Precision Mulching: Boosting Nutritional Content of Wheat Herbage through Timing and Application Rate Control

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Abstract

Wheat (*Triticum* spp.) is one of the most diverse and substantial families, Poaceae, which provides about 20% of food energy and protein worldwide. Wheat is also highly palatable and an excellent digestible energy source for farm animals. This research examined the effects of different rates of mulching (3, 6, and 9 t ha^{-1}) and application timing (sowing, stem elongation and heading) on the macro (N, P, K, Ca and Mg) and micro elements (Mn, Na, Cu, Fe and Zn) of durum wheat variety (*Triticum durum* Desf.) and milk fever (Ca/P) and tetany (K/(Ca + Mg)) contents under Mediterranean ecological conditions. This study was conducted in a randomized complete block design with 4 replications in 2016 and 2018. The study results revealed significant differences in the wheat macro and microelement contents, where the most effective mulch rates for plant nutrition were 3 and 6 t ha^{-1}. The highest positive correlations were observed between Ca and Mg, and Mn and milk fever. In contrast, Tetany, Ca, and milk fever had the most negative correlations, where Cu and milk fever also had a significantly negative correlation ($p \le 0.01$). Mulching increased the macro- and micro-nutrients of the wheat compared to the control at all application times.

1. Introduction

Over the past two decades, the shift toward conventional agriculture has intensified efforts to meet the growing demand for animal feed. Producing on-farm feed has become a priority as it can significantly reduce feed costs, one of the most substantial expenses in livestock production, and help resolve roughage supply issues. Consequently, the cultivation of forage crops has increased to provide both affordable and high-quality roughage, which is essential in animal nutrition (Kizilgeci et al. 2021).

Among forage crops, durum wheat (*Triticum durum Desf.*) has become increasingly important due to its high yield and nutritional quality. Wheat grain (*Triticum spp.*) is a staple food that supplies approximately 20% of the world's food energy and protein. It is also highly palatable and a rich, digestible energy source for livestock. In 2007, 102 million tons, representing 16.7% of global wheat production, were used for animal feed, with even higher proportions in industrialized nations. For example, in the EU-27, 42% of wheat production was allocated to feed in 2007 (FAO 2011). Feed wheat typically includes surplus or low-quality grain unsuitable for human consumption (e.g., low test weight, damaged grain), although wheat is also grown specifically for feed purposes. When prices of maize, barley, or sorghum rise or wheat prices decline, wheat becomes a cost-effective alternative. In many countries, the use of homegrown feeds has gained popularity due to their lower costs, prompting greater inclusion of wheat in livestock rations.

Global warming and intensive land use have driven researchers and practitioners to seek alternative methods for fertilization, irrigation, pest management, and weed control. It is known that soil amendment methods have a significant effect on plant quality and development (Uslu et al. 2023). Mulching is a particularly effective practice that helps preserve soil moisture, protect plant roots from temperature extremes, enrich soil with nutrients and organic carbon, and suppresses weed growth (Awopegba et al. 2017). Organic plant residues, rich in nutrients and with high water-holding capacity, should be incorporated into the soil to promote soil health and sustainable productivity. A 22-year study evaluating various mulch applications (800–1600 kg ha^{-1}) and tillage methods showed significant improvements in soil physical and hydraulic properties (Kahlon et al. 2013). Mulching has also been shown to positively influence plant productivity, soil quality, and soil conservation (Battaglia et al. 2023; Erenstein 2002).

Improving soil stability requires increasing organic matter content, promoting aggregate formation, and maintaining plant residues in the field (Diatta et al. 2023; Ozlu et al. 2022). Studies have found that macroaggregates (> 250 μm) exhibit higher hydraulic conductivity and water content in the upper 10 cm of soil (Ozlu 2020). The incorporation of wheat stalks has been shown to reduce bulk density by 40–50%, increase water retention by 30%, and significantly improve aggregate stability, especially in the top 5 cm of soil. Mulch applications of 8- and 16-tons ha^{-1} increased the proportion of large macroaggregates (> 5 mm) by 6- and 12-fold, respectively, compared to control plots (Blanco-Canqui and Lal 2007). Similarly, straw mulch (6750 kg ha^{-1}) increased water use efficiency by 17% and winter wheat yield by 16% (Huang et al. 2005). Other studies have also reported significant improvements in crop yield, physiological traits, and soil health with mulch applications of 1500–5000 kg ha^{-1} (Stagnari et al. 2014). The effectiveness of mulch in stabilizing wheat yield and water use efficiency across years of variable rainfall and drought has been well documented. For instance, mulch applications increased grain yield by 35% and water use efficiency by 25% compared to conventional systems (Chen et al. 2015). Studies across Asia, South America, and Africa have consistently shown that residue retention improves soil moisture and structure (Turmel et al. 2015). In contrast, without adequate soil moisture, photosynthesis and growth are suppressed, and chlorophyll content declines.

Macro- and micro-nutrients are also critical in livestock nutrition. These elements are vital for bone and tooth development, muscle and nerve function, growth, reproduction, digestion, regulation of osmotic pressure, and pH balance. Trace elements such as boron, iron, copper, cobalt, zinc, iodine, selenium, manganese, and molybdenum are essential for plant and animal health. Those like Ca, P, Mg, and Zn serve as structural components in the animal body. Electrolytes such as sodium, potassium, calcium, and magnesium play physiological roles in blood and tissue function. Minerals also act as enzyme activators and cofactors in metalloenzymes and hormones (MNL 2010). For example, calcium ions influence gene transcription and signal transduction (Hatfield and Gladyshev 2002), while calcium and phosphorus are crucial for skeletal development and cell signaling. Copper is essential for cuproenzymes and iron absorption, and enzymes such as CuZnSOD require both copper and zinc for function. Mineral deficiencies can be identified by reduced activity of metalloenzymes and lower concentrations of metalloproteins.

In the semi-arid Mediterranean climate, practices that conserve soil moisture during the rainy season and optimize its use from pre-flowering to harvest are essential. Further research is needed to explore optimal combinations of fertilization and mulching strategies. This study, therefore, aims to investigate the effects of various mulch application rates and different harvesting periods on the macro- and micro-nutrient contents of wheat grown under Mediterranean ecological conditions.

2. Materials and Methods

This study was conducted at the Field Crops Research Farm of Kahramanmaraş Sütçü İmam University for 3 years from 2016 to 2018 under rainfed conditions. The trial site is in a typical Mediterranean climate zone characterized by hot, dry summers and heavy winter rainfall. Long-term weather data (1981–2010) indicate that January is the coldest month (mean temperature: 4.7°C) and August the warmest (27.9°C), Table 1. During the first growing season (November 2016 to June 2017), total precipitation was 563.8 mm with a mean temperature of 12.6°C, while in the second growing season (November 2017 to June 2018), precipitation totaled 525.9 mm with a mean temperature of 18.3°C. These values were both drier and warmer than the long-term averages of 617.6 mm and 12.3°C, respectively.

Table 1
The climate values of the research region

	Total Precipitation (mm)				Mean Temperature (°C)			
	2016	2017	2018	Long Term	2016	2017	2018	Long Term
January	140.5	126.7	155.3	159.6	4.1	3.8	7.4	4.7
February	30.1	3.7	61.5	87.6	11.0	7.2	9.7	6.1
March	61.3	74.5	49.0	85.9	12.8	12.2	14.2	10.2
April	17.6	67.8	46.8	67.5	19.3	15.7	18.4	14.9
May	16.6	105.0	52.9	38.6	20.6	19.6	21.7	19.7
June	17.8	3.1	39.4	12.5	26.7	26.2	25.4	24.5
July	0.0	0.0	0.3	0.4	30.0	30.9	28.6	27.8
August	0.0	0.0	0.0	0.3	30.2	29.8	29.1	27.9
September	24.6	0.0	0.6	16.0	24.8	27.8	27.2	24.5
October	13.6	42.9	115.0	41.8	20.5	19.4	19.8	18.5
November	36.8	87.6	33.2	58.0	11.2	12.2	12.7	11.5
December	146.2	33.4	239.5	107.8	4.5	8.9	8.3	6.5

The soils of the Kahramanmaraş Plain consist of diverse groups, including red-brown, red Mediterranean, brown forest soils, alluvial, colluvial, and organic types. However, the dominant soil type is vertisol, due to its high clay and lime content. Soils at the 0–30 cm depth in the experimental site area were classified as sandy clay, with a sand content of 50–60%, pH 7.28, electrical conductivity 0.30%, lime content of 1–4%, organic matter below 2.0%, potassium at 98.25 mg kg^{-1}, calcium at 4856 mg kg^{-1}, and phosphorus at 7.75 mg kg^{-1} (Kara et al. 2021).

The experiment used the Balcali-85 variety of *Triticum durum* Desf. (Durum wheat), which is widely cultivated in Kahramanmaraş and the surrounding Eastern Mediterranean region for both grain (pasta production) and green forage. Under irrigated conditions, this variety yields 7.5–8 t ha^{-1} of grain, while under dryland conditions, yields range from 5.5–6 t ha^{-1}. Green forage yields reach 18–20 t ha^{-1}, with dry forage yields of 6–7 t ha^{-1} (Karabulut and Cacan 2018).

Experimental plots received wheat straw mulch applied by hand at four rates (0, 3, 6, and 9 t ha^{-1}) and during three phenological stages: sowing (S), stem elongation (SE), and heading (H). A factorial design with four replications was arranged in a randomized complete block design. Standard field preparation practices were followed: summer and autumn plowing, disc harrowing, rolling, and seeding with a mono machine. No irrigation or other agricultural treatments were applied. Plots measured 8 m × 1 m with a planting density of 500 plants m^{-2}. Sowing occurred each November, with 6 kg ha^{-1} of nitrogen and P_2O_5 applied at planting and an additional 8 kg ha^{-1} of nitrogen during the stem elongation stage.

Crop phenological stages were monitored using randomly labeled plants in each plot. Green herbage was harvested once at the grain-filling stage. In each plot, two 70 cm × 70 cm quadrats were randomly placed for sampling. The harvested plants were dried at 70°C, ground to a fine powder, and prepared for nutrient analysis. Nitrogen was determined using the modified Kjeldahl method (Bremner 1965). Potassium, Na, and Ca were measured using a flame photometer, while Mg, Fe, Zn, Mn, and Cu were analyzed with an atomic absorption spectrometer.

Data analysis was performed using SAS software (SAS 2014). Means were compared using the Least Significant Difference (LSD) test at $p < 0.05$. Pearson's correlation was used to examine relationships among chemical properties ($p < 0.05$). Discriminant analysis based on a correlation matrix was conducted using SPSS 15 software to explore similarities and differences across mulch doses and application times. The discriminant analysis included macro-elements (N, K, Ca, P, Mg), micro-elements (Zn, Mn, Cu, Fe), and selected nutrient ratios (Ca/P and K/(Ca + Mg)). All analyses were based on a sample size of n = 72. Figures were generated using Microsoft Excel 2010.

3. Results

This study investigated the nutritional properties of wheat green forages grown under varying mulch application timings and rates, focusing on macro- and micronutrient content. Over-cultivation and intensive management have reduced soil fertility and agricultural productivity. Mulching, a longstanding practice particularly valuable in subtropical and semi-arid regions, enhances soil fertility and water retention. In this study, the concentrations of macronutrients (nitrogen, phosphorus, potassium, calcium, and magnesium), micronutrients (sodium, iron, zinc, copper, and manganese), milk fever (Ca/P), and tetany (K/(Ca + Mg)) contents of durum wheat variety (*Triticum durum* Desf.) of wheat were measured. Mulching with wheat straw significantly affected the concentration of all elements except Mn and Cu, while the timing of mulching influenced the concentrations of K, P, Mg, Na, Fe, Zn, and Mn (Table 2; Figs. 1 and 2).

Table 2. The values of macro and micro elements of wheat grass according to two-year averages with mulching doses and application times

	N (%)	**K (%)**	**Ca (%)**	**P (%)**	**Mg (%)**	**Na (mg kg^{-1})**	**Fe (mg kg^{-1})**	**Cu (mg kg^{-1})**	**Zn (mg kg^{-1})**	**Mn (mg kg^{-1})**	**Ca/P**	**K/(Ca+Mg)**
Doses (t ha^{-1})												
Control	1.36 a	0.695 b	0.24 b	0.155 b	0.070 b	221.1 b	100.9 c	7.12a	24.62 b	24.67b	1.59 b	2.28 b
3	1.25 b	0.818 a	0.29 a	0.159 ab	0.102 a	241.9 b	139.7 a	6.78a	28.31 a	28.50a	1.83 a	2.12 bc
6	1.25 b	0.711 b	0.27 a	0.163 a	0.093 a	377.3 a	127.0 ab	7.03a	27.56 a	26.84a	1.69 b	2.05 c
9	1.33 a	0.785 a	0.24 b	0.165 a	0.080 b	256.3 b	115.1 bc	7.49a	27.54 a	26.72a	1.45 c	2.53 a
LSD	0.046	0.059	0.019	0.007	0.012	83.69	16.27	0.327	1.716	1.343	0.121	0.172
Times												
S	1.29a	0.79 a	0.27a	0.168a	0.097 a	258.0 ab	143.2 a	7.22a	29.28 a	27.54 a	1.59a	2.22a
SE	1.30a	0.76 a	0.26a	0.158b	0.086 b	235.8 b	114.4 b	7.18a	26.77 b	26.65 ab	1.70a	2.23a
H	1.29a	0.70 b	0.25a	0.156b	0.075 c	328.6 a	104.5 b	6.90a	24.97 c	25.84 b	1.63a	2.29a
LSD	0.040	0.051	0.017	0.006	0.010	72.48	14.09	0.283	1.486	1.163	0.105	0.149
CV (%)	5.17	11.46	10.74	6.57	20.19	44.96	19.86	6.78	9.36	7.41	10.90	11.30
D	**	***	*	*	***	*	***	ns	*	ns	***	*
AT	ns	*	ns	***	***	*	***	ns	***	*	ns	ns
D × AT	***	***	***	***	***	**	***	***	***	***	***	***

***Significant at $p \leq 0.001$; **Significant at $p \leq 0.01$; *Significant at $p \leq 0.05$; ┼ ns: No significant differences, D: Doses, AT: Application Times, S: Sowing, SE: Stem Elongation, H: Heading.

3.1. Macronutrients (N, P, K, Ca, and Mg) of durum wheat variety (*Triticum durum* Desf.)

Nitrogen concentrations in wheat varied from 1.15% to 1.46% (DM), below the optimum level of 2% for forage quality. The lowest N content (1.15%) was recorded with 3 t ha^{-1} mulch applied at stem elongation, while the highest (1.46%) was found with 9 t ha^{-1} applied at the same stage (Fig. 1a). Although mulch application timing did not significantly impact N content, mulch rate did, with lower N observed at 3 and 6 t ha^{-1}. Overall, 9 t ha^{-1} mulch applied at stem elongation improved N content by 8% over the control.

Phosphorus content in wheat plants ranged from 0.14% to 0.18% (DM), lower than optimal values, consistent with the soil's low available P (10.46 mg kg^{-1}). Mulch doses and application times significantly affected P concentrations ($p \leq 0.05$). The highest values were recorded at earlier growth stages with higher mulch rates (Fig. 1b).

Potassium concentrations in wheat ranged from 0.63% to 0.93% DM (Fig. 1c) and were significantly influenced by mulch dose and timing. The highest K levels were observed in mulch applied at sowing and stem elongation stages.

Calcium content ranged from 0.18% to 0.31% DM (Fig. 1d), increasing under 3- and 6-t ha^{-1} mulch applications, particularly at sowing and stem elongation. Application of 9-t ha^{-1} during heading significantly reduced the Ca content.

Magnesium concentrations ranged from 0.042% to 0.117% DM (Fig. 1e). Mulch applications at 3 and 6 t ha^{-1} improved Mg levels, particularly when applied at sowing. However, 9 t ha^{-1} applications showed diminishing returns, likely due to competition with increasing K content.

3.2. Micronutrients (Mn, Na, Cu, Fe, and Zn) of durum wheat variety (*Triticum durum* Desf.)

Zinc concentrations in wheat forage increased from 24.62 to 29.28 mg kg^{-1} DM with mulch, particularly at 3 t ha^{-1} applied at sowing (Fig. 1f).

Mn levels varied between 24.67 and 28.50 mg kg^{-1}, with moderate increases from mulching (Fig. 2a). While no statistically significant differences were found among mulch doses, application time influenced Mn uptake, with planting being the most effective.

Sodium concentrations increased with mulch application, ranging from 221.1 to 377.3 mg kg^{-1} DM, with a maximum value of 616.7 mg kg^{-1} observed at 6 t ha^{-1} applied at heading (Fig. 2b).

The Cu level ranged from 6.15 to 7.58 mg kg^{-1} DM, with the highest values recorded at 9 t ha^{-1} applied during stem elongation (Fig. 2c). No statistically significant differences were found among the treatments. However, all values were above the critical deficiency threshold.

Iron concentrations peaked at 3 t ha^{-1} mulch (202.7 mg kg^{-1}) at sowing, with the lowest value at 9 t ha^{-1} applied at heading (64.7 mg kg^{-1}), Fig. 2d. While mulch increased Fe content over the control, values remained within acceptable limits for forage (25–150 mg kg^{-1}).

3.3. Tetany (K/(Ca + Mg)) and Milk fever (Ca/P) contents of durum wheat variety (*Triticum durum* Desf.)

The K/(Ca + Mg) ratio exceeded the 2.2 threshold in both the control (2.28) and 9 t ha^{-1} treatments (2.53) (Fig. 2e). The lowest ratio was found in the 6 t ha^{-1} treatment at 2.05. Mulching had no statistically significant effect on D ($p < 0.05$) or D*AT interactions ($p < 0.001$).

The Ca/P ratio ranged from 1.45 to 1.83, with the highest values at 3 t ha^{-1} (Fig. 2f). The 3 t ha^{-1} treatment was 15% higher than the control and 26% higher than the 9 t ha^{-1} treatment. Although there were statistically significant differences at the $p < 0.001$

level in the applied dose and D*AT interactions, no statistically significant difference was found in the treatment by time ($p > 0.05$).

3.4. Nutrient correlations and discriminant analysis

Correlation analysis revealed significant positive associations between Ca, Mg, and Mn, while K and Na were negatively correlated with some micronutrients (Table 3). K concentrations in plants have a positive relationship with Mg, $P < 0.05$. The Ca had a positive correlation with Mg, Mn, Ca/P, and Fe, whereas Ca had a negative correlation with K/(Ca + Mg). Moreover, the P had a positive correlation with Zn, Mg, Fe, and Mn, whereas a negative correlation was observed with K/(Ca + Mg). The Na had a negative correlation only with Cu. However, Cu had a positive correlation with K/(Ca + Mg). Finally, K/(Ca + Mg) was negatively correlated with Mn and Ca/P (Table 3). This suggests potential antagonistic effects, particularly at higher mulch rates.

Table 3. Correlation matrix of macro-micro nutrients of durum wheat (Pearson) (n=72)

Variables	N (%)	K	Ca	P	Mg	Na	Fe	Cu	Zn	Mn	Ca/P	K/(Ca+Mg)
N (%)	**1**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K		**1**	ns	ns	0,646*	ns	ns	ns	ns	ns	ns	ns
Ca			**1**	ns	0,936**	ns	0,729*	ns	ns	0,868**	0,816**	-0,814**
P				**1**	ns	ns	ns	ns	0,911**	ns	ns	ns
Mg					**1**	ns	0,791**	ns	ns	0,852**	ns	-0,712*
Na						**1**	ns	-0,670*	ns	ns	ns	ns
Fe							**1**	ns	ns	0,880**	ns	-0,706*
Cu								**1**	ns	ns	-0,842**	0,639*
Zn									**1**	ns	ns	ns
Mn										**1**	ns	-0,706*
Ca/P											**1**	-0,803**
K/(Ca+Mg)												**1**

**Significant at $p \leq 0.01$; *Significant at $p \leq 0.05$; ┼ No significant differences are indicated by ns.

In the discriminant analysis, periods, sowing, stem elongation, and heading were categorized into separate groups (Fig. 3A). Regarding mulch doses, the 3, 6, and 9 t ha^{-1} applications formed a different group from the control area, with 3 and 6 t ha^{-1} applications clustering together (Fig. 3B). Discriminant analysis showed that sowing-stage mulch applications at 3 and 9 t ha^{-1} resulted in nutrient-rich forages, forming distinct clusters in multivariate space (Fig. 3). This analysis also showed slightly overlapping groups of samples (Fig. 3) corresponding to the interactions of sampling periods and mulching doses. The sample differentiation pattern concerning the chemical parameters is pronounced regarding the overlap of distinct periods and mulching doses in durum wheat data. Discriminant analysis concludes that the sowing period was the most suitable period in regard to increasing macro- and micro-nutrient concentrations by under mulch application at 3 t ha^{-1} than other doses.

4. Discussion

4.1. Macronutrients (N, P, K, Ca, and Mg) of durum wheat variety (*Triticum durum* Desf.)

Soils in these regions have been cultivated since ancient times, and they are, in general, low in nitrogen and carbon (Babur et al. 2021). Adding organic matter to the soil prolongs the supply of nutrients through gradual decomposition, but it may also delay the release of nitrogen to the plant. Previous studies (Tian et al., 1993; Guo et al., 2019) support our findings, showing that mulching can improve N content when applied with adequate organic materials. However, excessive mulching may lead to N immobilization, reducing plant uptake. Nitrogen in forage is also affected by soil organic matter, which was relatively low (2.08%) in our study area. These deficiencies can adversely affect other nutrient uptakes, particularly phosphorus.

The study findings of P concentration align with Korkanç and Şahin (2021), who reported significant P increases with mulch type and dose. Other studies (Wang et al. 2016; Awopegba et al. 2017) also found mulch to improve plant P uptake. Feeding studies suggest that maintaining sufficient P (≥ 2.8 g P kg^{-1} DM) is essential for animal health (Valk and Sebek 1999), indicating that supplemental feeding may be needed when using wheat forage grown under these conditions.

The results suggest that early mulch application improves root uptake and maintains higher K availability in the rhizosphere. Mulching contributes to K supply not only by releasing K from the organic matrix but also by minimizing leaching losses. Akhtar et al. (2019) and Chrysargyris et al. (2017) showed similar results, emphasizing the role of organic mulches in nutrient retention. Adequate K is essential for osmotic regulation, enzyme activation, and stomatal function. Low K levels (< 1% DM) like those observed here can reduce drought resistance and biomass accumulation. An important consideration is the antagonistic relationship between K and Mg, as excessive K can inhibit Mg uptake. Thus, optimizing mulch rate is critical to avoid K-induced imbalances in nutrient acquisition.

Application of 9-t ha^{-1} at heading significantly reduced Ca content, probably due to reduced root uptake or cation competition. Ca plays a vital role in plant cell wall stability and stress signaling, and is a major nutrient required for skeletal development in animals. Despite being less mobile in plants, adequate root-zone availability is critical during vegetative growth. The positive Ca response to mulching may result from improved soil aggregation and moisture conditions that facilitate Ca mobility and root uptake (Nzeyimana et al., 2020). In livestock, forage Ca below 0.3% DM is considered deficient, especially for lactating cows. The drop in Ca content at high mulch rates applied late in the growth cycle suggests that mulching strategies should prioritize early applications to ensure optimal Ca nutrition.

Mg uptake is sensitive to K and Ca levels due to shared transport pathways (Rietra et al. 2017). Thus, while mulch increases Mg availability through mineralization, excessive mulch could indirectly suppress Mg through K dominance in the cation exchange complex. Grass tetany, a fatal metabolic disorder in ruminants, is directly linked to low forage Mg (< 0.2% DM) and high K levels. Mg deficiency is common in temperate and tropical grasses and has implications for animal health (Jumba et al. 1995). Given that most of our observed values fall below this threshold, livestock grazing on this forage may require mineral supplementation, particularly in early spring or periods of rapid growth.

4.2. Micronutrients (Mn, Na, Cu, Fe, and Zn) of durum wheat variety (*Triticum durum* Desf.)

Zn uptake is typically limited in alkaline soils or low-organic matter systems. Mulch improves Zn availability by increasing microbial activity and organic chelation. Adequate Zn is essential for enzyme function, immune system development, and reproductive performance in animals. Wheat forages with Zn levels below 20 mg kg^{-1} are considered deficient (Underwood and Suttle 1999). Thus, the increase from mulch is nutritionally meaningful. Similar trends were observed in maize and potatoes by Chaudhary et al. (2017) and Sorrato et al. (2020), respectively, showing mulch and fertilization synergistically enhance Zn uptake.

Although Mn concentrations are lower than those reported for other crops (Silva et al. 2014), they fall within acceptable forage nutrition ranges. Mn availability is governed by soil pH and redox potential, both influenced by mulch. Organic acids released during mulch decomposition may chelate Mn and enhance root uptake. Mn supports chloroplast structure and photosynthetic function in plants, while in animals, it is essential for bone development and enzyme systems. The observed values are sufficient for most livestock classes but may be suboptimal for high-yielding dairy herds. This highlights the need for periodic micronutrient assessments in forage production systems using organic amendments. For instance, the interaction between K and Mn uptake should be considered when formulating fertilizer regimes (Sorrato et al. 2020).

Sodium is not essential for plants but plays a key role in animal health, especially in regulating osmotic balance and nerve function. Mulching may indirectly enhance Na accumulation through improved soil moisture retention and ionic mobility. Mulching enhances Na uptake, potentially mitigating deficiencies commonly found in temperate pastures (Minson, 1990). While root crops, root by-products, and animal products are very high in sodium, most grains and plant protein sources (except sunflower) are relatively low in sodium (MNL 2010). In livestock nutrition, particularly in warm climates, forage with < 0.2 g Na kg^{-1} DM can result in hyponatremia. The values observed in this study suggest moderate improvements from mulch but may still necessitate salt supplementation for optimal animal performance.

Although not significantly different among treatments, all values were above the critical deficiency threshold; mulch dose and timing influenced trends. Animals grazing on pastures low in Cu see a fall in the pregnancy rate, whereas animals consuming large amounts of Cu may have symptoms including anorexia, diarrhea, and jaundice (Molin et al. 2021). Cu is also essential for iron metabolism, immune response, and fertility in livestock. Soil Cu availability is affected by pH and organic matter, both influenced by mulch. However, high soil Fe or Mo may antagonize Cu uptake in animals, even when plant Cu levels are adequate. Although changes were not documented for wheat, existing studies did report higher Cu leaf content with increasing K fertilizer doses for cassava (*Manihot esculenta*) and carrot (*Raphanus sativus* L.) (Fernandes et al. 2017; Gouveia et al. 2018). These findings support the conclusion that moderate mulch applications improve trace element density in forage, but holistic mineral management should also account for interactions among nutrients.

While the mulching application increased Fe content over the control. This can be attributed to increased organic acid production and improved moisture conditions that enhance Fe solubility in soils. Adding organic matter through cattle manure application raises leaf average Fe contents in Noni, 351.6–488.8 mg Fe kg-1 (Silva et al. 2014). Fe is the most abundant trace mineral in the animal body (Pasricha et al. 2021; Yang et al. 2023) and is essential for hemoglobin synthesis and oxygen transport. While forage Fe levels above 100 mg kg^{-1} are generally sufficient, excess Fe can hinder Cu and Zn absorption, emphasizing the importance of a balanced micronutrient profile.

4.3. Tetany (K/(Ca + Mg)) and Milk fever (Ca/P) contents of durum wheat variety (*Triticum durum* Desf.)

The K/(Ca + Mg) ratio exceeded the 2.2 threshold associated with grass tetany risk (Kemp and Hart, 1957) in both the control and 9 t ha^{-1} treatments. This suggests a potential imbalance in cation ratios that may affect livestock health. Mulch application timing and dosage must therefore be managed carefully to avoid cationic imbalances that compromise forage safety.

Calcium (Ca) and phosphorus (P) constitute approximately 70% of the mineral content in the animal body. Deficiencies or excessive consumption of these minerals can cause serious health problems and may have harmful or toxic effects. The Ca/P ratio is within or near the recommended range for livestock health (1.5–2.0), though ratios > 7:1 can induce milk fever (Buxton and Fales 1994). These ratios reflect nutritionally balanced forage, particularly under 3 t ha^{-1} mulch applications, and are important for preventing metabolic disorders such as milk fever or urinary calculi.

Our findings showed strong relationships between Ca and Mg, consistent with Kara et al. (2021), who reported a strong negative relationship between these elements. So, mulching significantly improved the macro- and micronutrient concentrations in wheat forages, particularly at 3 t ha^{-1} applied at sowing.

5 Conclusions

Mineral deficiencies in grazing animals—particularly of phosphorus, sodium, and zinc—are often linked to soils lacking available forms of these nutrients for plant uptake. Mulching nutrient-poor soils offers multiple benefits: it introduces organic matter, buffers against environmental stresses, and reduces water loss. In this study, varying mulch doses applied to soils low in organic matter and lime significantly influenced mineral uptake by wheat plants. The mulching applied to slightly alkaline soil (pH 7.28) enhanced nutrient availability and overall plant nutrition.

Results indicated that mulch applications altered the macro- and micronutrient composition of Durum wheat, with 3 and 9 t ha^{-1} doses being the most effective. Notably, planting concurrent with mulch application yielded the highest nutrient concentrations. This treatment enhanced fertility, promoted nutrient uptake, and increased forage quality. These improvements in nutritional quality suggest that mulching can help meet the dietary needs of grazing animals.

Overall, the use of shrub and herbaceous mulches represents a cost-effective and sustainable management practice promising to enhance soil fertility, increase productivity and wheat nutrient content, and support sustainable production systems—particularly for resource-limited farmers with minimal reliance on inorganic fertilizers.

Declarations

Competing interest

The authors declare no competing interests

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Author Contribution

O.S.U., E.B., E.O. wrote the main manuscript text, O.S.U., E.B.: prepared all Figures, Data Curation: C.Y., H.K., A.R.D., M.T., A.R.O., Review & Editing: A.R.D., M.T., A.R.O., Methodology, Review & Editing: E.B., E.O., H.K., Conceptualisation, Supervision: A.R.D., M.T., A.R.O, Writing—Review & Editing: O.S.U., C.Y., E.B., E.O., H.K., A.R.D., M.T., A.R.O.

Data Availability

No datasets were generated or analysed during the current study.

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Figures

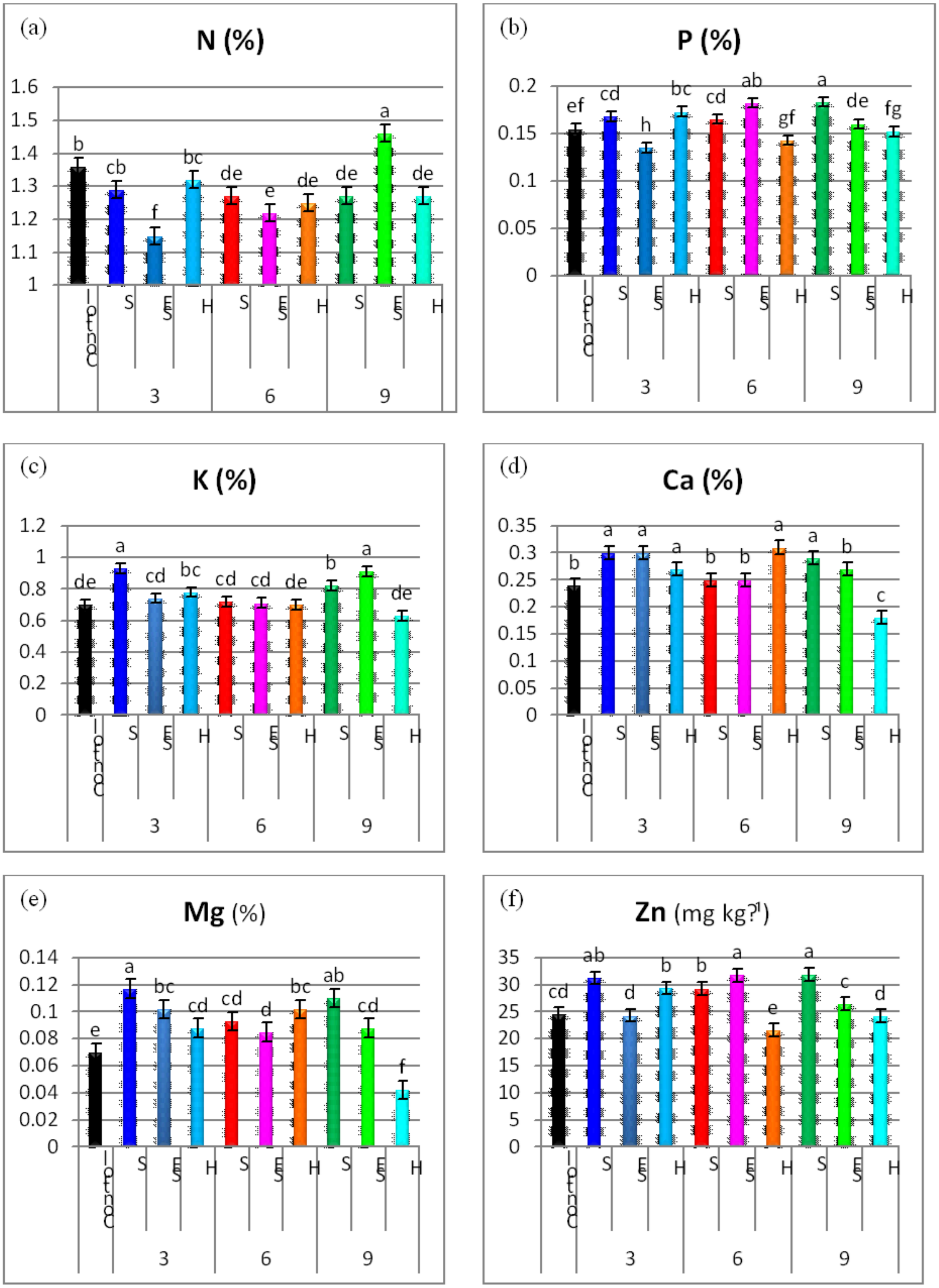

Figure 1

a-f. The comparisons of N, P, K, Ca, Mg, and Zn contents in wheat forage with mulch applications at different times and doses (Error bars shows ± standard errors. Different letters stand for statistically significant differences at p<0.05 (Fisher LSD test)).

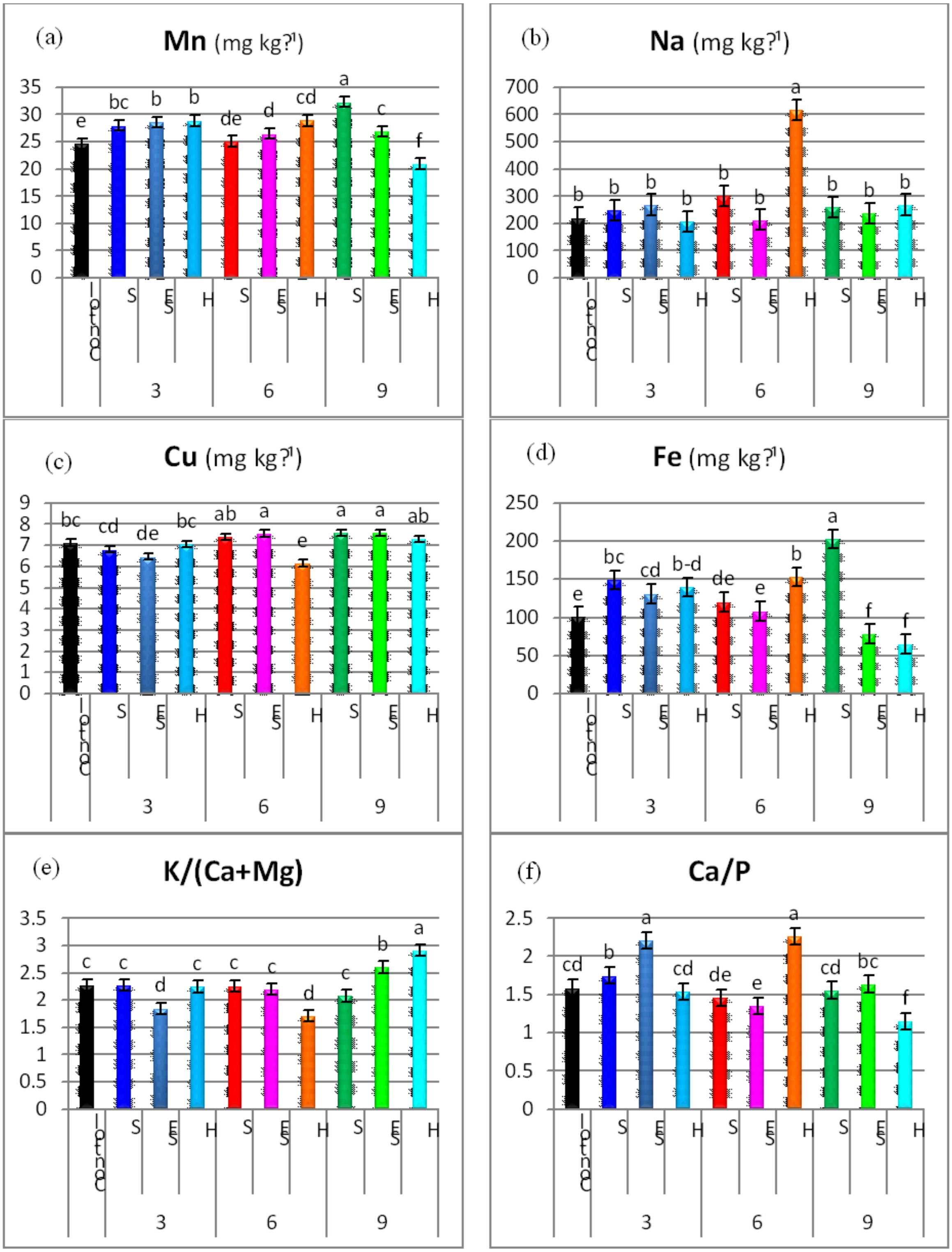

Figure 2

a-f. The comparisons of the mean of Mn, Na, Cu, Fe, K/(Ca+Mg), and Ca/P contents in wheat forage with mulch applications at different times and doses (Error bars shows ± standard errors. Different letters stand for statistically significant differences at $p<0.05$ (Fisher LSD test)).

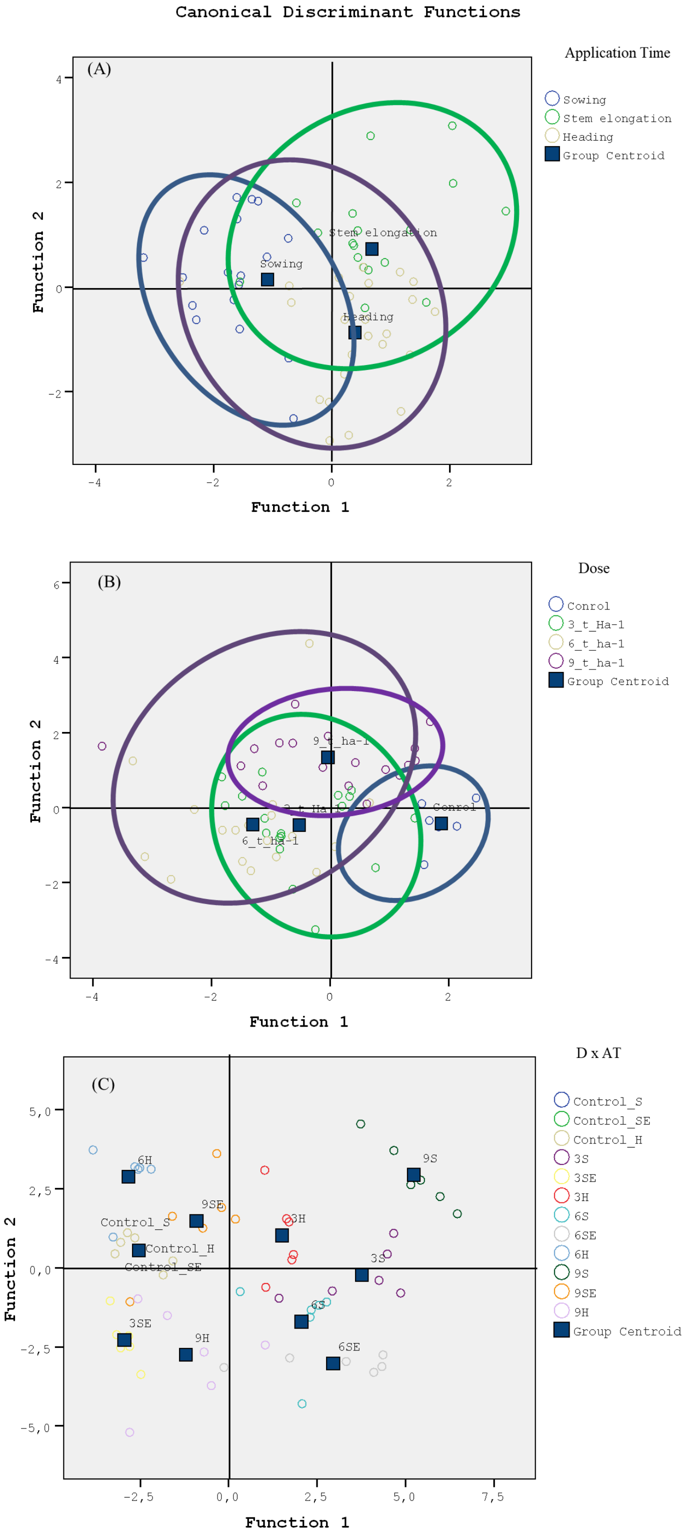

Figure 3

Discriminant analysis ordination diagram (F1 vs. F2) for chemical concentration variables collected from sites in different (A) Application Time, (B) Dose, and (C) Dose * Application time interaction.