Al-Qadisiyah Journal of Pure Science
ISSN(Printed): 1997-2490 ISSN(Online): 2411-3514
DOI: 10.29350/jops
Al-Qadisiyah Journal of Pure Science

Response of Vegetative Growth Parameters of *Medicago sativa L.* to Conventional and Nano Potassium (Nano-K) Fertilization under Different Water Stress Levels

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Received: 23/03/2026; Revised: 29/03/2026; Accepted: 12/04/2026; Published Online: 12/04/2026.

Abstract
This study aimed to evaluate the effect of conventional potassium fertilization and Nano potassium (Nano-K) foliar application on the vegetative growth of alfalfa (*Medicago sativa L.*) under different water stress levels. The experiment was conducted using a factorial arrangement in a Randomized Complete Block Design (RCBD) with three replicates, including potassium source (conventional and nano) and irrigation levels (100%, 75%, 50%, and 25% of field capacity). The results revealed that Nano-K fertilizer application significantly improved all vegetative growth parameters compared to conventional potassium and control treatments. The Nano-K concentration of 2 g L^{-1} recorded the highest values for plant height (47.08 cm), number of leaves (31.83 leaves $plant^{-1}$), fresh weight (3.48 g $plant^{-1}$), and dry weight (0.64 g $plant^{-1}$), while the concentration of 3 g L^{-1} showed superiority in leaf area (26.04 cm^2). Conventional potassium also improved growth traits, particularly at 4 g kg^{-1} soil, but remained less effective than Nano-K. Water stress significantly reduced most growth parameters, with the lowest values observed at 25% field capacity. However, Nano-K application alleviated the adverse effects of water stress, particularly under moderate and severe stress conditions. In conclusion, Nano-K fertilization, especially at 2 g L^{-1}, can be recommended as an effective strategy to enhance alfalfa growth and improve tolerance to water stress, offering a promising alternative to conventional potassium fertilizers.

Keywords: Conventional potassium fertilizer, nano potassium fertilizer, water stress, alfalfa.

1. Introduction

*Medicago sativa L.** is a perennial forage crop of high agricultural and economic value worldwide. It is widely cultivated due to its integrated productive and functional characteristics, including high biomass productivity, excellent nutritional quality, and its ability to fix atmospheric nitrogen, which contributes to improving soil fertility [1,2]. It belongs to the Fabaceae family and is widely used in livestock feeding systems due to its high protein content, digestibility, and richness in essential vitamins and minerals, making it a fundamental component in forage production systems, particularly in arid and semi-arid regions [3–5].
Alfalfa productivity is significantly affected by abiotic stress factors, particularly water stress, which is considered one of the most critical limiting factors for agricultural production worldwide. This issue is more

pronounced in arid and semi-arid regions, where water scarcity and irregular rainfall patterns reduce crop productivity. Drought stress induces several physiological and morphological disturbances, including stomatal closure, inhibition of photosynthesis, chlorophyll degradation, and oxidative stress caused by the accumulation of reactive oxygen species, ultimately leading to reduced biomass and crop quality [8–10].
Mineral nutrition is a key factor in enhancing plant tolerance to environmental stresses. Potassium (K) is an essential macronutrient required for plant growth and development, particularly in legumes. It plays a vital role in enzyme activation, protein synthesis, energy transfer, and regulation of stomatal movement, which controls gas exchange and water relations. In addition, potassium contributes to osmotic regulation, carbohydrate transport, and maintaining ionic balance, thereby improving water-use efficiency and enhancing plant tolerance to both biotic and abiotic stresses [12–16]. Conventional potassium fertilizers, such as potassium sulfate, have been widely used to improve crop productivity; however, their efficiency may be limited due to nutrient losses and low utilization efficiency under certain conditions [13].
In recent years, nanotechnology has emerged as an advanced approach in agriculture to improve nutrient use efficiency and crop performance. Nanoparticles are characterized by their small size, high surface area, and increased reactivity, which enhance their ability to penetrate plant tissues and improve nutrient absorption and translocation [17–19]. Nano potassium (Nano-K) fertilizers represent a modern form of fertilization that provides controlled and gradual nutrient release, ensuring higher availability of potassium near absorption sites. This contributes to improving plant growth and productivity, particularly under stress conditions [20–22].

Therefore, this study aimed to evaluate the effect of conventional and Nano-K fertilization on the vegetative growth characteristics of *Medicago sativa L.* under different levels of water stress, and to determine the efficiency of Nano-K in improving plant performance and mitigating the adverse effects of drought conditions compared to conventional potassium fertilization.

2. Materials and Methods

2-1. Study Site

The experiment was conducted in a nursery belonging to the Directorate of Agriculture in Al-Muthanna, located in the center of Al-Samawah city, on 4/10/2025. The experiment aimed to evaluate the effect of conventional and Nano-K fertilization on the vegetative traits of alfalfa (*Medicago sativa L.*) under water stress conditions. Seeds of a local alfalfa variety were obtained from a local market and cleaned of impurities prior to planting. The seeds were sown in plastic pots with a capacity of 20 kg, filled with 11 kg of mixed soil at a ratio of 3:1 (soil: peat moss).
A representative soil sample was taken before planting to conduct physical and chemical analyses at the U Science Laboratory in Al-Diwaniyah city, as shown in Table (1).

Table (1): Physical and Chemical Properties of the Experimental Soil Before Planting [23, 24]

Property	Value	Unit
pH	7.30	–
Electrical Conductivity (EC)	2.06	ms/cm
Organic Matter (OM)	1.12	%
$CaCO_3$	36	%
$CaSO_3$	1.15	%
Bulk Density	1.13	$g \cdot cm^{-3}$
Available N	2.8	mg/kg
Available K	108.65	mg/kg
Available P	7.48	mg/kg

Soluble K	51.43	mg/kg
Na	273.6	mg/kg
Ca	216	mg/kg
Cl	441	mg/kg
Mg	200.08	mg/kg
HCO_3	280	mg/kg
SO_4	878.42	mg/kg
Sand	77.2	%
Silt	20.5	%
Clay	11.1	%
Soil Texture	Sandy loam	–

2-2. Experimental Design

The experiment was designed according to the Randomized Complete Block Design (RCBD) in a two-factor factorial arrangement with three replicates.

The first factor included the source of potassium, comprising seven treatments: three levels of conventional potassium fertilizer (4, 6, and 8 g kg^{-1} soil, with 6 g kg^{-1} adopted as the standard level), three levels of Nano potassium fertilizer (Nano-K) (1, 2, and 3 g L^{-1}, where 2 g L^{-1} represents the recommended concentration), in addition to a control treatment.

The second factor consisted of water stress levels, where irrigation was applied at 25%, 50%, and 75% of field capacity, along with full irrigation (100%) for all treatments of the first factor.

Thus, the total number of experimental units reached 84 units (7 × 4 × 3), randomly distributed within three replicates.

2-3. Experimental Treatments

The study included three experimental factors: potassium source, application level, and water stress.

Conventional potassium fertilizer was added to the soil of pots after germination through soil application at levels of 4, 6, and 8 g kg^{-1} soil, equivalent to (44, 66, and 88 g pot^{-1}) based on the pot weight of 11 kg. The total amount was divided into two equal applications.

Nano-K, produced by the Iranian company KHAZRA, was prepared as solutions at concentrations of 1, 2, and 3 g L^{-1}, where 2 g L^{-1} represents the recommended level. It was applied as foliar spraying in two doses.

Water stress treatments were implemented at levels of 100%, 75%, 50%, and 25% of the soil field capacity.

Seeds were sown on 4 October 2025. Conventional potassium fertilizer was applied in two equal doses after plant establishment, while Nano-K was applied as foliar spray in two applications at specific growth stages.

Vegetative growth parameters were measured 60 days after planting.

2-4. Determination of Field Capacity of the Soil Used in Cultivation

The field capacity of the experimental soil was determined based on the method described by (Al-Sharifi, 2023) [25].

Three pots containing 11 kg of soil each were used. The soil was air-dried until a constant weight was achieved, then irrigated to full saturation and covered with plastic bags to minimize evaporation losses. The pots were left for 48 hours to allow gravitational water to drain through the bottom openings.

Afterward, the pots were reweighed to determine the gravimetric moisture content. Field capacity was calculated using the following equations:

- Water weight = Wet soil weight − Dry soil weight
- Moisture percentage (%) = (Water weight ÷ Dry soil weight) × 100

The average field capacity of the soil was found to be 25%. Based on the gravimetric method, irrigation water amounts were determined at 100%, 75%, 50%, and 25% of field capacity, corresponding to 2.7, 2.0, 1.4, and 0.7 L pot^{-1}, respectively.

2-5. Vegetative Growth Parameters and Measurement Methods

2-5-1. Plant Height

Plant height was measured using a metric measuring tape for each experimental unit. Measurements were taken from the point of plant attachment to the soil up to the plant apex.

2-5-2. Number of Branches

The number of branches on the main stem was counted for plants in each replicate within each treatment.

2-5-3. Number of Leaves

The total number of leaves was counted, including those on the main stem and its branches.

2-5-4. Fresh Weight of the Plant

The fresh weight of the vegetative parts (stems and leaves) was measured after harvesting the plant at soil surface level by cutting the stem at the base. The vegetative parts of each sample were collected, cleaned thoroughly from soil, gently wiped with absorbent tissues to remove excess water, then weighed using a sensitive balance. The weight was recorded in grams [26].

2-5-5. Dry Weight of the Plant

Plant samples were placed in an electric oven at 65°C for 48 hours until a constant weight was reached. They were then weighed using a sensitive balance, and the weight was recorded in grams [27].

2-5-6. Leaf Area

Leaf area was measured using the gravimetric method. A leaf was taken from the top of the plant and weighed using a sensitive electronic balance (DENVER, German origin) to obtain its fresh weight. Then, a disc of 1 cm^2 was cut from the leaf and weighed. Total leaf area was calculated using the following equation:

$$\text{Leaf area} = 1\ cm^2 \times (\text{leaf weight} \div \text{disc weight})\ [28, 29]$$

2-6. Statistical Analysis

All data were analyzed using analysis of variance (ANOVA) in SAS software based on a factorial experiment within a Randomized Complete Block Design (RCBD). Significant differences among treatment means were determined using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$, and the interaction between factors was also evaluated.

3. Results

3-1. Effect of Conventional Potassium Application and Nano Potassium Foliar Spray under Different Water Stress Levels on Some Vegetative Traits of Alfalfa

3-1-1. Plant Height (cm)

The results presented in Table (2) indicate a significant effect of Nano-K foliar application on alfalfa plant height. Treatments sprayed with concentrations of 2, 3, and 1 g L^{-1} showed significant superiority according to DMRT at $P \leq 0.05$, respectively, compared to the control treatment, which recorded a mean plant height

of 33.67 cm. The highest mean height was recorded at a concentration of 2 g L^{-1} (47.08 cm), with no significant difference compared to the 3 g L^{-1} concentration.
The addition of conventional potassium fertilizer to the soil also showed a significant effect on plant height compared to the control. The treatment of 4 g kg^{-1} recorded the highest mean plant height of 39.25 cm.
The results further demonstrated a significant effect of water stress levels, where a gradual decrease in plant height was observed with increasing stress intensity. The highest mean plant height was recorded at 100% irrigation level (42.76 cm), while the lowest mean was recorded at 25% irrigation level (34.95 cm), with no significant difference compared to the 50% irrigation level.
Regarding the interaction between fertilization treatments and water stress levels, the results showed that the Nano-K spray treatment at a concentration of 3 g L^{-1} under 100% irrigation level achieved the highest plant height (53.00 cm). In contrast, the lowest mean height (24.00 cm) was recorded for the interaction between conventional potassium at 6 g kg^{-1} and the 25% irrigation level.

Table (2): Effect of Conventional and Nano-K Fertilization on Mean Plant Height (cm) of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	39.67 c–h	36.00 f–i	30.00 ijk	29.00 ijk	33.67 c
Nano K (2 g L^{-1})	50.33 ab	45.67 a–e	48.33 abc	44.00 b–f	47.08 a
Nano K (> recommended 3 g L^{-1})	53.00 a	44.33 b–f	45.67 a–e	43.00 b–f	46.50 a
Nano K (< recommended 1 g L^{-1})	47.00 a–d	41.00 c–g	39.67 c–h	39.33 d–h	41.75 b
K (4 g kg^{-1})	46.00 a–d	40.67 c–h	37.00 e–i	33.33 g–j	39.25 b
K (6 g kg^{-1})	37.00 e–i	33.00 g–k	29.00 ijk	24.00 k	30.75 cd
K (8 g kg^{-1})	26.33 jk	25.33 jk	25.67 jk	32.00 h–k	27.33 d
Mean	**42.76 a**	**38.00 b**	**36.48 bc**	**34.95 c**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

3-1-2. Number of Branches

The results of the statistical analysis presented in Table (3) indicate a significant effect of Nano-K foliar application on the number of branches of alfalfa plants. All spraying treatments at concentrations of 1, 2, and 3 g L^{-1} showed significantly higher values compared to the control treatment, which recorded 2.33 branches per plant. The highest mean was achieved at a concentration of 1 g L^{-1} (3.00 branches per plant), with no significant difference compared to the concentrations of 2 and 3 g L^{-1}.
In contrast, the application of conventional potassium fertilizer to the soil did not show significant differences compared to the control treatment, although the highest mean (2.67 branches per plant) was recorded at the 4 g kg^{-1} potassium treatment.
The results also revealed a significant effect of water stress levels on the number of branches. The highest mean (2.67 branches per plant) was recorded at the 75% irrigation level, with no significant difference compared to the 100% and 25% irrigation levels. Meanwhile, the lowest mean (2.24 branches per plant) was observed at the 50% irrigation level.
Regarding the interaction effects, the combination of Nano-K spraying at 2 g L^{-1} with the 25% irrigation level produced the highest mean number of branches (4.00 branches per plant). In contrast, the lowest mean (1.67 branches per plant) was recorded at the interaction between the 6 g kg^{-1} potassium level and 50% irrigation, as well as at the interaction of the 8 g kg^{-1} potassium level with 100%, 50%, and 25% irrigation levels.

Table (3): Effect of Conventional and Nano-K Fertilization on Mean Number of Branches of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	2.67 b–e	2.33 c–e	2.33 c–e	2.00 de	2.33 bc
Nano K (2 g L^{-1})	2.33 cde	2.67 b–e	2.67 b–e	4.00 a	2.92 a
Nano K (> recommended 3 g L^{-1})	3.00 a–d	3.00 a–d	2.33 cde	3.33 abc	2.92 a
Nano K (< recommended 1 g L^{-1})	3.33 abc	3.67 ab	2.33 cde	2.67 b–e	3.00 a
K (4 g kg^{-1})	3.00 a–d	2.67 b–e	2.67 b–e	2.33 cde	2.67 ab
K (6 g kg^{-1})	2.33 cde	2.33 cde	1.67 e	2.00 de	2.08 cd
K (8 g kg^{-1})	1.67 e	2.00 de	1.67 e	1.67 e	1.75 d
Mean	**2.62 ab**	**2.67 a**	**2.24 b**	**2.57 ab**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

3-1-3. Number of Leaves

The results of the statistical analysis presented in Table (4) indicate a significant effect of Nano-K foliar application on the average number of leaves of alfalfa plants. All spraying treatments at concentrations of 2, 3, and 1 g L^{-1} showed superiority compared to the control treatment, which recorded 18.50 leaves per plant. The highest mean was achieved at a concentration of 2 g L^{-1} (31.83 leaves per plant), with no significant difference compared to the 3 g L^{-1} concentration.

The addition of conventional potassium fertilizer to the soil also showed a significant effect compared to the control treatment, as the 4 g kg^{-1} treatment recorded the highest mean (23.83 leaves per plant).

The results further indicated no significant effect of water stress levels on this trait, despite the highest mean (22.90 leaves per plant) being recorded at the 100% irrigation level.

Regarding the interaction effects, the combination of Nano-K spraying at 2 g L^{-1} with the 50% irrigation level recorded the highest mean (40.00 leaves per plant). In contrast, the lowest mean (10.33 leaves per plant) was observed at the interaction of the 8 g kg^{-1} potassium level with both 100% and 25% irrigation levels.

Table (4): Effect of Conventional and Nano-K Fertilization on Mean Number of Leaves of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	20.00 d–i	19.67 d–i	17.00 e–l	17.33 e–l	18.50 c
Nano K (2 g L^{-1})	27.67 b–e	29.00 bcd	40.00 a	30.67 a–d	31.83 a
Nano K (> recommended 3 g L^{-1})	37.00 ab	29.00 bcd	23.33 c–g	32.00 abc	30.33 a
Nano K (< recommended 1 g L^{-1})	25.00 c–g	28.00 b–e	21.67 c–h	24.00 c–g	24.67 b
K (4 g kg^{-1})	24.00 c–g	25.67 c–f	21.67 c–h	24.00 c–g	23.83 b
K (6 g kg^{-1})	16.33 f–i	14.33 g–i	14.00 hi	11.67 hi	14.08 cd
K (8 g kg^{-1})	10.33 i	14.33 g–i	12.00 hi	10.33 i	11.75 d
Mean	**22.90 a**	**22.86 a**	**21.38 a**	**21.43 a**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

3-1-4. Fresh Weight of the Vegetative Growth (g)

The results of the statistical analysis presented in Table (5) indicate a significant effect of Nano-K foliar application on the fresh weight of the vegetative growth of alfalfa plants. All spraying treatments at concentrations of 2, 3, and 1 g L^{-1} showed superiority compared to the control treatment, which recorded 1.64 g $plant^{-1}$. The highest mean was achieved at a concentration of 2 g L^{-1} (3.48 g $plant^{-1}$), with no significant difference compared to the 3 g L^{-1} concentration.

The addition of conventional potassium fertilizer to the soil also showed a significant effect compared to the control treatment, as the 4 g kg⁻¹ treatment recorded the highest mean (2.58 g plant⁻¹).
The results further revealed a significant effect of water stress levels, where the fresh weight decreased with increasing water stress intensity. The highest mean was recorded at the 100% irrigation level (2.88 g plant⁻¹), while the lowest mean was observed at the 50% irrigation level (1.65 g plant⁻¹).
Regarding the interaction effects, the combination of Nano-K spraying at 3 g L⁻¹ with the 100% irrigation level recorded the highest mean (4.54 g plant⁻¹), whereas the lowest mean (0.84 g plant⁻¹) was observed at the interaction of the 8 g kg⁻¹ potassium level with the 25% irrigation level.

Table (5): Effect of Conventional and Nano-K Fertilization on Mean Fresh Weight of Vegetative Growth (g) of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	2.17 c–i	1.92 d–j	1.40 ghi	1.05 hi	1.64 d
Nano K (2 g L⁻¹)	3.89 ab	3.38 a–d	3.10 b–e	3.54 abc	3.48 a
Nano K (> recommended 3 g L⁻¹)	4.54 a	2.78 b–g	1.55 f–i	2.95 b–f	2.95 ab
Nano K (< recommended 1 g L⁻¹)	3.03 b–f	2.12 c–i	1.65 e–i	2.24 c–i	2.26 c
K (4 g kg⁻¹)	3.38 a–d	2.88 b–g	1.61 e–i	2.44 b–h	2.58 bc
K (6 g kg⁻¹)	2.02 d–i	1.65 e–i	1.27 hi	1.10 hi	1.51 d
K (8 g kg⁻¹)	1.15 hi	0.98 hi	0.98 hi	0.84 i	0.99 d
Mean	**2.88 a**	**2.25 b**	**1.65 c**	**2.02 bc**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

3-1-5. Dry Weight of the Vegetative Growth (g)
The results of the statistical analysis presented in Table (6) indicate a significant effect of Nano-K foliar application on the dry weight of the vegetative growth of alfalfa plants. All spraying treatments at concentrations of 2, 3, and 1 g L⁻¹ showed superiority compared to the control treatment, which recorded 0.25 g plant⁻¹. The highest mean was recorded at a concentration of 2 g L⁻¹ (0.64 g plant⁻¹).
The addition of conventional potassium fertilizer to the soil also showed a significant effect compared to the control treatment, as the 4 g kg⁻¹ treatment recorded the highest mean (0.39 g plant⁻¹).
The results further demonstrated a significant effect of water stress levels, where a decrease in dry weight was observed with increasing stress intensity. The highest mean was recorded at the 100% irrigation level (0.49 g plant⁻¹), while the lowest mean was observed at the 50% irrigation level (0.31 g plant⁻¹), with no significant difference compared to the 75% and 25% irrigation levels.
Regarding the interaction effects, the combination of Nano-K spraying at 3 g L⁻¹ with the 100% irrigation level achieved the highest mean (0.79 g plant⁻¹), whereas the lowest mean (0.15 g plant⁻¹) was recorded at the interaction of the 8 g kg⁻¹ potassium level with the 25% irrigation level.

Table (6): Effect of Conventional and Nano-K Fertilization on Mean Dry Weight of Vegetative Growth (g) of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	0.34 d–h	0.29 e–h	0.22 fgh	0.14 h	0.25 d
Nano K (2 g L⁻¹)	0.70 ab	0.63 abc	0.60 abc	0.63 abc	0.64 a
Nano K (> recommended 3 g L⁻¹)	0.79 a	0.50 b–e	0.31 d–h	0.52 bcd	0.53 b
Nano K (< recommended 1 g L⁻¹)	0.53 bcd	0.35 d–h	0.34 d–h	0.44 c–f	0.41 c

K (4 g kg^{-1})	0.53 bcd	0.41 c–g	0.29 e–h	0.34 d–h	0.39 c
K (6 g kg^{-1})	0.36 d–h	0.24 d–h	0.22 fgh	0.19 gh	0.25 d
K (8 g kg^{-1})	0.20 gh	0.17 h	0.16 h	0.15 h	0.17 d
Mean	**0.49 a**	**0.37 b**	**0.31 b**	**0.35 b**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

3-1-6. Total Leaf Area (cm^2)

The results of the statistical analysis presented in Table (7) indicate a significant effect of both Nano-K foliar application and soil application of conventional potassium fertilizer on the leaf area of alfalfa plants.
Spraying treatments at concentrations of 3, 2, and 1 g L^{-1} showed superiority compared to the control treatment, which recorded 18.08 cm^2. The highest mean leaf area was recorded at a concentration of 3 g L^{-1} (26.04 cm^2).
The addition of conventional potassium fertilizer to the soil also showed a significant effect compared to the control treatment, as the highest mean (21.42 cm^2) was recorded at the 4 g kg^{-1} level.
The results further revealed a significant effect of water stress levels, where leaf area decreased with increasing stress intensity. The highest mean was recorded at the 100% irrigation level (23.31 cm^2), with no significant difference compared to the 25% irrigation level, while the lowest mean (18.19 cm^2) was observed at the 50% irrigation level.
Regarding the interaction effects, the combination of Nano-K spraying at 3 g L^{-1} with the 25% irrigation level recorded the highest mean leaf area (30.25 cm^2), whereas the lowest mean (13.66 cm^2) was observed at the interaction of the 8 g kg^{-1} potassium level with the 50% irrigation level.

Table (7): Effect of Conventional and Nano-K Fertilization on Mean Leaf Area (cm^2) of Alfalfa under Water Stress

Potassium Treatment	**100%**	**75%**	**50%**	**25%**	**Mean**
Control	19.89 i–l	19.46 jkl	16.63 mn	16.33 no	18.08 e
Nano K (2 g L^{-1})	25.17 cde	23.62 def	22.14 f–i	27.69 b	24.66 b
Nano K (> recommended 3 g L^{-1})	27.06 bc	25.94 bcd	20.93 g–k	30.25 a	26.04 a
Nano K (< recommended 1 g L^{-1})	26.25 bc	20.33 h–k	20.19 h–l	29.91 a	24.17 b
K (4 g kg^{-1})	23.32 efg	22.07 f–j	18.39 k–n	21.90 f–j	21.42 c
K (6 g kg^{-1})	22.53 fgh	20.55 h–k	15.38 no	20.13 h–l	19.65 d
K (8 g kg^{-1})	18.95 klm	17.70 l–o	13.66 p	17.63 l–o	16.99 e
Mean	**23.31 a**	**21.38 b**	**18.19 c**	**23.41 a**	

Means followed by different letters are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

4. Discussion

The results of this study indicate that both nano and conventional potassium fertilizers play a significant role in improving the vegetative growth of alfalfa under varying levels of water stress, with a clear superiority of Nano-K treatments. The enhancement observed in plant height, number of leaves, fresh and dry weights, and leaf area under Nano-K application is consistent with several previous studies that emphasized the efficiency of nano-fertilizers in improving plant growth performance under both normal and stress conditions. Similar findings were reported by Mahdi *et al.* (2023) [30], who observed significant increases in vegetative growth traits of stevia following Nano-K application, and by Al-Ajili and Al-Saeedi (2023) [31], who found that Nano-K at 2 g L^{-1} improved plant height and growth indicators in wheat. This improvement can be attributed to the high surface area and reactivity of nanoparticles, which enhance nutrient absorption, translocation, and utilization efficiency within plant tissues, leading to improved physiological activities such as photosynthesis and enzyme activation [1].

The positive effect of potassium, even in its conventional form, on vegetative growth observed in this study agrees with previous research indicating that potassium is a key macronutrient involved in regulating plant growth processes. Khalifa *et al.* (2025) [32] demonstrated that increasing potassium levels significantly improved plant height, leaf area, and biomass in faba bean, while Appiah *et al.* (2024) [1] reported that potassium fertilization increased dry matter yield and improved overall plant performance in alfalfa. These findings highlight the importance of potassium in enhancing plant growth under different conditions [33].

The reduction in vegetative growth parameters under increasing water stress levels observed in this study is in agreement with numerous studies that reported the negative impact of drought on plant growth. Mouffok & Belhamra (2020) [34] and Abid *et al.* (2015) [35] showed that water stress significantly reduces plant height, biomass, and leaf development due to decreased relative water content and impaired physiological processes. Similarly, Prince *et al.* (2022) [36] reported reductions in shoot and root biomass of alfalfa under drought conditions. These effects are associated with reduced photosynthesis and increased oxidative stress, ultimately leading to decreased plant growth and productivity.

Despite the negative effects of water stress, the results of this study demonstrated that potassium application, particularly in nano form, alleviated the adverse effects of drought. This finding is consistent with Alharbi *et al.* (2024) [37], who reported that Nano-K significantly improved plant height, biomass, and nutrient uptake in sorghum under drought stress conditions. Ahmad *et al.* (2023) [38] also confirmed that potassium application enhances drought tolerance by improving water relations and photosynthetic efficiency. These results highlight the role of potassium in supporting plant growth under water deficit conditions [35].

Furthermore, the improvement in leaf area and biomass under Nano-K treatments may be attributed to enhanced physiological efficiency. Seiam *et al.* (2020) [39] demonstrated that combined soil and foliar potassium application increased relative water content, chlorophyll concentration, and biomass production in alfalfa grown under saline conditions. Similarly, El-Shal *et al.* (2022) [40] found that Nano-K significantly improved shoot dry weight and plant height in alfalfa under salt stress. These findings support the role of Nano-K in improving plant performance under stress conditions.

The interaction between potassium fertilization and water stress observed in this study further confirms the important role of potassium in mitigating stress effects. The highest values of growth parameters under full irrigation combined with Nano-K application are in agreement with findings by Al-Daami (2015) [41], who reported that the combination of adequate irrigation and potassium fertilization resulted in maximum growth and biomass in zinnia. Similarly, studies conducted in Iraq and elsewhere have shown that potassium fertilization enhances water use efficiency and improves plant performance under limited water availability [42].

In addition, Nano-K has been reported to regulate nutrient release and improve nutrient availability near absorption sites, which enhances nutrient uptake efficiency and reduces losses compared to conventional fertilizers. This is supported by El-Sharkawy *et al.* (2017) [43], who demonstrated that nano potassium sulfate improved growth and stress tolerance in alfalfa more effectively than conventional potassium under saline conditions. The improved performance under nano fertilization can also be attributed to enhanced antioxidant defense systems [44].

Moreover, potassium plays a crucial role in carbohydrate transport and energy transfer within the plant, which supports growth and biomass accumulation. Jabborova *et al.* (2025) [45] indicated that potassium enhances the translocation of photosynthates and prevents reductions in root and shoot biomass under stress conditions. Similarly, Hui *et al.* (2025) [46] confirmed that optimal potassium supply improves photosynthetic efficiency and yield components of alfalfa through better nutrient availability and metabolic activity.

The slight variation in response among different growth parameters, such as the relatively lower sensitivity of branch number compared to other traits, may be attributed to the genetic and physiological characteristics of alfalfa, which allow partial adaptation to moderate stress levels. This observation is supported by Mouradi *et al.* (2016) [47], who reported variability among alfalfa genotypes in response to water stress, indicating differences in tolerance mechanisms.
Overall, the results of this study are consistent with a broad range of previous research, confirming that water stress negatively affects vegetative growth, while potassium especially in nano form plays a critical role in mitigating these effects by improving physiological processes, enhancing nutrient uptake, and maintaining water balance within the plant. These combined effects ultimately lead to improved plant growth and productivity under stress conditions.

Conclusion

The application of nano potassium fertilizer was more efficient than conventional potassium in enhancing vegetative growth of alfalfa under both normal and water stress conditions. The concentration of 2 g L^{-1} Nano-K was the most effective overall, while 3 g L^{-1} showed superiority in some traits such as leaf area. Water stress negatively affected most growth parameters, but Nano-K application significantly improved plant tolerance to stress conditions. Therefore, Nano-K fertilization can be recommended as a promising strategy to improve alfalfa growth and productivity, particularly under water-limited conditions, while reducing reliance on higher doses of conventional fertilizers.

Acknowledgement

The authors would like to thank the Department of Biology, College of Education, University of Al-Qadisiyah, for their support, and the Directorate of Agriculture in Al-Muthanna for facilitating the experimental work.

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