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IMPACT OF DROUGHT STRESS AND PHOSPHORUS FERTILIZATION ON PRODUCTION AND QUALITY OF *ATRIPLEX NUMMULARIA* FODDER GROWN IN SALT-AFFECTED SOIL

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Abstract

The sustainable fodder production in salt-affected soils is essential for livestock farming in arid regions. Climate change-mediated drought stress is a major challenge, highlighting the urgent need to explore strategies such as phosphorus (P) fertilization to enhance resilience and productivity. This study investigates the effects of three drought stress levels, well-watered (100% field capacity, FC), moderately drought-stressed (80% FC), and severely drought-stressed (60% FC), and three P fertilizer rates (0, 50, and 100 mg kg^{-1} soil) on the productivity, nutritive value, and *İn vitro* digestibility of *Atriplex nummularia* fodder cultivated in semi-arid condition. Drought significantly reduced plant height, leaf area, chlorophyll contents and biomass production of *A. nummularia,* however, P fertilization enhanced drought tolerance. Drought stress also significantly lowered mineral uptake, higher concentrations of Ca (1.2%), P (0.9%), K (3.4%), Mg (0.9%), and Na (2.0%) were observed under well-watered conditions with P fertilization at 100 mg kg^{-1} of soil. Under drought, P fertilization increased crude protein (43%), fiber (30-33%), essential amino acids (44-47%) and non-essential amino acids (30-34%) concentrations, decreasing the adverse impacts of drought. Drought alone reduced fodder palatability by 31% and *İn vitro* digestibility by 18%. In contrast, P fertilization under drought improved palatability by 66% and digestibility by 32% compared to the non-fertilized drought control. The present findings demonstrate that P fertilization can significantly improve yield, nutritional quality, and digestibility of *A. nummularia* fodder under drought stress in salt-affected soil, offering a practical management strategy for arid-region livestock systems.

Key words: Acid detergent fiber; Fodder quality; *İn vitro* digestibility; Neutral detergent fiber; Oldman saltbush

Introduction

Drought is one of the main impacts of climate change, with drought events tripled in frequency over the last 30 years (Dahri *et al.,* 2021). Droughts directly impact agricultural production and quality (King-Okumu, 2021). These climate change associated changes demand to develop new approaches to mitigate the negative impact of drought. Phosphorus (P) is major plant nutrient involved in several crucial roles in crop production. P fertilization plays an important role in mitigating the adverse effect of drought by enhancing plant growth, leaf water contents, photosynthetic efficiency and antioxidant enzyme activities (Tariq *et al.,* 2017; 2018). The impact of water levels on P availability and plant uptake is well documented, water stress generally leads to reduction in P availability and plant uptake (Farooq *et al.,* 2019; 2020; 2025).

Salinization is a global issue affecting over 100 countries, from temperate to tropical zones, (Foster *et al.,* 2018; Singh, 2018). Saline soils have high concentration of dissolved salts in soil profile which directly influence crop production (Wong *et al.,* 2010). In Pakistan, most of the agriculture land is saline-sodic and about 25% of yield loss in major crops is only due to salinity (Kahlown & Azam, 2002).

Atriplex nummularia L., belonging to the family Amaranthaceae and also known as oldman saltbush, is a potential forage crop for arid areas. *A. nummularia* plants effectively improve soil quality and reduce toxic elements in metal-contaminated soils, offering a safe and effective phytoremediation technique (Ding *et al.,* 2020). Repeated seasonal grazing positively impacts *A. nummularia* shrub growth, fodder production and plant compactness (Ruiz-Mirazo & Robles, 2011). *A. nummularia* shrubs provide good quality food for arid zones, with high crude protein content and digestible energy for goats (Colomer & Passera, 1990). Fodder shrub plantations in semi-arid areas significantly increase soil sodium adsorption ratio (SAR) and organic carbon (OC) in the top layer (0-10 cm) (Zucca *et al.,* 2013). Feeding *A. nummularia* alone can maintain dwarf goats on salt-affected lands, with supplementation needed for growth and maintenance (Nawaz *et al.,* 1994). *A. nummularia* leaves and twigs provide valuable fodder for sheep in shrub lands, but their phosphorus (P) content is insufficient to meet nutritional needs and their sodium

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content exceeds their maximum dietary sodium requirements (El-Shatnawi & Turuk, 2002). Young and well-developed *A. nummularia* plantations have the strongest impacts on soil and landscape functions, mainly due to the localized synergistic effect (Zucca *et al.,* 2013).

A. nummularia is a versatile species that promotes ecosystem function, serves as a food source for mammals and arthropods, and can be used for phytoremediation and renewable energy in low-rainfall regions (Walker *et al.,* 2014). Studies have revealed that water stress reduce the growth of all plant parts of *A. nummularia* (Trione & Passera, 1993). In Pakistan, *A. nummularia* has recently been introduced as an invasive weed and has spread in various locations due to its strong adaptability to local agro-ecological conditions. Large variation in sensitivity of Atriplex species to herbicides such as desmedipham, dimethenamid-P, ethofumesate, lenacil, metamitron, phenmedipham, and triallate makes it difficult to control (De Cauwer *et al.,* 2018). We hypothesized that P fertilization in *A. nummularia* can help reduce the impact of drought and support its sustainable production. Weeds are considered more resilient to the effects of climate change and can be managed non-chemically by utilizing them as fodder for livestock (Farooq *et al.,* 2021; Abbas *et al.,* 2024; Abbas *et al.,* 2025). *A. nummularia* has spread in arid regions that are more prone to drought stress and have saline soils. Studies on the role of P fertilization in mitigating the negative impact of drought stress on *A. nummularia* are currently lacking. Therefore, this study was designed with the following objectives: 1) to assess the impact of varying levels of drought stress on *A. nummularia;* 2) to evaluate the effectiveness of phosphorus fertilization in enhancing drought tolerance and production of *A. nummularia;* and 3) to investigate the effects of stress conditions on the nutritive value, palatability and digestibility of *A. nummularia* fodder.

Material and Methods

Seed and soil collection: The *A. nummularia* fruits were collected in 2021 from the plants growing along road side uncultivated area near College of Agriculture (31.14°N, 72.69°E), University of Sargodha (UOS), Pakistan. Fruits were stored in well aerated dry conditions and in darkness for approximately 6 months until used. Salt-effected soil was collected from Soil Salinity Research Institute Pindi Bhattian (31.84°N, 73.25°E), Pakistan. Soil samples from various depths ranging from 0 to 45 cm were collected. The salt affected soil had following characteristics, ECe 17.13 dS m^{-1}, pH 8.6, organic matter 0.72%, available P 7.5 mg kg^{-1} and available potassium (K) 220 mg kg^{-1}. A method by Walkley and Black (1934) was followed to analyze soil organic carbon. The available soil phosphorus contents were analyzed by extracting soil with 0.5M $NaHCO_3$ (pH 8.5) following procedure of Olsen *et al*., (1954) procedure. Soil EC was measured by taking extract from saturated soil paste by following the procedure of Dellavalle (1992). Soil pH was measured using procedure of Dellavalle (1992).

Experimental design and treatment plan: The soil was dried in the air and sieved to remove large size particles of soil and other materials. Pots of 12 cm square size with 25 cm depth were filled with 10 kg of soil. The experiment was laid out in a completely randomized design (CRD) with three replicates. Experiment was conducted and *A. nummularia* was sown as a test crop. Three pre-germinated seeds of *A. nummularia* were sown in each pot, and one plant per pot was maintained after 14 days. Drought stress was applied after the formation of a uniform stand, depending on the soil's water retention capacity. Three different moisture stress conditions including well-watered (D_1), moderately drought-stressed (D_2), and severely drought-stressed (D_3), respectively were kept at 100%, 80%, and 60% of field capacity (FC) in the controlled environment (Farooq *et al*., 2025). Soil moisture levels were adjusted daily based on gravimetric water content to maintain the target water stress condition throughout the experimental period. Two levels of P fertilizers were 50 mg P kg^{-1} of soil (P_1) and 100 mg P kg^{-1} of soil (P_2) were maintained along with control. Single superphosphate was used as a source of P fertilizer. Fertilizer treatments were incorporated in soil at the time of pots filling. The trial was conducted under greenhouse with seed sowing in the months of February 2022 and 2023. The greenhouse conditions maintained a daytime temperature of 15-25°C and a nighttime temperature of 10-28°C, with relative humidity of 30-60% during the day and 25-50% at night. At 120 days after sowing, the above ground portions of the plants were harvested. These samples were carefully washed with tap water, followed by a 0.1% HCl solution containing 0.01% non-ionic detergent, to eliminate inorganic surface deposits. After a final rinse with ultrapure water, the samples were oven-dried at 70°C until a constant weight was achieved to determine the dry biomass. Leaf chlorophyll content index was determined by using Opti-Sciences CCM-200 plus hand-held chlorophyll meters and leaf area (LA) was recorded by measuring tape.

Fodder nutritional quality analysis: To determine the nutritional quality of *A. nummularia* under different drought stress conditions and P fertilization, dried plant samples were digested with sulfuric acid and total P contents were measured by vanadate molybdate method by visible spectrometer (Jones *et al*., 1991). Atomic absorption spectrophotometer method was used to determine quantity of different minerals including calcium (Ca), P, K, magnesium (Mg) and sodium (Na) (Jones *et al*., 1991).

Neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were quantified with a FOSS Fibertec™ 8000 automatic fiber analyzer. The P concentration was determined using a FOSS Kjeltec 8400 Kjeldahl analyzer, following the method of Romero *et al.,* (2000). Water-soluble carbohydrates were analyzed by the phenol-sulfuric acid method. Essential and non-essential amino acids concentration of *A. nummularia* fodder was determined with standard acid hydrolysis followed by ion-exchange chromatography. The leaf samples were oven dried and exposed to acid hydrolysis in 6N HCl at 110°C for twenty-four hours under a N atmosphere to prevent oxidation. Than hydrolysates were filtered and evaporated to remove HCl, and reconstituted in a loading buffer. The analysis of amino acid was performed with Hilger Chromaspek Amino Acid Analyzer, using the method described by Guo *et al*., (2008). The lysine, methionine, alanine, and glutamine concentrations were quantified and expressed as a percentage of dry-matter.

Goats were used as test species to evaluate the palatability of *A. nummularia* fodder. The *A. nummularia* fodder was offered alongside the common alfalfa fodder over a period of a week. Goats behavior and preference for *A. nummularia* compared to alfalfa fodder was recorded. Palatability core was determined with range from 0 to 10

(0 preference; 10 maximum preference to eat). To determine the *in-vitro* dry matter digestibility of *A. nummularia*, rumen fluid was collected from four local goats. Goats were fed on the *A. nummularia* shrubs. Four runs were performed, one for each goat's rumen fluid. In each run, *A. nummularia* leaves were digested using the rumen fluid of one goat. *In vitro* true dry matter digestibility was determined using the procedure of Enri *et al*., (2020). The collected rumen contents were filtered and maintained at 39°C. Digestibility was estimated following the ANKOM procedure (ANKOM, 2017). This design resulted in a total of 16 replicates, comprising four plant samples and four rumen fluid sources.

Statistical analyses

Data collected from repeated experiments were pooled as no significant difference between two repetitions were observed. Analysis of variance was run on the data as a two factor analysis with Statistix 8.1 (Steel *et al.,* 1997). The mean values of each treatment were separated using the $p<0.05$ by Tukey HSD test for interactive effect of drought and P fertilization at $p<0.05$.

Results

***A. nummularia* growth and yield:** Soil moisture and P fertilizer levels showed statistically significant effect on height, leaf area, chlorophyll content index, biomass and dry matter % of *A. nummularia* (Table 1). Maximum plant height (35.2 cm), leaf area (120 cm^2), chlorophyll content index (86.42), biomass (10.5 g) and dry matter % (80.5) were achieved in those plants which were well-watered and fertilized with P at 100 mg kg^{-1} of soil. While the plants under severe drought stress and no P fertilizer application produced smaller plant height (18.8 cm), leaf area (46 cm^2), chlorophyll content index (55.32), biomass (3.4 g) and dry matter % (65.6) compared to other treatments. For example, at 0 mg P kg^{-1}, severe drought stress reduced the dry biomass of *A. nummularia* by 37% compared to the same P treatment under well-watered conditions. However, at 100 mg P kg^{-1}, this reduction was only 29%, demonstrating that P fertilization lessened the drought induced growth reductions.

Mineral concentrations of *A. nummularia* fodder: Soil moisture and P fertilizer levels had significant ($p<0.05$) effect on mineral concentrations of *A. nummularia* fodder (Table 2). Maximum Ca (1.2%), P (0.9%), K (3.4%), Mg (0.9%) and Na (2.0%) contents were achieved in pots which were well-watered and fertilized with P at 100 mg kg^{-1} of soil. While the plant under severe drought stress and without P fertilizer application produced minimum Ca (0.5%), P (0.4%), K (2.1%), Mg (0.3%) and Na (1.2%) compared to other treatments. A significant reduction in *A. nummularia* mineral concentration was recorded under drought, however pots treated with P at 100 mg kg^{-1} of soil showed less reduction under drought compared to pots without P fertilizer application.

Crude protein, fiber and ash percent *A. nummularia* fodder: All tested soil moisture regimes and P fertilizer levels caused significant ($p<0.05$) effect on crude protein, neutral detergent fiber, acid detergent fiber and ash percent of *A. nummularia* fodder (Table 3). Highest percentage of crude protein (15.2%) and ash (7.10%) were achieved in the plants that were well-watered and fertilized with P at 100 mg kg^{-1} of soil. However, the highest percentage of neutral detergent fiber (50%) and acid detergent fiber (30.87%) were observed under moderate drought condition with P at 100 mg kg^{-1} of soil. While the plants under severe drought stress and without P fertilizer application produced minimum Ca (0.5%), P (0.4%), K (2.1%), Mg (0.3%) and Na (1.2%) compared to other treatments. Fodder quality of *A. nummularia* was reduced under drought, plants treated with P at 100 mg kg^{-1} of soil showed less reduction in fodder quality under drought compared to without P fertilizer application.

Amino acids, palatability and digestibility of *A. nummularia* fodder: All tested soil moisture and P fertilizer levels showed statistically significant ($p<0.05$) effect on essential amino acids as well non-essential amino acids, palatability score and digestibility percentage of *A. nummularia* fodder (Table 4, Fig. 1). Highest percentage of essential amino acids (lysine 12.5% and methionine 8.7%), non-essential amino acids (alanine 18.3% and glutamine 22.1%), palatability score (6.8) and digestibility (67.3%) were recorded when plants were well-watered and fertilized with P at 100 mg kg^{-1} of soil. The lowest percentage of essential amino acids (lysine 8.1% and methionine 5.3%), non-essential amino acids (alanine 13.0% and glutamine 15.4%), palatability score (3.8) and digestibility (48.3%) were observed in plants subjected to severe drought stress and without P fertilizer application compared to other treatments. Drought stress also caused reduction in essential amino acids as well non-essential amino acids (%), palatability score and digestibility of *A. nummularia* fodder. However, plants treated with P at 100 mg kg^{-1} of soil showed less reduction for these traits under drought compared to pots with no P fertilizer application. In general, P fertilization enhanced the drought tolerance of *A. nummularia,* preserving fodder amino acid content, palatability and digestibility.

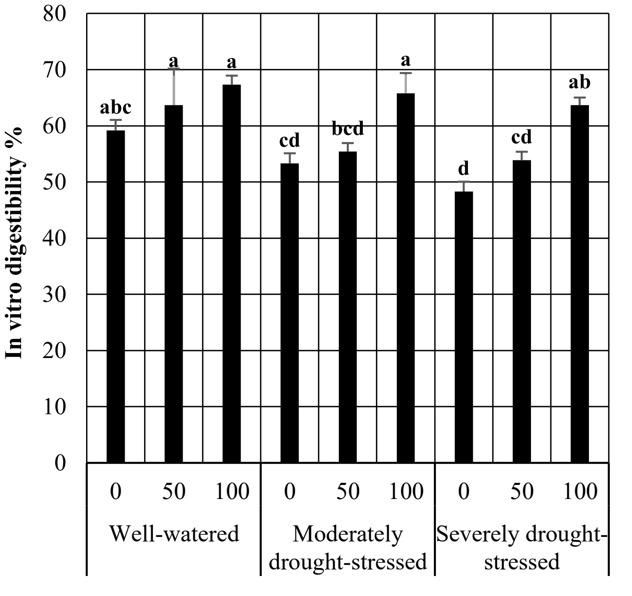

Fig. 1. Well-watered (100% FC), moderately drought-stressed (80% FC), severely drought-stressed (60% FC). FC: Field capacity. P fertilizer 0, 50 and 100 mg P kg^{-1} of soil. Bars show SE. Bars with different letters are indicating statistical difference in treatments at $p<0.05$ by Tukey HSD.

Table 1. The effect of drought and P levels on growth traits of *A. nummularia*.

Irrigation levels	P fertilizer (mg P kg^{-1} of soil)	Plant height (cm)	Leaf area (cm²)	Chlorophyll content index	Biomass (g)	Dry matter (%)
Well-watered	0	22.3 ± 1.68 de	65 ± 1.96 e	69.21 ± 1.90 c	5.4 ± 0.16 e	75.8 ± 2.29 bc
	50	27.8 ± 2.10 c	90 ± 2.71 c	76.21 ± 3.38 b	7.8 ± 0.24 c	78.2 ± 2.36 ab
	100	35.2 ± 2.66 a	120 ± 3.62 a	86.42 ± 2.37 a	10.5 ± 0.32 a	80.5 ± 2.43 a
Moderately drought-stressed	0	20.1 ± 1.52 f	55 ± 1.66 g	65.21 ± 1.79 cde	4.3 ± 0.13 g	72.5 ± 2.19 d
	50	22.6 ± 1.70 d	75 ± 2.26 d	68.23 ± 1.87 cd	4.8 ± 0.14 f	74.2 ± 2.24 cd
	100	31.5 ± 2.38 b	105 ± 3.17 b	75.41 ± 2.07 b	9.2 ± 0.28 b	79.5 ± 2.49 a
Severely drought-stressed	0	18.8 ± 1.42 f	46 ± 1.39 h	55.32 ± 1.74 f	3.4 ± 0.10 i	65.6 ± 2.06 f
	50	20.4 ± 1.54 ef	61 ± 1.84 f	60.23 ± 1.65 ef	3.9 ± 0.12 h	69.4 ± 2.18 e
	100	28.6 ± 2.16 c	89 ± 2.68 c	63.21 ± 2.37 de	7.4 ± 0.22 d	73.9 ± 2.32 cd

Well-watered (100% FC), moderately drought-stressed (80% FC), severely drought-stressed (60% FC). In a column different letters are indicating statistical difference in treatment means at $p<0.05$ by Tukey HSD. Data represent mean ± standard error (SE). FC: Field capacity

Table 2. The effect of drought and P levels on mineral concentrations of *A. nummularia* fodder.

Irrigation levels	P fertilizer (mg P kg^{-1} of soil)	Calcium (%)	Phosphorus (%)	Potassium (%)	Magnesium (%)	Sodium (%)
Well-watered	0	0.8 ± 0.03 cd	0.6 ± 0.022 d	2.7 ± 0.093 bc	0.5 ± 0.01 c	1.2 ± 0.031 c
	50	1.0 ± 0.10 b	0.7 ± 0.072 c	3.1 ± 0.318 ab	0.7 ± 0.07 b	1.6 ± 0.162 b
	100	1.2 ± 0.02 a	0.9 ± 0.016 a	3.4 ± 0.074 a	0.9 ± 0.02 a	2.0 ± 0.052 a
Moderately drought-stressed	0	0.6 ± 0.03 ef	0.4 ± 0.025 f	2.2 ± 0.090 d	0.3 ± 0.01 d	1.2 ± 0.031 c
	50	0.7 ± 0.02 de	0.5 ± 0.014 e	2.5 ± 0.069 cd	0.4 ± 0.01 cd	1.2 ± 0.031 c
	100	1.0 ± 0.04 b	0.8 ± 0.027 b	3.3 ± 0.0149 a	0.8 ± 0.05 ab	1.6 ± 0.106 b
Severely drought-stressed	0	0.5 ± 0.02 f	0.4 ± 0.022 f	2.1 ± 0.088 d	0.3 ± 0.01 d	1.2 ± 0.031 c
	50	0.6 ± 0.02 ef	0.5 ± 0.014 e	2.3 ± 0.063 cd	0.4 ± 0.01 cd	1.6 ± 0.042 b
	100	0.9 ± 0.01 bc	0.8 ± 0.01 b	3.2 ± 0.058 a	0.7 ± 0.02 b	1.6 ± 0.042 b

Well-watered (100% FC), moderately drought-stressed (80% FC), severely drought-stressed (60% FC). In a column different letters are indicating statistical difference in treatment means at $p< 0.05$ by Tukey HSD. Data represent mean ± SE. FC: Field capacity

Table 3. The effect of drought and P levels on quality traits of *A. nummularia* fodder.

Irrigation levels	P fertilizer (mg P kg^{-1} of soil)	Crude protein (%)	Neutral detergent fiber (%)	Acid detergent fiber (%)	Ash (%)
Well-watered	0	11.8 ± 0.46 e	35.0 ± 1.06 g	21.39 ± 0.64 c	5.89 ± 0.18 bc
	50	13.5 ± 0.41 c	40.2 ± 1.21 e	24.67 ± 2.57 bc	6.53± 0.68 ab
	100	15.2 ± 0.36 a	45.5 ± 1.37 d	27.80 ± 0.84 ab	7.10 ± 0.21 a
Moderately drought-stressed	0	9.5 ± 0.43 h	37.8 ± 1.14 f	23.10 ± 0.70 c	5.30 ± 0.16 cd
	50	10.5 ± 0.32 f	47.2 ± 1.42 c	28.84 ± 0.87 a	5.50 ± 0.17 cd
	100	14.3 ± 0.29 b	50.0 ± 1.51 b	30.87 ± 2.10 a	6.81 ± 0.47 ab
Severely drought-stressed	0	8.5 ± 0.37 i	38.5 ± 1.16 f	23.21 ± 0.70 c	4.10 ± 0.12 e
	50	9.9 ± 0.30 g	47.9 ± 1.44 c	28.88 ± 0.87 a	4.80 ± 0.14 de
	100	12.2 ± 0.26 d	51.2 ± 1.54 a	30.21 ± 0.93 a	5.89 ± 0.18 bc

Well-watered (100% FC), moderately drought-stressed (80% FC), severely drought-stressed (60% FC). In a column different letters are indicating statistical difference in treatment means at $p<0.05$ by Tukey HSD. Data represent mean ± SE. FC: Field capacity

Table 4. The effect of drought and P levels on amino acid %, palatability and digestibility of *A. nummularia* fodder.

Irrigation levels	P fertilizer (mg P kg^{-1} of soil)	Essential amino acids (%)		Non-essential amino acids (%)		Palatability score
		Lysine	Methionine	Alanine	Glutamine	
Well-watered	0	10.5 ± 0.31 bc	6.8 ± 0.21 bc	15.9 ± 0.45 bc	18.7 ± 0.56 bc	5.5 ± 0.19 bc
	50	11.8 ± 1.18 ab	7.9 ± 0.78 a	17.5 ± 1.74 ab	20.8 ± 2.09 ab	6.1 ± 0.62 ab
	100	12.5 ± 0.26 a	8.7 ± 0.16 a	18.3 ± 0.39 a	22.1 ± 0.47 a	6.8 ± 0.15 a
Moderately drought-stressed	0	9.2 ± 0.30 cde	5.8 ± 0.20 cd	13.8 ± 0.44 cd	16.3 ± 0.54 cd	4.5 ± 0.18 de
	50	9.8 ± 0.25 cd	6.3 ± 0.15 cd	14.5 ± 0.36 cd	17.2 ± 0.44 cd	5.1 ± 0.14 cd
	100	12.1 ± 0.60 a	8.3 ± 0.37 a	18.0 ± 0.90 ab	21.5 ± 1.07 a	6.5 ± 0.30 a
Severely drought-stressed	0	8.1 ± 0.29 e	5.3 ± 0.19 d	13.0 ± 0.43 d	15.4 ± 0.51 d	3.8 ± 0.17 e
	50	8.5 ± 0.21 de	6.0 ± 0.14 cd	13.5 ± 0.33 d	16.8 ± 0.43 cd	4.4 ± 0.12 de
	100	11.7 ± 0.20 ab	7.8 ± 0.13 ab	17.4 ± 0.32 ab	20.1 ± 0.39 ab	6.3 ± 0.10 ab

Well-watered (100% FC), moderately drought-stressed (80% FC), severely drought-stressed (60% FC). In a column different letters are indicating statistical difference in treatment means at $p<0.05$ by Tukey HSD. Data represent mean ± SE. FC: Field capacity

Discussions

Drought and salinity stress are among the major effects of climate change that can affect crop production globally. Current study assesses the impact of drought on *A. nummularia* fodder grown on salt affected soil and the role of P fertilization to reduce the adverse impacts of drought. Results revealed that drought stress caused significant adverse impact on *A. nummularia* growth, yield and quality traits. The P fertilization helped to reduce the effect of drought on *A. nummularia* grown in salt-effected soil. Plant height, leaf area, chlorophyll content index, biomass and dry matter % were reduced in *A. nummularia* under drought stress. This is because water plays a central role in several physiological processes and considered as most limiting factor in plant growth and biomass production (Farooq *et al.,* 2011). *A. nummularia* is a halophyte and can survive under drought and high EC conditions. However, De Melo (2018) reported reduced growth and biomass production of *A. nummularia* under drought and salt stress. P fertilization reduced the impact of drought on *A. nummularia* and exhbited better growth and biomass production. The application of P mitigated the negative effects of drought by improving photosynthetic efficiency and nutrient uptake, our results are consistent with previous findings (Tariq *et al*., 2017).

Drought stress reduced the mineral concentration of *A. nummularia* fodder, however application of P fertilizer reduced negative effect of drought on mineral concentration. Bouras *et al*., (2021) reported positive impact of P fertilization to reduce the effect of salinity stress on forage yield. Inhibitory effects of drought stress on nutritional value of corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) fodder have been reported (Safian *et al.,* 2022). Improved crop growth due to P fertilization reduced the adverse impacts of drought stress which contributed to better mineral composition of *A. nummularia* fodder (Tariq *et al.,* 2017; Tariq *et al.,* 2018; Farooq *et al.,* 2020; 2021).

The reduction in crude protein, neutral detergent fiber, acid detergent fiber and ash percentage observed in *A. nummularia* fodder under drought condition, along with the mitigation of these negative effects through P fertilization, can be justified with better growth and mineral concentration observed in this study. Neutral detergent fiber % was increased (38.5%) in drought stress compared to well water condition (35.0%). However, crude protein contents were reduced with increasing in drought intensity. Similarly, Tariq *et al*., (2017) reported that drought stress enhanced fiber %, while reduce protein content in corn and sorghum.

Concentration of essential and non-essential amino acids was also reduced with the increase in drought intensity, while P fertilization reduced the adverse impact of drought. This trend can be justified on the base of similar trend which has been observed for growth, biomass production, mineral concentration and crude protein contents in this study. Better performance of *A. nummularia* under drought stress with P fertilization contributed to enhanced percentage of essential and non-essential amino acids (Tariq *et al.,* 2017; De Melo *et al.,* 2018).

Fodder palatability and digestibility are of vital importance as they directly influence the consumption and utilization of fodder by livestock (Mertens & Grant, 2020). Better palatability and digestibility of fodder is crucial for optimizing animal nutrition and maximizing fodder use efficiency. Integrated impact of drought stress and P fertilization revealed that drought reduced the palatability *A. nummularia* fodder, while addition of P fertilization averted this negative impact of drought. More leaf area was achieved under P fertilized pots compared to non P fertilized pots possibly associated with better fodder palatability. Improved growth and fodder quality under P fertilized pots also contributed to better *A. nummularia* fodder palatability under severe drought stress conditions (Rossi *et al.,* 2023). The fodder digestibility of *A. nummularia* was also reduced with increasing drought stress and enhanced with increasing P fertilizer dose. The enhanced fiber contents observed in this study contributed to reduction in fodder digestibility (Ferreira *et al.,* 2023). In literature variable effects of drought stress have been reported on fodder digestibility. Whereas some studies revealed that drought stress enhanced the digestibility (Allahdadi & Bahreininejad, 2020), while other reported decrease in digestibility under drought stress (Ferreira *et al.,* 2023).

The drought stress negatively impacted *A. nummularia* fodder productivity, nutritive value, palatability and digestibility. The P fertilization improved the drought tolerance of *A. nummularia*, resulting in enhanced fodder production, nutritive value, palatability, and digestibility. The observed drought tolerance by P fertilization can be attributed to the dual physiological role of P in regulating osmotic adjustment and removing reactive oxygen species (Tariq *et al*., 2018). By enhancing accumulation of solutes and supporting the antioxidant defense system of plants, P helps in maintaining cellular turgor and membrane integrity under drought stress, which directly improved growth and nutrient assimilation (Khan *et al*., 2023).

Drought is a major climate change effect, and the agriculture sector is directly affected by its negative impacts. Understanding the impact of drought and P fertilizer under salt-affected soil conditions will help to enhance *A. nummularia* fodder production, which is an important fodder crop with resilience to climate change. This greenhouse study provides foundational insights but does not address field-scale dynamics; future field studies should further explore the drought-mitigating role of P fertilization in *A. nummularia.*

Conclusion

Phosphorus fertilization significantly mitigates the adverse effects of drought on *A. nummularia* grown in salt-affected soils by enhancing growth, nutritive value, fodder digestibility. Field trials are recommended to optimize the P fertilization rate for drought stress in salt-effected soils, a key step toward climate-resilient farming practice for arid regions.

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