KSÜ Tarım ve Doğa Derg 29 (4), 1078-1088, 2026
KSU J. Agric Nat 29 (4), 1078-1088, 2026
DOI:10.18016/ksutarimdoga.vi.1784319

Effects of Boric Acid and Sodium Chloride Additives on the Nutrient Composition, Fermentation Characteristics, Aerobic Stability, Physical Properties, and Relative Feed Value of High Moisture Corn Silages

Emre YILMAZ[1✉], Soner UYSAL[2], Şeyma TAŞ[3], Zekeriya Safa İNANÇ[4], Bora BÖLÜKBAŞ[5], Mehmet Akif YÖRÜK[6]
[1]Department of Animal Nutrition and Nutritional Disease, Faculty of Veterinary, Atatürk University, Erzurum, Türkiye, [2]Department of Animal Nutrition and Nutritional Disease, Faculty of Veterinary, Atatürk University, Erzurum, Türkiye, [4]Department of Animal Nutrition and Nutritional Disease, Faculty of Veterinary, Selcuk University, Konya, Türkiye, [5]Department of Animal Nutrition and Nutritional Disease, Faculty of Veterinary, Ondokuz Mayis University, Samsun, Türkiye, [6]Department of Animal Nutrition and Nutritional Disease, Faculty of Veterinary, Ondokuz Mayis University, Samsun, Türkiye
[1]https://orcid.org/0000-0003-1004-6531, [2]https://orcid.org/0000-0003-0372-9895, [3]https://orcid.org/0009-0008-1259-9213
[4]https://orcid.org/0000-0003-0832-9209, [5]https://orcid.org/0000-0002-0732-0192, [6]https://orcid.org/0000-0002-5833-9803
✉: emre.yilmaz@atauni.edu.tr

ABSTRACT
This study investigated the effects of boric acid (45 and 90 mg/kg) and/or 1% NaCl supplementation on silage quality and fermentation characteristics of high-moisture corn silages. The experiment consisted of six groups: control (C), 1% NaCl (S), boric acid at 45 and 90 mg/kg (B45, B90), and their combinations with 1% NaCl (SB45, SB90). The findings demonstrated that 45 mg/kg boric acid reduced ADF content, limited mold growth, and enhanced dry matter digestibility and relative feed value. The S group showed the lowest digestibility, lactic acid concentration, and fermentation efficiency, while the SB90 group exhibited the highest lactate concentration but reduced Flieg score, CO_2 production, and relative feed value, indicating that high-dose boric acid supplementation (90 mg/kg) negatively affected certain aspects of silage quality. In conclusion, low-dose boric acid supplementation appears promising for improving the quality of high-moisture corn silages.

Animal Science

Research Article

Article History
Received : 15.09.2025
Accepted : 28.11.2025

Keywords
Aerobic stability
Boric acid
Fermentation
High-moisture corn silage
Sodium chloride

Yüksek Nemli Mısır Silajlarında Bor ve Sodyum Klorür Katkılarının Besin Kompozisyonuna, Fermentasyon Özelliklerine, Aerobik Stabilitesine, Fiziksel Özelliklerine ve Nispi Yem Değerine Etkileri

ÖZET
Bu çalışma, yüksek nemli mısır silajlarında borik asit (45 ve 90 mg/kg) ve/veya %1 NaCl ilavesinin silaj kalitesi ve fermantasyon özellikleri üzerine etkilerini araştırmıştır. Deneme kontrol (C), %1 NaCl (S), 45 ve 90 mg/kg borik asit (B45, B90) ile bu dozların %1 NaCl ile kombinasyonlarını (SB45, SB90) içeren altı gruptan oluşmuştur. Bulgular özellikle 45 mg/kg borik asit, ADF içeriğini azalttığını, küf gelişimini sınırlardırdığını, kuru madde sindirilebilirliğini ve nispi yem değerini artırdığını gösterdi. Buna karşın, S grubunda sindirilebilirlik, laktik asit düzeyi ve fermantasyon etkinliği en düşük bulunurken, SB90 grubunda laktat konsantrasyonu en yüksek olmasına rağmen Flieg skoru, CO_2 üretimi ve nispi yem değeri düşmüş; yüksek doz borik asit (90 mg/kg) uygulamasının silaj kalitesini bazı yönlerden olumsuz etkilediği belirlenmiştir. Sonuç olarak, düşük doz borik asit uygulamasının yüksek nemli mısır silajlarının kalitesini artırmak için umut vaad edici olduğu belirlendi.

Zootekni

Araştırma Makalesi

Makale Tarihçesi
Geliş Tarihi : 15.09.2025
Kabul Tarihi : 28.11.2025

Anahtar Kelimeler
Aerobik stabilite
Borik asit
Fermentasyon
Sodyum klorür
Yüksek nemli mısır silajı

Atıf İçin : Yılmaz, E., Uysal, S., Taş, Ş., İnanç, Z.S., Bölükbaş, B., & Yörük, M.A. (2026). Yüksek Nemli Mısır Silajlarında Bor ve Sodyum Klorür Katkılarının Besin Kompozisyonuna, Fermentasyon Özelliklerine, Aerobik Stabilitesine, Fiziksel Özelliklerine ve Nispi Yem Değerine Etkileri. *KSÜ Tarım ve Doğa Derg 29* (4), 1078-1088. DOI: 10.18016/ksutarimdoga.vi.1784319.

To Cite: Yılmaz, E., Uysal, S., Taş, Ş., İnanç, Z.S., Bölükbaş, B., & Yörük, M.A. (2026). Effects of Boric Acid and Sodium Chloride Additives on the Nutrient Composition, Fermentation Characteristics, Aerobic Stability, Physical Properties, and Relative Feed Value of High Moisture Corn Silages. *KSU J. Agric Nat 29* (4), 1078-1088. DOI: 10.18016/ksutarimdoga.vi.1784319.

INTRODUCTION

Corn silage is one of the most widely used roughage sources in ruminant nutrition due to its high energy content and palatability. However, the quality of this silage and its effect on animal performance largely depend on its dry matter (DM) content (Zhang et al., 2025). For proper fermentation, the DM concentration of corn silage is generally recommended to be within the range of 30–35% (Kılıç, 1984; Zhang et al., 2025). Studies have reported that silages with lower DM content are prone to undesirable fermentation processes, which may lead to nutrient losses, mold development, and, consequently, reduced feed quality (Weinberg & Muck, 1996; Kung & Shaver, 2001; Keleş & Çıbık, 2014).

One of the main factors directly affecting silage DM content is harvest time (Gürsoy et al., 2021). Harvesting time, in turn, varies depending on seasonal conditions, physiological maturity of the variety, irrigation status, plant density, and harvesting technique (Kılıç, 1984; Keleş & Çıbık, 2014). In regions with high altitude and harsh climatic conditions, such as Erzurum in Eastern Türkiye, the growing season of some corn varieties is short, and only one harvest is generally possible. This situation may prevent the crop from reaching full maturity, leading to silage with high moisture content and low DM levels (Bulut et al., 2008; Güney et al., 2010). Since the low DM content of silages obtained under Erzurum conditions can negatively affect feed value and animal performance, various additives are being investigated to optimize DM content and improve fermentation quality (Yitbarek & Tamir, 2014; Besharatı et al., 2020; Besharatı et al., 2021).

Sodium chloride is considered a potential additive for improving silage quality due to its antimicrobial and preservative properties (Sofos, 1984). A source published in Türkiye suggests that sodium chloride at 1–1.5% is appropriate (Kutlu, 2025). However, studies on the use of this additive in silages are rather limited, and some inconsistencies have been reported (Shockey & Borger, 1991; Koç et al., 1999; McLaughlin et al., 2002). In one study, the effects of 4% sodium chloride (4 g/100 g fresh forage) on the fermentation of alfalfa silage were examined. It was observed that sodium chloride at concentrations of 100 mM or higher inhibited the growth of Clostridium butyricum, but also suppressed the development of lactic acid bacteria. Addition of sodium chloride alone did not provide adequate protection in silages inoculated with Clostridium, whereas inoculation with lactic acid bacteria improved silage quality more effectively (Shockey & Borger, 1991). In another study, the application of sodium chloride at a rate of 22.5 kg/121 m² to the upper layer of corn silage after ensiling was investigated for its effects on fermentation characteristics and silage quality. In the treated sections, reductions in pH, NDF content, zearalenone concentration, and total aerobic bacteria counts were observed, indicating improved fermentation and reduced spoilage. It was concluded that the top-layer application of sodium chloride could reduce spoilage, making it an economically effective method for minimizing silage losses (McLaughlin et al., 2002). Similarly, in a study conducted in Türkiye, the addition of sodium chloride to corn–soybean mixture silages decreased pH and ammonia concentrations while increasing DM content (Koç et al., 1999).

In addition to sodium chloride, boron is another micronutrient with high potential as a silage additive that has not been extensively studied. Boron plays a role in several biological processes, including maintenance of cell wall structure, membrane permeability, and regulation of microbial interactions (Marschner, 1995; Yarnia et al., 2013). The addition of boric acid (a form of boron) during ensiling has been suggested to influence microbial metabolism, thereby improving fermentation quality. However, despite these potential benefits, the use of boric acid in animal nutrition must be approached with caution due to its known toxicity at elevated levels. Therefore, understanding the toxicological thresholds and safety considerations of bor is essential before it can be recommended as a silage additive. Studies on the toxicity of boron have not yet reached a clear consensus and have reported adverse effects on health and performance beginning at doses ranging from 13 to 59 mg/kg in rats (Khalid et al., 2018). However, research conducted in sheep and dairy cows has shown that dietary boric acid at levels between 30 and 180 mg/kg has no negative effects and also has reported improvements in certain health and performance parameters (Sizmaz et al., 2022; Uysal & Yoruk, 2025). Therefore, the silages with low DM content, and the combined use of boric acid and sodium chloride, may exert synergistic effects. Because boric acid and sodium chloride can reduce the levels of microorganisms that can negatively affect silage fermentation, and their combination can improve silage quality. The objective of this study was to determine the effects of boric acid and sodium chloride supplementation on the fermentation characteristics, physical properties, nutritional composition, and relative feed value of corn silage with low dry matter content.

MATERIAL and METHOD

Materials and Silage Preparation

Corn plants (*Zea mays* L.) used in the study were obtained from a farm in Erzurum (Türkiye) shortly before the dough stage of maturity on September 22, 2023. The silage material was chopped into pieces averaging 2–4 cm in length and thoroughly homogenized. The prepared material was placed into durable, leak-proof plastic bags in 1

kg portions. To ensure standardization of procedures, all materials were weighed and packed into bags without a device by the same researcher, manually compressed to remove ambient oxygen.

Six experimental groups were established: the control group (C) received no additives; the S group was supplemented with 1% sodium chloride (TEKKIM, ≥99,5%); B45 and B90 groups were supplemented with 45 and 90 mg/kg boric acid (TEKKIM, ≥99,5%), respectively; and SB45 and SB90 groups received 45 and 90 mg/kg boric acid combined with 1% sodium chloride, respectively. Each group consisted of seven replicates (n = 7). The prepared mini silos were incubated in a dark environment at 25 ± 2 °C for 30 days to allow fermentation.

Sensory Evaluation

Sensory evaluation was conducted by a six-member panel trained specifically for the study. Silage was assessed for odor, structure, and color using a scoring system described by Kılıç (1984), and the scores were summed. The same panel visually inspected silage samples for mold development at the end of the fermentation period by opening each bag. To ensure evaluation of the entire sample rather than only the surface, material was sampled approximately 2–3 cm below the surface.

Analytical Procedures

From each opened silo, 25 g samples were collected from the inner portions after discarding the top layers. Samples were homogenized in 100 ml of distilled water using a blender. The pH of the resulting slurry was measured using a pH meter (Hanna pH-211). For the determination of short-chain fatty acids (SCFA), 1 ml of the homogenate was mixed with 0.2 ml of 25% metaphosphoric acid and transferred to microcentrifuge tubes. Lactic acid analysis samples were stored without additives. For ammonia nitrogen analysis, another 1 ml portion was mixed with 20 µl sulfuric acid and transferred to microcentrifuge tubes. Ammonia nitrogen, SCFA, and lactic acid concentrations were determined according to the methods of Cobellis et al. (2015) and Weatherburn (1967).

Dry matter, crude ash, crude fat, and crude protein analyses of silage samples were performed according to AOAC (1990). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed using the methods described by Van Soest et al. (1991).

Determination of Flieg Score, Relative Feed Value, and Aerobic Stability

Flieg scores were calculated based on laboratory-measured DM and pH values (Karakozak and Ayasan, 2010). Aerobic stability was determined by assessing CO_2 production from silage samples (Ashbell et al., 1991). For the aerobic stability test, polyethylene bottles were cut into two parts: a 0.5 L cap and a 1 L base. The base portion contained 100 ml of 20% KOH, and 250 g of silage was placed in the cap, which was inverted onto the base. The assembled test setups were kept at room temperature for five days.

Relative feed value (RFV) was calculated according to formulas developed by Rohweder et al. (1978). In these calculations, dry matter digestibility (%DMD) was estimated from ADF content, and dry matter intake (%DMI) was estimated from NDF content.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics (version 20, IBM Corp., Armonk, NY, USA). Before performing ANOVA, the normality of data distribution was examined using the Shapiro–Wilk test, while homogeneity of variances was verified through Levene's test. Continuous variables, including nutritional composition, sensory attributes, fermentation parameters, Flieg scores, aerobic stability, and relative feed value, were analyzed using One-Way ANOVA. Differences among groups were determined using Duncan's multiple range test. Statistical significance was set at $P < 0.05$.

RESULTS

Nutrient Composition

Analysis of the chemical composition of the silages revealed statistically significant differences among groups, particularly in ether extract (EE), NDF, ADF, and ash contents (Table 1). The highest EE content was observed in the C and B45 groups, whereas B90 and SB45 had significantly lower values. Additionally, compared to the C group, EE values were lower in the S and SB90 groups, but higher in the B90 and SB45 groups. Following fermentation, NDF content was highest in the B90 group compared with the C group, and no significant differences were observed among the other groups. Regarding ADF levels, only the difference in the S group was statistically significant compared to the C group. Moreover, the addition of 45 mg/kg boric acid reduced ADF content compared to the B90 and SB90 groups. In terms of ash content, only the B90 group had a higher value compared to C, while

SB90 showed a statistically significant decrease compared to B90. No significant differences were observed among groups in dry matter (DM) and crude protein (CP) content ($p = 0.527$ and $p = 0.137$, respectively).

Table 1. Nutrient composition of high moisture corn silages treated with different additives (% on DM basis)
Çizelge 1. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının besin madde bileşimi (% KM bazında)

Group *Grup*	DM (%)	CP (%)	EE (%)	NDF (%)	ADF (%)	Ash (%) *Kül (%)*
C	21.1±0.173	11.7±0.184	4.85±0.133^{a}	49.9±0.458^{b}	29.9±0.371^{bc}	7.11±0.110^{bc}
S	20.8±0.292	12.1±0.171	4.06±0.048^{b}	49.1±0.518^{b}	30.9±0.133^{a}	7.15±0.094^{abc}
B45	20.8±0.134	12.3±0.363	5.05±0.062^{a}	49.8±0.976^{b}	29.1±0.171^{c}	7.45±0.107^{ab}
B90	21.2±0.238	12.5±0.168	2.56±0.131^{c}	53.4±.0460^{a}	30.7±0.371^{ab}	7.48±0.111^{a}
SB45	21.0±0.320	12.3±0.169	2.50±0.129^{c}	50.6±0.256^{b}	29.9±0.309^{bc}	7.20±0.127^{abc}
SB90	20.6±0.175	11.9±0.225	3.97±0.253^{b}	50.5±0.227^{b}	30.5±0.364^{ab}	6.93±0.117^{c}
p	*0.527*	*0.137*	***<0.001***	***<0.001***	***0.002***	***0.013***

$^{a–c}$ Values in the same column that do not share a common superscript are significantly different. Data are presented as mean ± SEM (n = 7). Abbreviations: ADF: Acid detergent fiber; B45: Group supplemented with 45 mg/kg boric acid; B90: Group supplemented with 90 mg/kg boric acid; C: Control; CP: Crude protein; DM: Dry matter; EE: Ether extract; NDF: Neutral detergent fiber; S: Group supplemented with 1% sodium chloride; SB45: Group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: Group supplemented with 90 mg/kg boric acid and 1% sodium chloride.

$^{a–c}$ Aynı sütunda ortak üst simgeye sahip olmayan değerler istatistiksel olarak farklıdır. Veriler ortalama ± SEM (n = 7) olarak sunulmuştur. Kısaltmalar: ADF: Asit deterjan lif; B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; CP: Ham protein; DM: Kuru madde; EE: Eter ekstrakt; NDF: Nötral deterjan lif; S: %1 sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup; SB90: 90 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup.

Fermentation Characteristics

Evaluation of fermentation characteristics revealed that ammonia levels were significantly higher in all additive-treated groups (except B90) compared to the control (Table 2, p = 0.004).

Table 2. Nutrient characteristics of high moisture corn silages treated with different additives
Çizelge 2. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının fermentasyon özellikleri

Group *Grup*	Ammonia *Amonyak* (mmol/L)	Lactate *Laktat* (mmol/L)	Propionate *Propiyonat* (mmol/L)	Acetate *Asetat* (mmol/L)	Butyrate *Bütirat* (mmol/L)	pH
C	5.92±0.190^{b}	2.37±0.076^{c}	ND	3.93±0.723^{c}	ND	3.95±0.053
S	6.77±0.187^{a}	0.917±0.081^{d}	ND	4.77±0.502^{c}	ND	4.01±0.022
B45	6.75±0.174^{a}	3.78±0.192^{b}	0.118±0.038	24.6±0.975^{a}	0.278±0.074^{a}	4.01±0.018
B90	5.92±0.344^{b}	2.65±0.128^{c}	ND	11.3±0.364^{b}	ND	4.02±0.040
SB45	6.72±0.132^{a}	3.45±0.316^{b}	0.218±0.051	5.24±0.318^{c}	0.122±0.023^{b}	3.97±0.050
SB90	6.77±0.138^{a}	7.97±0.320^{a}	0.196±0.046	5.80±0.675^{c}	0.080±0.005^{b}	4.15±0.071
p	***0.004***	***<0.001***	*0.144*	***<0.001***	***0.017***	*0.080*

$^{a-c}$ The means that do not share a common superscript on the same column are significantly different. Data are presented as mean ± SEM (n=7). Abbreviations: B45: group supplemented with 45 mg/kg boric acid; B90: group supplemented with 90 mg/kg boric acid; C: Control; ND: No data (analysis performed; value determined as zero); S: group supplemented with 1% sodium chloride; SB45: group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: group supplemented with 90 mg/kg boric acid and 1% sodium chloride.

$^{a-c}$ Aynı sütunda ortak üst simgeyi paylaşmayan ortalamalar istatistiksel olarak farklıdır. Veriler ortalama ± SEM (n=7) olarak sunulmuştur. Kısaltmalar: B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; ND: Veri yok (analiz yapıldı; değer sıfır olarak belirlendi); S: %1 oranında sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup; SB90: 90 mg/kg borik asit ile %1 sodyum klorür ilave edilen grup.

Additionally, lactic acid content varied with the addition of boric acid and sodium chloride. At the end of the trial, lactic acid concentrations were significantly higher in the B45, SB45, and SB90 groups than in the C group, whereas the S group showed a decrease. The highest lactic acid concentration was observed in SB90 ($p < 0.001$). Acetate content was higher only in B45 and B90 groups compared to C, while other groups were unaffected by additive application. For butyrate, three groups (C, S, and B90) had undetectable levels and were excluded from

statistical analysis; among the remaining groups (B45, SB45, SB90), B45 had significantly higher concentrations than the others ($p < 0.05$). No significant differences were observed among groups for propionate or pH levels.

Sensory Characteristics

Sensory evaluation results indicated no significant differences among groups in odor and appearance scores (Table 3, $p > 0.05$). However, color scores differed significantly, with the highest value recorded in the SB90 group ($p < 0.001$). Compared to SB90, both B45 and SB45 exhibited lower color scores.

Table 3. Sensory characteristics of high moisture corn silages treated with different additives
Çizelge 3. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının duyusal özellikleri

Group *Grup*	Odor *Koku*	Appearance *Tekstür*	Color *Renk*
C	10.3±1.19	3.43±0.369	1.43±0.130^{bc}
S	10.4±0.685	2.64±0.322	1.36±0.092^{bc}
B45	11.7±0.522	3.24±0.297	1.57±0.136^{b}
B90	10.8±0.558	3.43±0.270	1.55±0.140^{bc}
SB45	8.86±1.37	2.71±0.421	1.21±0.101^{c}
SB90	10.3±1.08	3.14±0.261	2.00±0.000^{a}
p	*0.466*	*0.376*	***<0.001***

$^{a-c}$ The means that do not share a common superscript on the same column are significantly different. Data are presented as mean ± SEM (n=7). Abbreviations: B45: group supplemented with 45 mg/kg boric acid; B90: group supplemented with 90 mg/kg boric acid; C: Control; S: group supplemented with 1% sodium chloride; SB45: group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: group supplemented with 90 mg/kg boric acid and 1% sodium chloride.
$^{a-c}$ Aynı sütunda ortak üst simgeye sahip olmayan ortalamalar istatistiksel olarak farklıdır. Veriler ortalama ± SEM (n=7) olarak verilmiştir. Kısaltmalar: B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; S: %1 oranında sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür birlikte ilave edilen grup; SB90: 90 mg/kg borik asit ile %1 sodyum klorür ilave edilen grup.

Flieg Scores, Aerobic Stability, and Mold Counts

Regarding Flieg scores, which reflect overall silage quality, only the SB90 group showed significantly lower values compared to the other groups and the control (Figure 1).

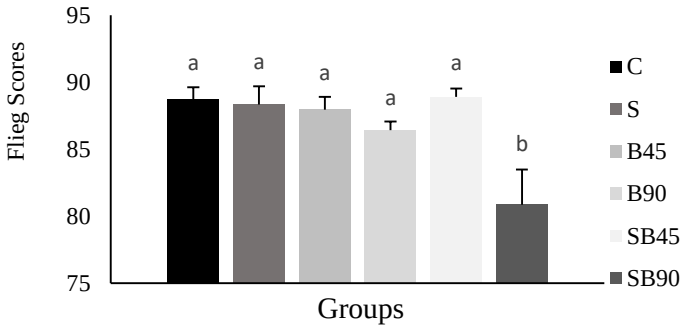

Figure 1. Flieg points of high moisture corn silages treated with different additives. Abbreviations: B45: group supplemented with 45 mg/kg boric acid; B90: group supplemented with 90 mg/kg boric acid; C: Control; S: group supplemented with 1% sodium chloride; SB45: group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: group supplemented with 90 mg/kg boric acid and 1% sodium chloride; *p= 0.002.*

Şekil 1. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının Flieg puanları. Kısaltmalar: B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; S: %1 oranında sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup; SB90: 90 mg/kg borik asit ile %1 sodyum klorür ilave edilen grup; p= 0.002.

A similar trend was observed for aerobic stability, with additive-treated groups generally higher than the control. The lowest CO_2 production values were observed in B45, SB45, and SB90 (Figure 2). When comparing the S and B90 groups, CO_2 production was lower in the group supplemented with 90 mg/kg boron.

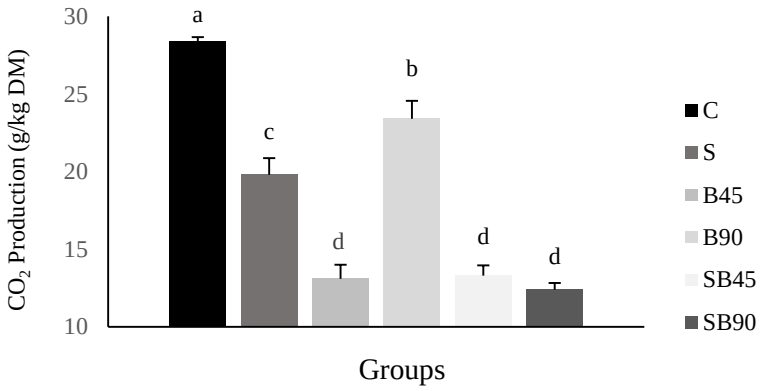

Figure 2. CO_2 production of high moisture corn silages treated with different additives. Abbreviations: B45: group supplemented with 45 mg/kg boric acid; B90: group supplemented with 90 mg/kg boric acid; C: Control; S: group supplemented with 1% sodium chloride; SB45: group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: group supplemented with 90 mg/kg boric acid and 1% sodium chloride; $p < 0.001$.

Şekil 2. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının CO_2 *üretimi. Kısaltmalar: B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; S: %1 oranında sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup; SB90: 90 mg/kg borik asit ile %1 sodyum klorür ilave edilen grup; $p < 0.001$.*

Relative Feed Values

Feed value parameters, including dry matter digestibility (DMD), dry matter intake (DMI), and relative feed value (RFV), differed significantly among groups (Table 4, $p < 0.05$).

Table 4. Relative feed values of high moisture corn silages treated with different additives
Çizelge 4. Farklı katkı maddeleri ile muamele edilmiş yüksek nemli mısır silajlarının nispi yem değerleri

Group *Grup*	DMD (%)	DMI (%, body weight) *(%, canlı ağırlık)*	RFV
C	65.7±0.288^{ab}	2.41±0.023^{a}	123±1.62^{a}
S	64.9±0.103^{c}	2.45±0.026^{a}	123±1.41^{a}
B45	66.3±0.134^{a}	2.42±0.048^{a}	124±2.52^{a}
B90	65.0±0.288^{bc}	2.25±0.020^{b}	113±1.44^{b}
SB45	65.6±0.240^{ab}	2.38±0.013^{a}	121±0.713^{a}
SB90	65.2±0.283^{bc}	2.37±0.011^{a}	120±0.692^{a}
p	***0.002***	***<0.001***	***<0.001***

$^{a-c}$ The means that do not share a common superscript on the same column are significantly different. Data are presented as mean ± SEM (n=7). Abbreviations: B45: group supplemented with 45 mg/kg boric acid; B90: group supplemented with 90 mg/kg boric acid; C: Control; DMD: Dry matter digestibility; DMI: Dry matter intake; S: group supplemented with 1% sodium chloride; SB45: group supplemented with 45 mg/kg boric acid and 1% sodium chloride; SB90: group supplemented with 90 mg/kg boric acid and 1% sodium chloride; RFV: Relative feed value.

$^{a-c}$ Aynı sütunda ortak üst simgeyi paylaşmayan ortalamalar istatistiksel olarak farklıdır. Veriler ortalama ± SEM olarak sunulmuştur (n=7). Kısaltmalar: B45: 45 mg/kg borik asit ilave edilen grup; B90: 90 mg/kg borik asit ilave edilen grup; C: Kontrol; DMD: Kuru madde sindirilebilirliği; DMI: Kuru madde tüketimi; S: %1 oranında sodyum klorür ilave edilen grup; SB45: 45 mg/kg borik asit ve %1 sodyum klorür ilave edilen grup; SB90: 90 mg/kg borik asit ile %1 sodyum klorür ilave edilen grup; RFV: Nispi yem değeri.

The highest DMD was 66.3% in the B45 group, followed by C and SB45. The lowest digestibility (64.9%) was recorded in the S group, and this change was statistically significant only when compared to C. Regarding DMI and RFV, a significant decrease was observed only in the B90 group; all other groups had similar DMI (approximately 2.37–2.42%) and RFV (approximately 120–123) values.

DISCUSSION

This study investigated the effects of different levels of boric acid and/or sodium chloride on the quality, fermentation characteristics, mold counts, and relative feed value of high-moisture corn silage. The findings indicate that both boric acid and sodium chloride, applied individually or in combination, have multifaceted effects on the nutritional value, stability, and microbial safety of high-moisture corn silage. From a practical and economic

standpoint, boric acid and sodium chloride are affordable, readily applicable additives for silage producers. Their widespread availability and low cost make them suitable for routine use, while their potential to enhance fermentation quality and nutrient preservation may reduce feed losses and improve overall silage value (Yitbarek & Tamir, 2014; Al-Amery & Khrbeet,2025). High-moisture corn silage exhibits certain compositional differences compared to conventional corn silage. In the present study, the mean values for dry matter (DM), crude protein (CP), ether extract (EE), NDF, ADF, and ash were 20.9%, 12.1%, 3.78%, 51.3%, 30%, and 7.21%, respectively. Previous studies evaluating nutrient composition of corn silages report that when silage DM is below 25%, average CP is ~10%, EE 2.6%, NDF 49.3%, ADF 27%, and ash 4.8%; nutrient quality tends to decline as DM increases (Andrieu, 1976; Kamalak et al., 2003; Salgado, 2013; Jatkauskas et al., 2024). In particular, corn harvested before the optimal stage with low DM (~16.4%) may have CP contents up to 11.1% or higher (Sarwatt et al., 1989).

Chemical analysis indicated that the addition of boric acid and sodium chloride increased EE, NDF, ADF, and ash content in corn silage. Although these increases do not necessarily indicate a negative effect, they reflect changes that could affect silage quality. EE levels differed among groups: decreases were observed in groups receiving high-dose boric acid or in combination with sodium chloride, while the control and low-dose boric acid groups maintained higher EE levels. To date, no studies have evaluated the effects of boric acid and/or sodium chloride on EE content in silage. Studies on the effects of organic acid additives on corn silage reported that formic acid (4 g/kg) increased EE, whereas combinations of formic, acetic, and propionic acids did not alter EE levels (Jiang et al., 2020; Gheller et al., 2021). These findings suggest that high levels of boric acid may either directly promote lipid degradation or inhibit microbial enzymes that protect lipids, reducing lipid solubility. In contrast, low-dose boric acid may help preserve lipids by maintaining microbial balance, similar to other acidifying additives such as propionic and butyric acids (Heimann et al., 2015; Cate et al., 2024). Sodium chloride, applied alone or with boric acid, may have indirectly reduced EE by osmotic effects, altering microbial activity responsible for lipid breakdown (Rojas and Huang, 2018).

ADF and NDF are critical parameters for evaluating silage quality as they reflect structural carbohydrate levels and directly affect chewing time, rumen function, and feed intake. In the present study, NDF content differed among groups, with the highest value observed in the group receiving 90 mg/kg boric acid; no significant differences were observed among the other groups. Differences in ADF were limited, with only the 1% sodium chloride (S) group showing significantly higher ADF compared to the control. Additionally, the B45 group (45 mg/kg boric acid) had lower ADF than the high-dose boric acid (B90) and boric acid plus sodium chloride (SB90) groups. While acidifying additives such as formic, citric, and malic acids often decrease NDF and ADF, similar findings to the present study have been reported (He et al., 2020; Zhao et al., 2021; Zi et al., 2021; Qui et al., 2024). These results suggest that high levels of boric acid may suppress microbial enzymes responsible for fiber degradation, thereby reducing the solubility of cell wall components. Although no studies have directly examined boric acid's effect on silage microbiota, in vitro studies suggest that high concentrations (e.g., 5 g/L) may inhibit cellulolytic bacteria (Cate et al., 2024). Sodium chloride had no pronounced effect on NDF, indicating a weaker influence on fiber fractions.

Ash content, reflecting total mineral content and digestibility, showed limited differences among additive-treated groups. Only the B90 group exhibited a significant increase compared to the control, while ash levels in the SB90 group decreased compared to the B90. Studies on organic acid additives show inconsistent effects on ash content, often linked to DM content, with higher DM correlating with higher ash due to residual inorganic material (Jiang et al., 2020; Gheller et al., 2021; Zhao et al., 2021; Sevim et al., 2023).

Understanding additive effects on fermentation parameters is essential for improving silage quality. In this study, ammonia levels were significantly increased in all additive-treated groups except B90, indicating accelerated protein breakdown or nitrogen transformation (Dai et al., 2022). While other acidifying additives typically reduce ammonia and improve silage quality (Zhang et al., 2018; He et al., 2020; Zhao et al., 2021; Zi et al., 2021; Lei et al., 2024), the observed increase suggests enhanced microbial activity, accelerating protein degradation. The absence of this increase in B90 may indicate microbial suppression by high-dose boric acid, consistent with other studies on acidified silages (Muck, 2010; Qui et al., 2024).

Lactic acid content was also influenced by additive application. Increased lactic acid levels in B45, SB45, and SB90 compared to control suggest stimulation of homofermentative lactic acid bacteria (Lei et al., 2024). The highest lactic acid in SB90 indicates a synergistic effect of boric acid and sodium chloride on fermentation (Woolford, 1978). Conversely, decreased lactic acid in the S group suggests that sodium chloride alone may negatively affect fermentation or fail to support the desired growth of lactic acid bacteria. Acetate, produced mainly by heterofermentative bacteria, contributes to aerobic stability. Significant increases were observed only in B45 and B90, suggesting dose-dependent stimulatory effects on heterofermentative bacteria. Butyrate, generally produced by *Clostridium* species and indicative of spoilage, was measurable only in B45, SB45, and SB90, with B45 showing

the highest levels. This implies that low-dose boric acid did not sufficiently suppress butyric acid activity, while sodium chloride alone did not induce butyrate formation; combining boric acid and sodium chloride increased butyrate formation, warranting further investigation.

Sensory properties, including color, odor, and appearance, are important indicators of feed quality and directly affect animal intake and acceptance (Kılıç, 1984; Canibe et al., 2014; Yörük et al., 2014; Koc et al., 2020; Agma Okur et al., 2022; Uygur, 2025). In this study, the SB90 group showed improved color, suggesting that high-dose boric acid and sodium chloride stabilized pigments and/or prevented oxidative color deterioration. Flieg scores, a key measure of silage quality, differed among treatments, with SB90 exhibiting lower scores, indicating potential negative effects of high-dose combinations. Besides, while additive-treated groups generally had lower CO_2 production, B45, SB45, and SB90 showed the highest stability, suggesting certain combinations may inhibit aerobic spoilage.. Interestingly, B90 showed greater aerobic stability than S, suggesting a dose-dependent protective effect of boric acid. The present study was performed under laboratory-scale ensiling conditions, which may not fully reflect practical farm applications. Furthermore, the absence of animal performance data limits the ability to extrapolate the observed effects on silage quality to ruminant productivity. The long-term impacts of boric acid and sodium chloride supplementation also remain uncertain. In addition, the antimicrobial effects of their use are likely to vary depending on microbial species and additive dosage, thereby introducing variability into silage fermentation outcomes.

CONCLUSION

The findings of this study demonstrate that applying boric acid at a low dose (45 mg/kg) generally improved the digestibility of high-moisture corn silage, thereby enhancing its nutritional value, and aerobic stability while simultaneously reducing mold development and supporting microbial safety. In contrast, higher levels of boric acid and/or its combination with sodium chloride partly exerted negatively affected certain quality attributes Flieg sores and RFV. These results suggest that boric acid, when applied at an appropriate dosage, has potential as a silage additive. However, its use requires careful optimization to prevent adverse impacts on fermentation quality. Future investigations should extend beyond laboratory-scale evaluations to farm-scale applications, incorporate assessments of long-term effects on ruminant performance, and employ molecular and metagenomic techniques to elucidate the influence of boric acid on the silage microbial community.

ACKNOWLEDGMENTS

We would like to express our gratitude to ERTETA Tarım, a staff member of Associate Professor Cihat Yıldız, who supported us by providing silage materials from his own silage production and packaging facility.

Contribution Rate Statement Summary of Researchers

The authors declare that they have contributed equally to the article.

Conflict of Interest

The authors of the articles declare that they have no conflict of interest.

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