3.66^{b}	4.00^{b}	5.00^{a}	0.19	0.007
overall	3.67^{b}	4.00^{b}	5.00^{a}	0.19	0.007

Control: basal diet without the addition of fennel seed powder; T1: contained 1.4% fennel seed powder replaced with barley grain; T2: contained 2.8% fennel seed powder replaced with barley grain. SEM: standard error of the mean .
$^{a, b}$ Means with different superscripts letters within same raw are significant (P≤ 0.05).

Concerning taste, tenderness, juiciness, and acceptability in general, the T2 group (2.8% fennel) scored the highest possible score of 5.00 compared to both the T1 and control groups. The T1 group also scored better than the control group, yet again, but differences were not always significant among all sensory attributes.

Antioxidant Activity

Table 5 shows the findings of the analysis of the antioxidant activity. The treatment groups showed a significant difference ($p \leq 0.05$).

Table 5: Effect of dietary fennel seed powder on antioxidant activity (μmol TE/g) of *Longissimus dorsi* meat in Karadi male lambs.

Treatment	Control	T1	T2	SEM	*P-Value*
Antioxidant Activity	292.43^{b}	336.24^{a}	269.35^{c}	5.89	0.001

Control: basal diet without the addition of fennel seed powder; T1: contained 1.4% fennel seed powder replaced with barley grain; T2: contained 2.8% fennel seed powder replaced with barley grain. SEM: standard error of the mean .
$^{a,\ b,\ and\ c}$ Means with different superscripts letters within same raw are significant ($P \leq 0.05$).

The T1 group exhibited the highest antioxidant activity (336.24 μmol TE/g), which was significantly more than that of the control group (292.43 μmol TE/g) and the T2 group (269.35 μmol TE/g). The T2 group showed the least antioxidant activity as compared to the other treatments.

Discussion

The current paper is an in-depth evaluation of dietary fennel seed powder supplementation on the performance of Karadi lamb, which shows a specific and dose-dependent effect on meat quality, fat compositions, and oxidative stability.

Physical Dissection of the Carcass

These results are consistent with the literature on phytogenic feed additives, where meaningful carcass cut changes exist. Hajalizadeh et al. [13] have also found that the addition of 1.5% fennel seed powder to the fattening lamb diets had significant effects on the weights of primary carcass parts, such as the leg and loin. The current study trend is to have higher fat deposition in the leg, loin, and rack; moreover, there is a higher lean percentage in the neck of lambs fed on fennel seed; however, it was not statistically significant. So, the current results are likely due to differences in animal age, basal diet and chemical composition, feeding duration, and management conditions.

Despite evaluating higher addition levels, the lack of a clear dose-response effect in this study suggests that increasing the fennel seed concentration alone may not proportionally improve carcass tissue deposition. Importantly, this study is the first to provide a detailed dissection of lean, fat, and bone tissue in each carcass cut (leg, loin, ribs, breast, flank, shoulder, foreshank, and neck) in lambs fed fennel seeds, offering a new perspective on carcass tissue distribution. The lack of statistical significance likely reflects the complexity and variability of tissue accumulation at the cut level, highlighting the need for longer feeding periods and larger sample sizes in future studies. These findings suggest that moderate inclusion of fennel seed powder is mostly a metabolic modulator, but not a repartitioning agent, which changes the tissue composition.

The increase in the percentage of fat deposits in some of the cuts (e.g., leg and loin of T1) may be related to the bioactive components in fennel, especially trans-anethole, that are capable of acting upon lipid metabolism. Mohammadabadi et al. [15] have also shown that fennel seed powder has the effect of regulating the expression of the DLK1 gene, one of the major adipogenesis regulators. The minor but nonsignificant variations in fat level across treatments in this study might be minor metabolic reactions to such control. However, these changes were not significant enough, which is why they did not have statistical significance, so such changes should not be viewed as a significant outcome. Notably, the overall similarity in carcass composition suggests that the supplementation of fennel at the level of 2.8 percent does not limit the carcass yield and the economic value of the key cuts.

Meat Chemical Composition

As Table 3 demonstrates, the supplementation of fennel seed powder had significant effects on the chemical composition of meat, particularly the intramuscular fat (IMF). IMF, or marbling, is an important factor of the eating quality—it is highly correlated with the juiciness, flavor, and tenderness [27]. The increasing trend of IMF as the fennel content is increasing in the samples is in agreement with the molecular study of Mohammadabadi et al. [15] and [16.] Masoudzadeh et al. [16] discovered that fennel seed powder increases the expression of the DLK1 gene in muscle and adipose tissue, resulting in adipocyte differentiation and lipid accumulation. This process is likely to be the basis of the increased IMF values in the T1 and T2 groups.

The relationship between the fat and protein or moisture content in the meat is known to be negative as well. The higher the lipid deposition, the lower, relative to an interest mass, is the proportion of water and protein in it—a dilution effect and not an actual decrease in the synthesis of protein [28]. This fat-driven change is associated with the great reduction in moisture among fennel-fed groups.

The fact that there are no major differences in ash content indicates that there cannot be a meaningful change in mineral composition with the fennel supplementation, as was found in other literature that used herbal feed additives [29]. The small changes in the percentage of ash in T1 can justify the research related to the mineral structure inherent in fennel.

Sensory Evaluation

The excellent scores on sensory that the T2 group has, as shown in Table 4, are directly proportional to its high level of intramuscular fat content.

Juiciness: IMF is also an important contributor to juiciness because fat is melted during cooking, which lubricates muscle fibers and helps retain meat moisture. This is because the fat level in T2 is better (6.90) than the control, which allows it to be rated highly on juiciness [27].

Tenderness: Intramuscular fat enhances tenderness by physically separating muscle fibers, thus decreasing connective tissue density. The T2 group is more likely to be marbled, and this tendency is reflected in the high score of the tenderness [27].

Flavor: Lipids are the major precursors of Maillard and oxidation-generated flavor compounds. Therefore, more IMF adds a rich and roasted taste. The maximum score of fennel (5.00) in T2 suggests that fennel increased the amount of fat and enriched the flavor quality, which could have been caused by the deposition of aromatic compounds such as trans-anethole in fennel essential oils [8].

General Acceptability: T2 was rated the highest in terms of overall acceptability, considering that it scored higher in terms of juiciness, tenderness, and flavor. The lack of any major changes in color is a positive result that indicated that the fennel supplementation had no undesirable discoloration or pigmentation effects that affect the consumer preference [18].

Antioxidant Activity

As can be seen in Table 5, the significant increase in antioxidant activity of the T1 group agrees with the well-known antioxidant effect of fennel. The seeds of fennel are rich in phenolics, flavonoids, and essential oils (e.g., trans-anethole and estragole), which have a strong free radical-scavenging ability [7, 8, 9]. By adding these bioactive compounds to the animal diet, it will be possible to improve the antioxidant status of tissues, thereby reducing the rate of lipid and protein oxidation and increasing the shelf life of meat [3, 10, 18].

The less antioxidant activity was, however, observed in the T2 group compared to both T1 and the control, which indicates the action of a non-linear dose-dependent effect. Biphasic reactions have also been observed in other studies on the use of phytogenic feed additives. There are a number of possible explanations:

Pro-oxidant Shift at Higher Concentrations: There are antioxidants that are pro-oxidant at higher concentrations depending on redox potential and environmental conditions [9]. Fennel compounds might have reached a certain point where oxidative reactions were caused at 2.8 percent inclusion.

Metabolic and Absorptive Variation: An increase in doses of fennel may change absorption or metabolism and decrease the bioavailability of antioxidant compounds or convert them into less active forms.

Rumen Microbial Interaction: Fennel has the ability to change rumen fermentation [11]; at increased levels of inclusion, changes of the microbiota may occur in the breakdown or transformation of antioxidant compounds to less efficient metabolites.

The findings highlight the point that the dose of natural additives does not always increase benefits when raised. The inclusion rate that maximizes the sensory quality is not necessarily the same as that which maximizes oxidative stability. In order to understand the mechanisms of this biphasic response, more research is required.

Conclusion

This research establishes that dietary supplementation using fennel seed powder is an effective natural approach towards the enhancement of the quality of lamb meat, the results of which greatly depend on the extent of addition. The most striking finding was noted at the 2.8 percent (T2) supplementation level, which had significant effects on raising intramuscular fat content. This increase in marbling resulted in a significant and consistent increase in all essential sensory characteristics—flavor, tenderness, juiciness, and overall acceptability—all scoring the highest ratings by the trained panel. The results are a clear indication that the addition of 2.8 percent fennel seed powder in the diets of lambs can result in meat that is of excellent palatability and that has great consumer preference. On the other hand, the 1.4% (T1) inclusion level was most effective in enhancing antioxidant activity of the meat, which is a very significant parameter in extending the shelf life of the meat as well as maintaining its quality in the storage period. Notably, both levels of supplementation did not have a negative impact on carcass yield and carcass composition. Therefore, production priorities should determine the optimum level of fennel seed powder inclusion. To obtain the highest sensory quality and market value, an inclusion of 2.8 is suggested, and an inclusion of 1.4 is rather desirable when prolonging the product and oxidative stability is to be achieved. Overall, fennel seed powder may be considered the innovative, versatile, and sustainable feed supplement that can customize the meat quality properties to meet the particular market requirements. Future studies can also be used to examine how meat in the T2 group is stored to shed more light on the long-term effects of its reduced antioxidant activity.

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تأثير مسحوق بذور الشمر على جودة اللحم واستقراره التأكسدي في ذكور حملان كرادي أثناء التخزين المبرد

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الخلاصة

هدفت هذه الدراسة إلى بحث تأثير مسحوق بذور الشمر على جودة لحم حملان كرادي وثباته التأكسدي. قُسِّم عشرون حملاً ذكراً إلى ثلاث مجموعات غذائية على مدى تسعين يوماً: مجموعة السيطرة (عدد=6 حملان) لم تتلقَّ أي مسحوق بذور الشمر، المجموعة التجريبية الاولى، (عدد=7 حملان) تلقت 1.4% من مسحوق بذور الشمر)، والمجموعة التجريبية الثانية ، (عدد=7 حملان) تلقت 2.8% من مسحوق بذور الشمر). في نهاية الدراسة، ذُبحت الحملان، ثم جُمعت عينات من العضلة الظهرية الطولية لتحليلها، مع التركيز على التركيب الكيميائي والتقييم الحسي والثبات التأكسدي، كما سُجِّلت نسب قطع الذبيحة. أشارت النتائج إلى أن المجموعة التجريبية الثانية ، حسَّنت بشكل ملحوظ محتوى الدهون داخل العضلات، وحسّنت التقييمات الحسية المتعلقة بالنكهة والطراوة والعصارة والمقبولية العامة (***P<0.05).*** بالمقارنة مع مجموعة السيطرة، أظهرت المجموعة التجريبية الاولى ترسبًا أعلى للدهون في الفخذ (15.75%) والقطنية (28.85%)، بينما أظهرت المجموعة التجريبية الثانية قيمًا متوسطة لهاتين القطعتين. وكانت نسبة العظام في الفخذ أعلى في مجموعة السيطرة (29.04%) مقارنةً بالمجموعة التجريبية الثانية (23.47%) ، مع نتائج مماثلة للمجموعة التجريبية الاولى. كما أنتجت المجموعة التجريبية الاولى نسبة أعلى من لحم الرقبة مقارنةً بالمجموعة التجريبية الثانية ، مع نتائج مماثلة لمجموعة السيطرة. وفيما يتعلق بنشاط مضادات الأكسدة في اللحم، أظهرت المجموعة التجريبية الاولى أقوى النتائج. ولم تُلاحظ فروق ذات دلالة إحصائية في مستويات المكملات الغذائية التي تؤثر على تركيب الذبيحة. وبشكل عام، يُعدّ مسحوق بذور الشمر مضافًا علفيًا طبيعيًا فعالًا لتحسين جودة لحم الحملان، حيث تُعتبر نسبة 2.8% مثالية للجودة الحسية، ونسبة 1.4% مثالية للاستقرار التأكسدي، وذلك حسب أهداف الإنتاج.

الكلمات المفتاحية: مسحوق بذور الشمر، حملان الكرادي، جودة اللحم، الخصائص الحسية، النشاط المضاد للأكسدة.