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DRIS-based evaluation of optimal nutrient ranges in sunflower under "different irrigation regimes and selenium application"

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Abstract

Achieving an optimal nutrient balance is fundamental to sustainable crop production, particularly for economically important oilseed crops such as sunflower (*Helianthus annuus* L.). In the face of increasing food demand and climate variability, strategies that improve both resource use efficiency and crop quality are becoming essential. The study examines the effect of selenium (Se) foliar application on sunflower seed and oil yield under varying levels of water stress using the diagnosis and recommendation integrated system (DRIS). Treatments included selenium concentrations (0, 5, 10, and 20 ppm) applied under full irrigation (100% WR), moderate stress (75% WR), and severe stress (50% WR) water requirement (WR). Results demonstrated that selenium application significantly enhanced seed and oil yield under water stress, particularly at 10 ppm under 75% WR. Nutrient content analysis revealed increased nitrogen (N), phosphorus (P), and potassium (K) concentrations with rising selenium levels, especially under limited water conditions. Nutrient balance indices and DRIS indices identified phosphorus as the most frequently limiting nutrient, with nutrient order often following the sequence $P > N > K$. Based on the reference norms for nutrient ratio interpretation, selenium application shifted nutrient ratios toward balanced or slightly excess levels, improving nutrient synchrony and physiological efficiency. The integration of selenium with deficit irrigation holds promise for optimizing nutrient balance and enhancing productivity in water-limited environments.

Keywords Sunflower, Nutrient content, Balance index, Physiological diagnosis, DRIS

1 Introduction

Sunflower (*Helianthus annuus* L.) plays a vital role in global agriculture due to its high oil content, nutritional value, and adaptability to diverse climates. Climate change has led to reduced water availability and higher temperatures, particularly in regions with limited or unpredictable rainfall [1]. These environmental shifts disrupt plant physiological functions essential for growth, development, and crop production [2, 3]. Among the key limiting factors, water stress plays a major role, as water makes up approximately 85–95% of living plant cells. Plants manage water in three forms, with bound water



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attached to salts and organic compounds being the most difficult to mobilize under stress [4]. The plant's water status directly and indirectly affects all physiological processes [5]. Maximizing the productivity and quality of sunflower grain depends heavily on precise nutrient management, particularly in arid and semi-arid regions where localized irrigation systems such as drip or micro-sprinkler irrigation are commonly used. These systems provide enhanced control over water and nutrient delivery, making them suitable platforms for site-specific nutrient optimization.

Among emerging micronutrients of agronomic interest, Selenium (Se), a trace element traditionally studied in the context of human and animal nutrition, has recently gained attention as an agronomically beneficial element. At low concentrations, Se exerts positive physiological effects on plants, including enhanced tolerance to abiotic stresses, improved photosynthetic efficiency, and increased antioxidant capacity. In sunflower, judicious Se application has been associated with improvements in seed yield and oil quality [6]. However, selenium exhibits a dual behavior, acting as a beneficial element at low doses while becoming toxic at higher concentrations; therefore, precise management is essential to prevent adverse effects on plant metabolism and nutrient interactions. Although selenium is not considered an essential nutrient for higher plants, it plays an important regulatory and modulatory role in plant nutrition. This functional role explains its pronounced influence on the uptake and balance of major nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K). Selenium affects NPK dynamics through interconnected physiological and biochemical mechanisms, including modulation of enzyme activity, enhancement of root growth and nutrient acquisition, and regulation of cellular redox homeostasis. These effects become especially significant under abiotic stress conditions such as drought, salinity, or low soil fertility constraints that commonly prevail in arid and semi-arid agro-ecosystems.

One of the most effective tools for evaluating plant nutritional status and determining nutrient balance is the diagnosis and recommendation integrated system (DRIS). Unlike conventional nutrient sufficiency ranges, DRIS evaluates nutrient ratios and interactions, offering a more robust framework for diagnosing deficiencies, toxicities, or imbalances, especially under variable irrigation and fertilization conditions [7]. Despite the recognized potential of selenium and DRIS in improving nutrient management, limited research has explored their combined application in sunflower cultivation under localized irrigation systems.

This study aims to determine the optimum ranges of macro- and micronutrients in sunflower grains using DRIS, with a specific focus on the influence of selenium application. The findings are expected to refine nutrient management strategies, reduce fertilization inefficiencies, and enhance productivity and quality in water-scarce environments.

2 Materials and methods

2.1 Experimental site and duration

Two field experiments were conducted during the summer growing seasons of 2020/2021 and 2021/2022 at the Research and Production Station, National Research Centre (NRC), Nubaria Province, Beheira Governorate, Egypt (30° 54' N, 29° 57' E). Each growing season extended from early May (sowing) to late September (harvest), with an average growth period of approximately 135–140 days.

2.2 Experimental design and treatments

The experiments were laid out in a split-plot design with three replicates. Main plots three irrigation regimes based on percentages of crop water requirements (WR) (100%, 75% and 50%). Sub-plots four foliar selenium (Se) application rates (0(control), 5 ppm, 10 ppm and 20 ppm). Each experimental plot measured 12.0 m². Units are expressed in hectares (ha) throughout the manuscript (1 fed = 0.42 ha).

2.3 Plant material and crop management

Seeds of sunflower (*Helianthus annuus* L.), cultivar Sakha 53, were obtained from the Agricultural Research Centre (ARC), Giza, Egypt, and sown during the first week of May in both seasons. Fertilization was applied according to the recommendations of the Egyptian Ministry of Agriculture as follows. Nitrogen (N): 192 kg N ha⁻¹, applied as urea (46% N) in two equal splits at 20 and 40 days after sowing (DAS). Phosphorus (P): 240 kg P₂O₅ ha⁻¹ as single superphosphate (15.5% P₂O₅), incorporated before planting. Potassium (K): 120 kg K₂O ha⁻¹ as potassium sulfate (50% K₂O), applied before planting.

2.4 Selenium foliar application

Selenium was applied in the form of sodium selenate (Na₂SeO₄) as a foliar spray. Selenium solutions (0, 5, 10, and 20 ppm Se) were prepared using distilled water without adjuvants. Foliar spraying was conducted at 30 and 45 days after sowing, corresponding to the early vegetative (V4–V6) and stem elongation stages, respectively. Applications were performed using a hand-held sprayer with a spray volume of 400 L ha⁻¹, ensuring full leaf surface coverage until runoff. The upper limit of 20 ppm Se was selected based on previous agronomic studies indicating beneficial physiological effects without phytotoxicity. All safety precautions for handling selenium compounds were followed.

2.5 Irrigation treatments

Three drip irrigation regimes, at (10-day intervals) applied as a percentage of the crop evapotranspiration (ET_c), employed computations according to [8], as follows:

$$ET_c = ET_o \times K_c$$

where: K_c = crop coefficient, ET_c is the crop water needs (mm day⁻¹), and ET_o is the reference evapotranspiration (mm day⁻¹). ET_o calculations used the technique of [8], as follows:

$$ET_o = E_{pan} \times K_p$$

where: E_{pan} is the evaporation from class A and K_p is the pan coefficient. The plants in all plots incurred irrigation at 10-day intervals with different amounts of water. Irrigation water quantities approximation used the following equation:

$$IWR = \frac{A \times ET_c \times I_i}{E_a \times 1000}$$

where: A = plot size (m²), ET_c is the reference evapotranspiration (mm day⁻¹), IWA is the irrigation water application (m³), I_i is the irrigation intervals (day), and E_a is the application efficiency (%). An irrigation water application (IWA) controller was a 50 mm diameter plastic pipe (spiles). Each plot had a single spile to transport water. The pumped

volume of water via a plastic pipe attained identification using [9]. Actual irrigation water volumes were controlled using calibrated plastic spiles (50-mm diameter). The applied seasonal irrigation amounts were approximately: Irrigation level seasonal water applied ($\text{m}^3 \text{ ha}^{-1}$) 100% WR (1920), 75% WR (1440) and 50% WR (960). The respective percentages of WR were maintained by adjusting the applied volume at each irrigation event.

2.6 Soil sampling and analysis

Before sowing, soil samples (0–30 cm depth) were collected and analyzed. The soil was classified as sandy loam, with the following properties: organic matter 0.57%, CaCO_3 1.36%, pH 7.34, and EC 0.96 dS m^{-1} . Available N, P, and K were 33.6, 7.14, and 13.8 mg kg^{-1} soil, respectively (re-verified value). Soil analyses were performed according to [10].

2.7 Sampling and measurements

At harvest, plants were randomly sampled from the inner rows of each plot to avoid border effects. Seed yield (ton ha^{-1}), Oil yield (ton ha^{-1}) was determined by multiplying seed yield (ton ha^{-1}) by seed oil percentage. Grain yield: It was obtained as the weight of clean grains of the plot after threshing, and then it was transformed into ton ha^{-1} . Oil yield (ton ha^{-1}) = Oil content percentage x Seed yield (ton ha^{-1}) Plant tissue samples (sunflower grains collected at harvest) were oven-dried, ground, and analyzed for N, P, and K according to [11]. Selenium concentration in plant tissues was also determined to confirm uptake and avoid toxicity.

2.8 DRIS indices

DRIS indices which are used in the current investigation are quantitative evaluations of the relative degree of imbalance of the nutrients under study and as calculated from the following equations:

$$N, index = + \left[\frac{f(N/P) + f(N/K)}{2} \right]$$

$$P, index = - \left[\frac{f(N/P) + f(K/P)}{2} \right]$$

$$K, index = + \left[\frac{f(K/P) - f(N/K)}{2} \right]$$

$$\text{where } f(N/P) = + \left(\frac{N/P}{n/p} - 1 \right) \frac{1000}{C.V}$$

When the actual value of $N/P > n/p$.

$$\text{Or } f(N/P) = \left(1 - \frac{n/p}{N/P} \right) \frac{1000}{C.V}$$

When the actual value of $N/P < n/p$, n/p is the mean value for N/P , and CV is the coefficient of variation for high-yielding populations. The other terms of $f(N/K)$ and $f(K/P)$ are derived in a similar way using the means of n/k for N/K and k/p for K/P , respectively in place of n/p . The DRIS indices have positive and negative values which always

sum to zero as they measure the relative balance among N, P and K or other elements that might be included. The order of plant nutrient requirements is affected by the value of the index; the most negative index reflects the most required nutrient [12, 13]. (The nutrient balance index (NBI) was calculated as the sum of the absolute values of individual DRIS indices for N, P, and K. Lower NBI values indicates a more balanced nutritional status, whereas higher NBI values reflect greater nutrient imbalance.)

2.9 Physiological diagnosis (PD) chart for N, P and K

The N/P, N/K and K/P forms of expression are interrelated in a three coordinate DRIS chart. The point of origin in the center of the chart represents the mean of each expression N/P, N/K and K/P for the populations of high yielding plants. In other words, this is the composition desired in order to increase the chances of obtaining a high yield. However, this desired composition should not be considered as a single inflexible point but rather as a range encompassed by the inner of the two concentric circles as shown in Fig. 1.

The diameter of the small circle is set at $4/3$ SD from the origin, which takes account of the variability in the population. A plant composition falling within this circle would be considered to be relatively balanced which denoted by a horizontal arrow ($\rightarrow$).

As one moves away from the central zone along any axis the degree of imbalance between the two elements increases. This zone of imbalance is divided into two sub-zones, the first being a zone of slight to moderate imbalance. This is denoted by an arrow at 45° degrees to the horizontal ($\nearrow$) ($\nwarrow$) and is encompassed by the outer of the concentric circle which has a diameter of $8/3$ SD. Beyond this circle is a zone of marked imbalance denoted by vertical arrows ($\uparrow$) ($\downarrow$) being either too high or too low. The reason why the two circles are set at diameters of $4/3$ SD and $8/3$ SD is dealt with fully by [14, 15].

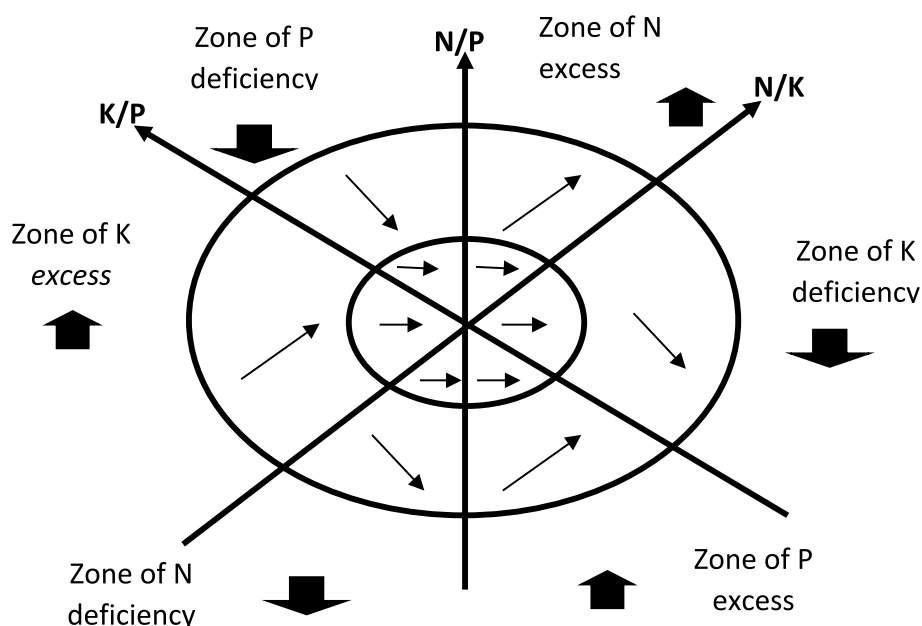


Fig. 1 Physiological diagnosis (PD) chart for direct determination of N, P and K status

There are two forms of expression for a pair of nutrients, although in DRIS calculations only one form is used. The way to select the form of ratio for a pair of nutrients to be used in DRIS calculation is described by [12, 16].

2.10 Statistical analysis

Data from both seasons were first tested for homogeneity of variance before combined analysis. As no significant season $\times$ treatment interaction was observed, data were pooled across seasons. Analysis of variance (ANOVA) was performed using the split-plot model. Treatment means were compared using least significant difference (LSD) at $P \leq 0.05$.

3 Results

3.1 Yield production

The data demonstrate that foliar selenium application significantly enhances seed and oil yield of sunflower, particularly under both optimal and deficit irrigation conditions. Seed and oil yields of sunflower responded positively to selenium foliar application under different water irrigation regimes (100%, 75%, and 50% water requirement—WR). Under 100% WR, the highest seed yield was observed with 20 ppm Se, reaching 5.04 ton ha⁻¹. Correspondingly, oil yield peaked at 1.85 ton ha⁻¹ with 20 ppm Se. At 75% WR, seed yield remained high with 20 ppm Se (4.54 ton ha⁻¹ while oil yield still reached 1.49 ton ha⁻¹. Under 50% WR, 20 ppm Se again resulted in the highest yield (4.45 ton ha⁻¹ and oil yield climbed to 1.27 ton ha⁻¹. The optimum selenium concentration was found to be 20 ppm, which consistently outperformed lower concentrations across all irrigation levels in Fig. 2.

3.2 Nutrient content, ratio and nutrient balance index (NBI)

The results demonstrate the positive role of selenium (Se) foliar application in improving nutrient uptake and balance under water stress conditions. Increasing selenium levels enhanced nitrogen, phosphorus, and potassium concentrations across all irrigation regimes, especially under water-deficient conditions (75% and 50% WR). Under 100%

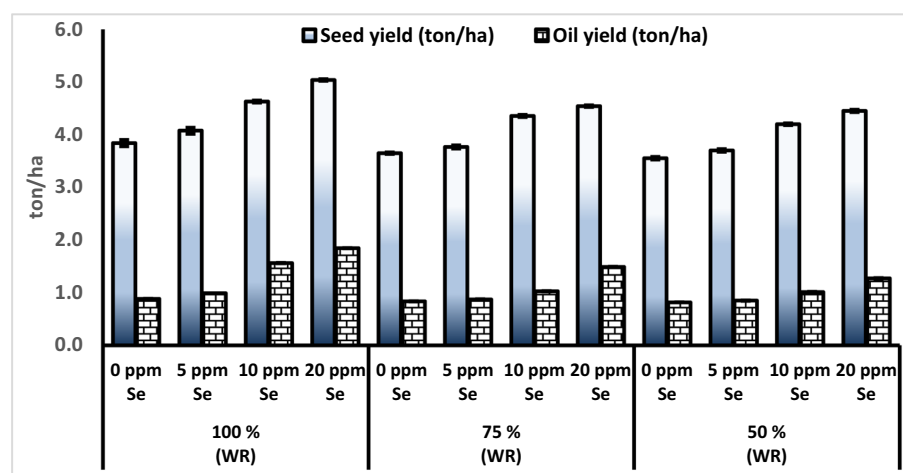


Fig. 2 Effect of selenium foliar spray on seed and oil yield production of sunflower under water stress conditions (WR) Water Requirement (Values represent means $\pm$ standard error; differences among treatments were tested using LSD at $P \leq 0.05$)

water requirement (WR), increasing selenium from 0 to 20 ppm led to gradual increases in N, P, and K concentrations. Nitrogen increased from 2.37 to 2.92%, phosphorus from 0.32 to 0.35%, and potassium from 2.20 to 2.88%. Correspondingly, nutrient ratios (N/P, K/P) and NBI values improved with higher selenium levels, peaking at an NBI of 603 under 20 ppm Se. Under 75% WR, nutrient contents were initially lower but showed noticeable improvement with selenium. The N content rose from 1.43% at 0 ppm to 2.76% at 20 ppm Se. Similar trends were observed in P and K. The NBI decreased from 627 at 0 ppm to 550 at 20 ppm Se, suggesting improved nutrient balance. A similar pattern was found under 50% WR, where the lowest nutrient values were recorded at 0 ppm Se. However, at 20 ppm Se, nutrient levels nearly matched those under 100% WR. NBI values also dropped from 646 to 524, confirming improved nutrient harmony. Negative N/K values may arise from DRIS ratio calculations and indicate relative nutrient imbalance rather than absolute negative concentration in Table 1.

3.3 DRIS indices for N, P and K and physiological diagnosis (PD) chart

Data presented that the effect of selenium foliar application on nutrient indices (N, P, K), nutrient ratios (N/P, N/K, K/P) illustrated by the PD chart, and the determined nutrient requirement order under different water regimes (WR: 100%, 75%, and 50%). Under 100% WR, the control treatment (0 ppm Se) exhibited moderate nutrient indices for N (82), P (166), and K (248), with a consistent nutrient requirement order of $P > N > K$ across all selenium levels. Increasing Se concentration from 0 to 20 ppm slightly enhanced nutrient indices, particularly P (from 166 to 231) and K (from 248 to 302). Under 75% WR, the control showed a drastic imbalance in nutrient indices, with N (248) highly elevated while P (65) and K (314) were either low or unbalanced, indicating nutrient antagonism ($\searrow$) and a need for better N management. Selenium at 10 and 20 ppm corrected the imbalance, shifting the nutrient order to $P > N > K$, and aligning PD chart symbols toward equilibrium ($\rightarrow$). Under 50% WR, the control again showed excessive N (260) and deficient P (63), with severe imbalance ($\searrow$). Selenium application at 10 and 20 ppm corrected the imbalance and improved nutrient equilibrium, with nutrient indices approaching optimum and the PD chart indicating improved status ($\rightarrow$, $\nearrow$). Again, the

Table 1 Nutrient content, ratio and (NBI) affected by selenium foliar application under water stress conditions

Treatments		NPK conc			NPK ratio			NBI
WR	Selenium	N	P	K	N/P	N/K	K/P	
100% (WR)	0 ppm Se	2.37	0.32	2.20	28	−192	305	496
	5 ppm Se	2.47	0.33	2.22	37	−183	303	486
	10 ppm Se	2.78	0.35	2.69	54	−203	359	562
	20 ppm Se	2.92	0.35	2.88	70	−210	393	603
75% (WR)	0 ppm Se	1.43	0.31	2.03	−148	−349	279	627
	5 ppm Se	1.83	0.32	2.17	−54	−273	301	573
	10 ppm Se	2.68	0.33	2.40	59	−180	329	509
	20 ppm Se	2.76	0.35	2.62	56	−198	352	550
50% (WR)	0 ppm Se	1.38	0.31	2.02	−157	−362	283	646
	5 ppm Se	1.71	0.32	2.10	−79	−289	289	578
	10 ppm Se	2.61	0.33	2.32	53	−179	320	499
	20 ppm Se	2.72	0.34	2.49	57	−187	336	524

WR water requirement, NPK nitrogen, phosphorus, and potassium, NBI nutrient balance index. Negative N/K values may arise from DRIS ratio calculations and indicate relative nutrient imbalance rather than absolute negative nutrient concentration

Table 2 Nutrient indices, Nutrient (PD) chart and require order affected by selenium foliar application under water stress conditions

Treatments		INDICE			Application of PD chart			Order
WR	Selenium	N	P	K	N/P	N/K	K/P	
100% (WR)	0 ppm Se	82	166	248	→	→	→	P>N>K
	5 ppm Se	73	170	243	→	→	→	P>N>K
	10 ppm Se	75	206	281	→	→	→	P>N>K
	20 ppm Se	70	231	302	→	→	→	P>N>K
75% (WR)	0 ppm Se	248	65	314	↘	↘	↘	N>P>K
	5 ppm Se	163	123	287	↘	→	→	N>P>K
	10 ppm Se	61	194	254	→	→	→	P>N>K
	20 ppm Se	71	204	275	→	→	→	P>N>K
50% (WR)	0 ppm Se	260	63	323	↘	↘	↘	N>P>K
	5 ppm Se	184	105	289	↘	→	↘	N>P>K
	10 ppm Se	63	186	249	→	↗	→	P>N>K
	20 ppm Se	65	197	262	→	→	→	P>N>K

PD physiological diagnosis

Table 3 Basis for physiological diagnosis, established norms for interpretation of the nutrient balance in sunflower grain (proposed reference data)

Symbol	Interpretation class	Mineral ratio		
		N/P	N/K	K/P
↓↓	Severe deficiency	< 5.57	< 1.51	< 1.46
↓	Deficiency	5.57–6.14	1.51–2.24	1.46–1.85
↘	Tendency (deficiency)	6.15–6.44	2.25–2.62	1.86–2.05
→	Balanced (normal)	6.45–7.03	2.63–3.37	2.06–2.46
↗	Tendency (excess)	7.04–7.33	3.38–3.75	2.47–2.66
↑	Excess	7.34–7.91	3.76–4.49	2.67–3.06
↑↑	Severe excess	> 7.91	> 4.49	> 3.06
Means for normal plant (norm)		9.10	7.10	1.29

nutrient requirement order shifted positively to P>N>K. The nutrient balance indices and requirement order suggest that foliar selenium significantly influences macronutrient dynamics under varying water stress levels in Table 2.

3.4 Physiological diagnosis and established norms of the nutrient balance

The established norms provide a valuable reference framework for evaluating nutrient balance in sunflower grain through the mineral ratio N/P, N/K, and K/P. These diagnostic ranges are crucial for assessing the nutritional status of sunflower crops under different growing conditions, especially when foliar treatments such as selenium are involved in Table 3.

3.4.1 Physiological diagnosis using nutrient ratios

According to the classification, A severe deficiency is indicated when N/P<5.57, N/K<1.51, or K/P<1.46. A balanced or normal nutrient condition corresponds to N/P between 6.45–7.03, N/K between 2.63–3.37, and K/P between 2.06–2.46. Severe excess is observed when N/P>7.91, N/K>4.49, or K/P>3.06. Using these norms, sunflower samples treated with selenium and evaluated under water stress can be diagnostically categorized for each treatment condition. For instance, in earlier presented Table 1, under 0 ppm Se with full irrigation, the N/P ratio was 7.41, which places it in the “Excess” class. Similarly, the N/K ratio of –192 is not physiologically realistic and may

indicate miscalculation or an error in the data unit interpretation. However, assuming normalized ratio data in subsequent treatments. At 10 ppm Se, if the N/P dropped to 6.28, it falls under the “Tendency (Deficiency)” category, indicating improved nutrient balance due to selenium application.

3.4.2 Application of diagnosis for field management

The application of these diagnostic norms allows agronomists to tailor fertilization strategies more precisely. For instance, if a sunflower crop shows an N/P of 5.2 (severe deficiency), it implies the need for phosphorus supplementation. Conversely, a $K/P > 3.06$ would suggest potassium is in excess and may interfere with the uptake of other cations. This is a DRIS (Diagnosis and Recommendation Integrated System) nutrient diagnosis chart a visual representation used to assess the nutritional balance of crops based on nutrient ratios rather than absolute concentrations.

3.5 The DRIS nutrient balance

The DRIS nutrient balance diagram illustrates the relative imbalances among nitrogen (N), phosphorus (P), and potassium (K) in sunflower tissue, based on the key DRIS ratios (N/P, N/K, K/P). The N/P ratio (8.723) was significantly higher than expected, indicating a pronounced relative excess of nitrogen compared to phosphorus, a condition often associated with P limitation in sunflower and potentially reducing yield potential. The K/P ratio (1.847) also exceeded the balanced norm, showing that potassium is proportionally more abundant than phosphorus; while K plays a vital role in oil yield and stress tolerance, excessive levels can limit P uptake. The N/K ratio (4.297), though closer to the optimal range, still suggested higher nitrogen relative to potassium, which can hinder carbohydrate transport and water use efficiency. Outward-pointing arrows on the diagram indicate nutrient excesses (notably N and K), whereas inward arrows suggest deficiencies (notably P), emphasizing phosphorus as the most limiting nutrient in this case. Therefore, correcting this imbalance may involve increasing phosphorus fertilization, especially at key growth stages, and adjusting nitrogen and potassium rates to avoid further nutrient skew. Regular foliar or soil P testing, coupled with DRIS index recalculation, is recommended to monitor nutrient status and guide precise fertilization, taking into account that sunflower nutrient requirements shift across growth stages (30, 45, 60, and 75 days after sowing) in Fig. 3.

4 Discussion

The DRIS analysis consistently diagnosed phosphorus (P) as the most limiting nutrient in sunflower, particularly under moderate and severe water stress. This diagnosis is physiologically meaningful, as phosphorus plays a central role in energy metabolism (ATP synthesis), membrane phospholipid stability, and carbon partitioning toward oil biosynthesis. In sunflower, adequate P nutrition has been directly linked to enhanced oil accumulation through improved photosynthetic transport to developing seeds and increased activity of enzymes involved in lipid synthesis, especially under drought conditions where energy demand and metabolic efficiency become critical [17, 18]. Moreover, phosphorus contributes to improved root growth and hydraulic conductivity, thereby enhancing drought resilience. The DRIS-identified P limitation therefore aligns well with known physiological constraints affecting sunflower productivity under water deficit.

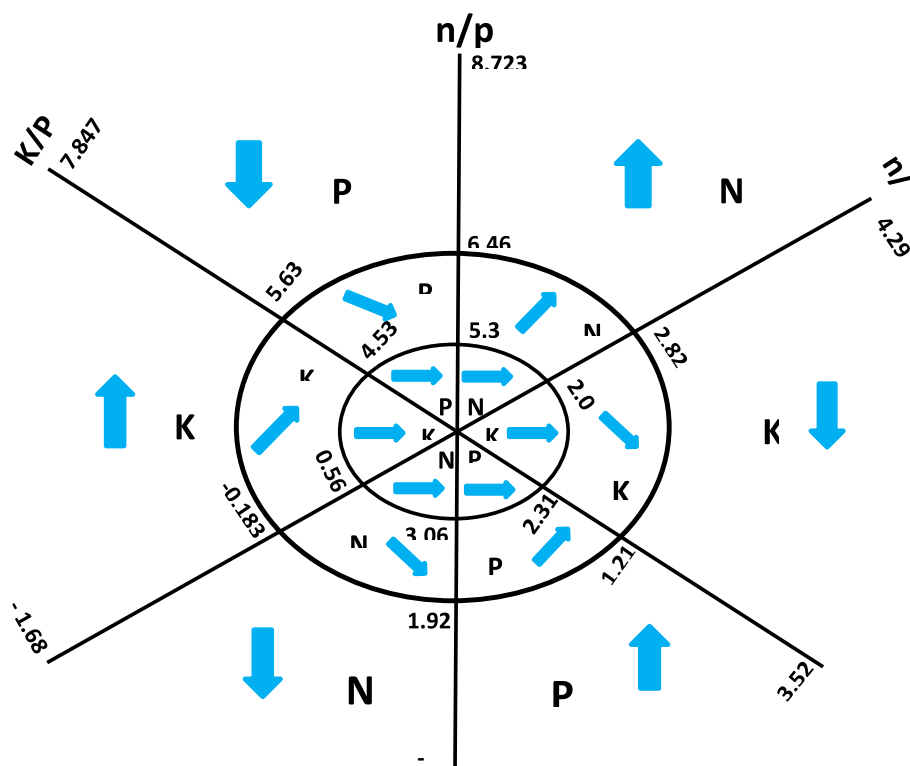


Fig. 3 The DRIS nutrient balance diagram

Foliar selenium application significantly enhances seed and oil yield of sunflower, particularly under both optimal and deficit irrigation conditions. This can be attributed to selenium's role in improving plant tolerance to abiotic stress, enhancing antioxidant defense systems, and stimulating growth and productivity processes. This aligns with previous studies where selenium at appropriate doses improved oilseed crop yield and mitigated drought effects [17, 19]. Water stress significantly reduced both seed and oil yield in untreated plants. However, selenium applications at moderate to high doses partially offset the yield losses caused by water stress. This result supports findings by [19–21]. Interestingly, oil yield under 50% WR with 20 ppm Se was higher than in many lower selenium treatments under full irrigation, indicating the potential of selenium to compensate for water deficiency stress when optimally applied. Although 20 ppm Se produced the highest absolute yield values, the 10 ppm dose under 75% WR provided a more agronomically efficient balance between yield improvement and nutrient stability, suggesting it as the optimal Se rate under moderate water deficit conditions.

The improved NPK ratios and reduced NBI (Nutrient balance index) values with selenium indicate enhanced nutrient synergy and reduced nutrient imbalance. Selenium likely boosts root activity and membrane permeability, thus facilitating nutrient absorption even under drought stress [22, 23]. The enhanced N and K uptake may be attributed to selenium's role in up regulating nutrient transporters and reducing oxidative stress [19, 24]. The highest NBI values at 0 ppm selenium under reduced irrigation levels (75% and 50%) highlight the disruption in nutrient equilibrium under stress. However, foliar application of selenium (especially 10–20 ppm) significantly corrected these imbalances, as seen from the lower NBI values. This suggests that Se foliar spraying can serve as a mitigation strategy to enhance nutrient use efficiency and maintain metabolic stability

under drought. Similar findings were reported by [25, 26], who observed increased nutrient assimilation and improved physiological functions with Se application under abiotic stress.

The nutrient balance indices and requirement order suggest that foliar selenium significantly influences macronutrient dynamics under varying water stress levels. Under full irrigation, selenium slightly increased nutrient uptake, particularly phosphorus and potassium, possibly due to its role in enhancing membrane permeability and nutrient transport [25–27]. However, the impact of selenium was more pronounced under moderate (75%) and severe (50%) water stress, where the untreated plants showed high nitrogen accumulation with suppressed P and K uptake an imbalance likely due to water stress-induced inhibition of root activity and nutrient translocation [18, 19]. Application of 10–20 ppm Se under water stress helped restore nutrient balance, reflected by more uniform PD chart symbols ($\rightarrow$) and a favorable nutrient requirement order ($P > N > K$), indicating improved nutrient synchrony. Selenium may mitigate oxidative stress, thereby supporting root function and nutrient mobilization [28]. This aligns with previous findings where selenium improved nutrient use efficiency under abiotic stress conditions [29]. Notably, the P index increased most significantly with selenium, highlighting selenium's potential to alleviate P deficiency under drought possibly by promoting root exudates that aid in phosphate solubilization or by influencing microbial activity in the rhizosphere [30]. These diagnostic categories reveal that foliar selenium spray tends to shift mineral ratios closer to the “balanced” zone, particularly for phosphorus, which often limits sunflower productivity. Similar observations were made by [31], who noted that selenium improves nutrient assimilation and optimizes nutrient ratios by enhancing root uptake dynamics and internal translocation. This approach is supported by [25, 32] who emphasized the importance of nutrient ratios (rather than absolute values) in diagnosing plant nutritional disorders. Moreover, integrating DRIS (Diagnosis and Recommendation Integrated System) with the interpretation norms (as done here) enhances precision in decision-making. This is a DRIS (Diagnosis and Recommendation Integrated System) nutrient diagnosis chart a visual representation used to assess the nutritional balance of crops based on nutrient ratios rather than absolute concentrations. Findings from previous sunflower DRIS studies indicate that optimal yields and the lowest nutrient imbalance index occur when P and K applications are balanced, particularly when the nutrient balance index is close to zero [33]. Selenium (Se) application in arid and semi-arid regions represents a cost-effective and practical agronomic strategy when applied at low, optimized doses. Because selenium is required in trace amounts, foliar application adds minimal input costs and can be readily integrated into existing crop management practices. Under water-limited conditions, selenium enhances stress tolerance, water-use efficiency, and yield stability, thereby improving economic returns. When appropriately managed, selenium use poses low environmental risk and supports sustainable crop production in arid agro ecosystems.

5 Conclusion

The findings clearly demonstrate the beneficial role of selenium foliar application in mitigating water stress effects on sunflower yield and nutrient dynamics. Specifically yield Enhancement: Selenium at 10 ppm notably improved seed and oil yield, particularly under 75% WR, indicating it as the most effective treatment under moderate water

deficit. Nutrient Uptake and Balance: Selenium enhanced NPK concentrations and positively influenced nutrient balance indices (NBI), with higher selenium levels reducing nutrient imbalances. DRIS Interpretation: DRIS indices and PD charts revealed that phosphorus was consistently the most deficient nutrient, followed by nitrogen and potassium. Selenium application helped shift nutrient order toward a more balanced $P > N > K$ profile. Ratio Classification: According to Table 3 norms, treatments with 10–20 ppm Se under partial irrigation moved nutrient ratios closer to the “Balanced” ($\rightarrow$) and “Tendency toward excess” ($\nearrow$) ranges, indicating improved nutritional status. Sustainable Implication: Moderate selenium supplementation can be strategically integrated with localized irrigation management to enhance sunflower resilience and productivity under water stress. These results emphasize selenium’s potential as a practical tool for improving crop performance in arid and semi-arid agricultural systems through enhanced nutrient use efficiency and water productivity.

Abbreviations

Se	Selenium
DRIS	Diagnosis and recommendation integrated system
N	Nitrogen
P	Phosphorus
K	Potassium
NBI	Nutrient balance index
WR	Water requirement

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44279-026-00496-5>.

Additional file 1.

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Author contributions

EB designed and performed the experiment, responsible of physiological analysis of the manuscript and also wrote and reviewed the manuscript, designed and performed the experiment, responsible of statistical analysis and also wrote and reviewed the manuscript, SE designed and performed the experiment and also wrote and reviewed the manuscript and designed and performed the experiment. All authors have read and agreed to the published version of the manuscript.

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Data availability

The datasets generated during and/or analyses during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

All experimental procedures involving sunflower (*Helianthus annuus* L.), including field trials, foliar selenium application, irrigation treatments, and plant material collection, were conducted in accordance with relevant institutional, national, and international guidelines and legislation governing plant research. The experiments were carried out at the Research and Production Station of the National Research Centre (NRC), Nubaria, Egypt, following the standard agronomic and environmental safety regulations approved by the NRC. No protected, endangered, or genetically modified plant species were used in this study, and all plant material was handled in compliance with Egyptian agricultural and biosafety regulations. All field experiments and plant material collection followed institutional, national, and international regulations.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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